Effects of Climate Signals on Shrimp and Crab Trawl Surveys in Ossabaw, St. Andrew, and Cumberland Sounds

Prepared for GA DNR – Coastal Resources Division

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December 2014

Georgia Coastal Research Council

Executive Summary

We analyzed the correlations between the GA DNR CRD trawl catch time series (blue crabs, brown shrimp, white shrimp, and pink shrimp) and river discharge, salinity, water temperature, and climate signals in three estuarine systems on the GA coast (Ossabaw, St. Andrew and Cumberland) . We also obtained fishery data from the Atlantic Coastal Cooperative Statistics Program and compared trawl catch rates with statewide catch per unit effort (CPUE) for the four species considered here. For available observations between 1986 and 2011, we found that the relationships between climate signal (Bermuda High Index, El Niño/Southern Oscillation Index, Atlantic Multidecadal Oscillation) patterns, precipitation, and river discharge that were revealed in the first phase of this analysis (Alber and Sheldon 2013) extended to salinity as well. Although the correlations were somewhat weaker, signals that were positively related to discharge were negatively related to salinity. We also found limited correlations of water temperature with climate signals, including correlations with the North Atlantic Oscillation, which did not show correlations with salinity or flow variables. Correlations between trawl catch and river discharge and salinity were limited and weak. Fall-winter river discharge (positively) and salinity (negatively) influenced blue crab catch at a lag of 0-1 month. Correlations with the three shrimp species were so weak and variable that they may have been just statistical artifacts. We found positive correlations of blue crab catch with temperature only in the coldest winter months in the upper and middle sectors of the estuaries, and no consistent correlations of temperature with the three shrimp species. We found no credible evidence of correlations of trawl catches of shrimp or crabs with any of the four climate signals. This is consistent with the apparent disconnect between trawl catch and physical variables (salinity, temperature) that were weakly to moderately influenced by the climate patterns. Comparisons between the trawl catch rates and fishery CPUE were limited to the period 2001 to 2011 due to changes in reporting practices over time. Correlations were moderate at best (white and brown shrimp in some sectors) and often very poor (pink shrimp, blue crabs), suggesting that extrapolating results from the trawl surveys to the effects of climate patterns on the larger populations that are susceptible to the statewide fisheries should be done with caution.

Background

The influence of climate on physical and biological systems has become a topic of great interest in the science and management of natural resources. In the case of estuaries, freshwater delivery can be affected by changing weather patterns over the watershed. The amount and timing of freshwater delivery greatly influences estuarine characteristics such as the salinity gradient, currents, sediments, and residence times of water and dissolved and particulate constituents. Temperature is another avenue for climate effects and can combine with salinity gradients to help shape estuarine habitats and define habitat availability for estuarine organisms.

We have previously investigated the relationships between large-scale climate patterns and freshwater inflow to the Altamaha River estuary in Georgia (Sheldon and Burd 2014). In the first phase of the present study, we extended that analysis to three other estuaries in Georgia where freshwater is supplied mainly by river discharge: Ossabaw Sound (Ogeechee River), St. Andrew Sound (Satilla River), and lower Cumberland Sound (St. Marys River). We found statistical linkages between three climate signals (Bermuda High Index (BHI), El Niño / Southern Oscillation (ENSO), and Atlantic Multidecadal Oscillation (AMO)) and precipitation and river discharge to these four Georgia estuaries. The position of the Bermuda High was associated with most of the late spring-early fall precipitation variability (after the mean annual cycle was accounted for), the ENSO cycle was associated with late fall and winter variability, and the AMO was associated with a long-term seasonal modulation. We found no linkages to four other climate signals: the Pacific Decadal Oscillation (PDO), the Pacific/North American Pattern (PNA), the central Pacific El Niño Modoki, or the North Atlantic Oscillation (NAO). The first phase analysis was described in Sheldon and Alber (2013); relevant results are summarized below in the context of the new information presented here.

In this report we evaluated the population monitoring data collected by Georgia DNR CRD for commercially important blue crabs and Penaeid shrimp in the three estuarine systems evaluated in phase one of the study (Ossabaw, St. Andrew and Cumberland). Our goals were to look for evidence of the large-scale climate patterns, and to assess climate effects on water column parameters (salinity, temperature) to see if these suggest mechanisms by which climate signals might affect the crabs and shrimp.

Methods

The correlation methods used in this study are the same as in Sheldon and Burd (2014) and Sheldon and Alber (2013) and are repeated here only in brief, with slight differences noted.

Ecological Monitoring Survey Trawl Data

The trawl data that were provided by GA DNR CRD from their Ecological Monitoring Surveys included samples from January 1976 to May 2014. Throughout this time period, samples were taken by otter trawl approximately monthly at 6-7 fixed sites within each estuarine system (Ossabaw, St. Andrew, and Cumberland). At least two sites are located in each of the following sectors within each system: the upper estuary in large creeks and rivers, the middle estuary or sound, and the ocean just outside the sound (Figure 1.). Gear has remained standardized throughout the study period: an otter trawl with a 40-foot flat net (no bycatch reduction device or turtle excluder device) is towed behind a research vessel for approximately 15 minutes (time recorded). Catches are sorted to species and weighed. Representative random samples are also weighed, counted and measured, although we used only the total weight data for this study. Historically the survey has focused on blue crabs (*Callinectes sapidus*) and commercially important Penaeid shrimp (northern white shrimp (*Litopenaeus setiferus*), northern brown shrimp (*Farfantepenaeus aztecus*), and northern pink shrimp (*Farfantepenaeus duorarum*)). In recent decades the survey was expanded to include finfish and other organisms, but we used only the shrimp and crab data because long time series are required for climate-related analyses. Ancillary data that are collected include latitude, longitude, tide stage, water temperature, salinity, and dissolved oxygen concentration.

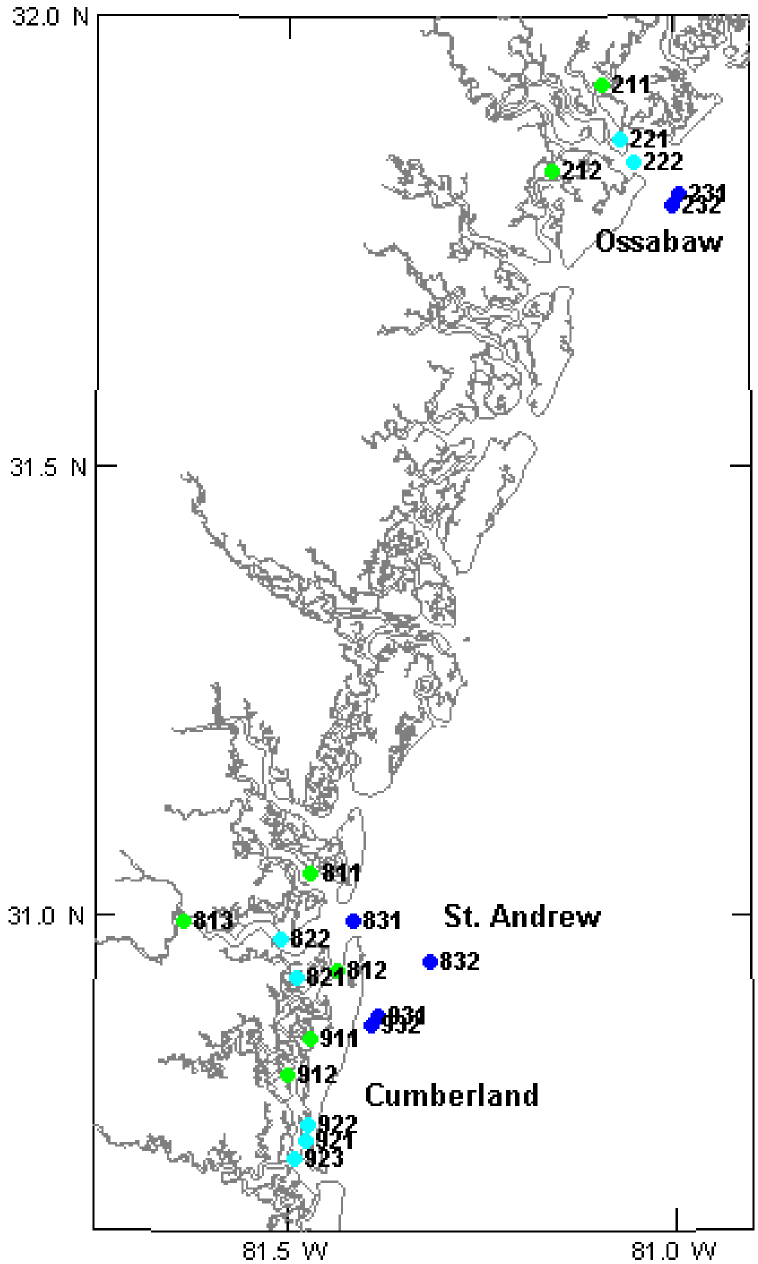

Figure 1. Nominal trawl site locations. Green dots: upper sectors (creeks/rivers); cyan dots: middle sectors (sounds); blue dots: lower sectors (nearshore ocean).

We established the following convention for referring to data at different levels of spatial aggregation. The data refer to fixed locations as "stations" but we follow our convention and use the word "site" to refer to a location, reserving the word "station" to refer to a specific sampling event at a site. Site codes are three-digit hierarchical numbers: the first digit represents the system (2=Ossabaw, 8=St. Andrew, 9=Cumberland); the second digit represents the sector (1=creek/river, 2=sound, 3=nearshore ocean); and the third digit represents the fixed site (1, 2, or 3). Therefore, a single digit refers to all sites within a system (e.g. System 2 is Ossabaw) and two digits refers to all sites within a sector (e.g. Sector 23 is offshore from Ossabaw Sound). Spatial coordinates for each site have differed slightly over the years, but nominal site locations are shown in Figure 1.

Analysis Timeframe

We inspected the data for quality control and corrected errors in cases where we could be reasonably sure of the correction. The first level of correction was applied to station information. Multiple data fields are used to record location information: beginning latitude, beginning longitude, ending latitude, ending longitude, system, site, and a "RefNum" (station code) that encodes system, date, and site. In cases where these fields were in disagreement, such as coordinates clearly not in the study area or site numbers that didn't match the sound designation, we could use a consensus of the information to establish the correct site for the record. In a few cases, sites had two records with different data for the same month. If one record had null fields and the other had data, we assumed the record with data was the correct one. In a few cases, a seemingly duplicated record was identified as a missing record in another series by matching dates and ancillary station data.

After station corrections, we assessed remaining sampling gaps and the length of time series at each site. Ossabaw sites had no samples from 1980 through 1985, and sampling in the St. Andrew and Cumberland systems was intermittent (not monthly) during that period, so we restricted the analysis to January 1986 and later. There was also a lot of missing data in 2012 and 2013, so we set the end date for analysis at December 2011. Within that time period, Table 1 lists the available data at each site and gaps remaining. This 26-year analysis period is considerably shorter than the 54-year period (December 1956 – May 2010) that we were able to analyze for the first phase of this study addressing climate patterns in precipitation and river discharge records (Sheldon and Alber 2013). It may therefore be more difficult to positively identify climate connections, especially with the climate signals that have longer frequencies such as the AMO.

Table 1. Sites used in this study, data within the analysis period Jan. 1986-Dec. 2011, station gaps, and sector parameter gaps that were filled.

Site	Series Begins	Series Ends	Station Gaps	Sector Parameter Gaps
Ossabaw				
211	1/1986	12/2011		8/2010 Temperature, Salinity
212	1/1986	12/2011		8/2010 Temperature, Salinity
221	1/1986	11/2011	12/2011	
222	1/1986	12/2011		
231	1/1986	12/2011		
232	1/1986	12/2011		
St. Andrew				
811	1/1986	12/2011		4/1986 Salinity
812	1/1986	12/2011		4/1986 Salinity
813	5/2006	12/2011		
821	1/1986	12/2011		4/1986, 2/1987 Salinity
822	1/1986	12/2011		4/1986, 2/1987 Salinity
831	1/1986	12/2011		4/1986, 1/1987 Salinity
832	1/1986	12/2011		4/1986, 1/1987 Salinity
Cumberland				
911	1/1986	12/2011		4/1986 Salinity, 8/2011 Pink Shrimp Weight
912	1/1986	12/2011		4/1986 Salinity, 8/2011 Pink Shrimp Weight
921	1/1986	12/2011		4/1986 Salinity
922	1/1986	12/2010	12/2009	4/1986 Salinity
923	12/2009	12/2011		
931	1/1986	12/2011		4/1986 Salinity
932	1/1986	12/2011	3/2009	4/1986 Salinity

Crab and Shrimp Catch Data

We checked for consistency among reported total species weights and counts, sample weights and counts, number per pound, and counts of males and females. Some zero values were converted to missing values based on the related information. We used only total species weights for our analysis, as we assumed that biomass would be more likely than counts to show any relationships with climate patterns. Trawl tow durations were not always the same, so we calculated species total weight caught per tow minute as a measure of catch per unit of effort (CPUE).

Water Column Parameters

We wanted to have the longest possible time series for climate analyses so we used only surface water parameters, which have been recorded throughout the survey period. However, we were able to use the bottom water parameters that have been recorded since 2005, as well as normal seasonal temperature trends, to check and correct surface water parameters that appeared to be outliers, such as surface salinity greater than bottom salinity, or temperature unlikely for the season. A few obvious field swaps (salinity for temperature) were identified and corrected in this way. Some questionable records (such as unseasonable temperatures) remain because they could not be positively identified as errors. We did not analyze dissolved oxygen patterns because it was not recorded prior to April 1989.

Spatial Aggregation of Survey Data

With motile organisms such as shrimp and crabs, having fixed survey sites raises the issue of whether the trawl survey is representative of the local abundance. Since the goal of this study was to assess climate patterns that we expect would exist on a regional scale, we first investigated the similarity in catch over time within sectors and whole estuarine systems by correlation analysis of site time series. In general, correlation in CPUE of each species between pairs/triplets of sites in the same sector was low (r^2 ranging from 0 to 0.58). In contrast, water parameter correlations at sites within sectors were much higher (r^2 ranging from 0.47 to 0.94 for salinity, 0.96 to 0.99 for temperature, 0.58 to 0.96 for dissolved oxygen). These results indicate that animal distributions within sectors appear to be much patchier than general water quality parameters. We concluded that site-level data are too localized to investigate for climate patterns, as any relationship found at one site would almost certainly not be found at nearby sites. We therefore decided to assess patterns only at larger spatial scales (sectors and systems) and to use the site data as random samples of the populations within those spatial scales.

River Discharge

We used the same river discharge data from the U.S. Geological Survey (USGS) as in phase one of this study (Sheldon and Alber 2013), but for the shorter analysis period used here. Briefly, for the Ogeechee/Ossabaw system we used USGS station 02202500 (Eden, GA), for the Satilla/St. Andrew system we used station 02228000 (Atkinson, GA), and for the St. Marys/Cumberland system we used station 02231000 (Macclenny, FL).

Gap Filling of Survey Data

We calculated average catch per minute and average water quality parameters across sites within sectors and systems for each calendar month. In order to do this, we used any available site data, which effectively let missing site values be estimated by the average of the available values at other sites for the same month. Within the chosen survey period, there were very few remaining gaps (months with no site data) to be filled in the time series of sector and system averages (see Table 1). The single missing temperature in sector 21 was estimated using a very strong correlation with sector 22 temperatures. Many sectors were missing salinity values for April 1986 (in addition to other times), precluding prediction from the most similar sector. Instead, we estimated missing salinity values from correlations of salinity with river flow and tide stage (see below). In all, only 9 sector salinity averages and 2 system salinity averages had to be estimated. For catch in terms of weight caught per minute, only one sector average for pink shrimp had to be estimated. We did this by using the sum of counts of males and females in the sample as an estimate of the total count, finding a seasonally appropriate mean number per pound for that month, and estimating total weight.

Climate Signals

We used the same climate signals data as in phase one of this study (Sheldon and Alber 2013), but for the shorter analysis period used here. Below we briefly reiterate the relevant characteristics of these climate patterns.

El Niño / Southern Oscillation (ENSO/SOI)

The Southern Oscillation is the atmospheric counterpart to the patterns in eastern tropical Pacific Ocean sea surface temperature known as El Niño (warm phases) and La Niña (cool phases). Collectively, this coupled ocean-atmosphere pattern is known as ENSO. The Southern Oscillation Index (SOI) is based on the difference in sea level pressure anomalies between Tahiti and Darwin, Australia (Australian Bureau of Meteorology).

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) describes north-south fluctuations in air pressure differences between the higher and central latitudes of the North Atlantic Ocean. We used monthly station-based (Azores – Iceland) index data from the National Center for Atmospheric Research (NCAR).

Bermuda High Index (BHI)

While the northern pole of the NAO generally remains in the vicinity of Iceland and Greenland, the southern pole moves east-west and is variously known as the Bermuda High or the Azores High depending on position. This oscillation is characterized by the Bermuda High Index (BHI), which is a relative index of the approximate position of the western edge of this high pressure area. We constructed the BHI as the monthly normalized pressure difference between Bermuda and New Orleans using NCAR station data (Katz et al. 2003).

Atlantic Multidecadal Oscillation (AMO)

The Atlantic Multidecadal Oscillation (AMO) is a long-term oscillation in North Atlantic Ocean sea surface temperatures. We used monthly unsmoothed index values from the U.S. NOAA ESRL Physical Sciences Division.

Preparation of Time Series for Analysis

As in phase one of this study, we took care to detect analytical problems due to autocorrelation (the correlation of time series elements with earlier values in the series). One such problem is that cross-correlating two series that have trends or cycles (autocorrelation) can produce spurious correlations that can be attributed to cycling at similar frequencies and not to real causal linkages. We first removed seasonal cycles by normalizing each time series month-by-month (e.g., January observations were normalized using the long-term mean and standard deviation for January). This produced division-by-zero errors for months that always have no catch (e.g. no brown shrimp were ever caught in January during this analysis period, so the January mean and standard deviation are both zero), so the errors were replaced with zeroes in these cases. If any series still exhibited autocorrelation, we fit an autoregressive moving average (ARMA) model and used the residuals for some subsequent analyses.

Correlation and Regression Analyses

In order to be able to fill gaps in salinity time series, we investigated relationships between salinity, river discharge, and tide stage at each site. First we used stepwise regression to determine whether discharge at lags 0 or 1 month should be included in each site's model for ln(surface salinity). (Using the natural logarithm of salinity helped to linearize the relationship with discharge.) We then performed analysis of variance for each site with ln(surface salinity) as the dependent variable, river discharge (at lags chosen by stepwise regression) as a continuous explanatory variable, and tide stage as a fixed categorical explanatory variable. Tide stage was categorical rather than continuous because the observations were binned to the nearest $1/8^{th}$ of the tidal cycle.

Using linear regression of both the monthly normalized values and the ARMA model residuals, we compared the CPUE for each species in each sector and estuarine system with the corresponding average salinity and temperature, river discharge to the system, and the four climate signals. Preliminary plots of CPUE vs. surface salinity did not indicate a need for nonlinear curve fitting. We also compared salinity and temperature with the climate signals to help determine how the climate signals might be affecting the species through their relationships with physical parameters of the water column. Since lags are expected from climate drivers through discharge, salinity and temperature to species abundance, variables were cross-correlated month by month (e.g. January crab catch with ENSO signal in each prior month for a year) in order to detect partial-year correlations and changing lag times. Correlations are shown if they are significant at $p<0.05$ and have Pearson $r^2 > 0.01$. Correlations are characterized using the Cohen scale where $0.1 < |r| < 0.3$ denotes weak, $0.3 < |r| < 0.5$ denotes moderate, and $|r| > 0.5$ denotes strong correlations.

If the correlation of ARMA model residuals produced significant results that corroborated the correlations between the original deseasonalized time series, then we considered that as evidence that the correlation could be due to causal linkages. Interpretation of all correlations for a variable of interest (deseasonalized time series and ARMA model residuals across all sectors and systems) was done as a group in order to separate consistent patterns from random correlations that are often due to a single extreme data value. The month-by-month sliding window for correlation analyses made it easier to detect variable lags and seasonal correlations but is prone to aligning extreme values in the two variables being analyzed. This often manifests as correlations of the climate signal in many months with a single isolated month of the dependent variable, whereas we expect real climate patterns to exist broadly over entire seasons. This approach was especially important for the AMO, which is a decades-long oscillation with strong autocorrelation at monthly time scales. Although this autocorrelation was removed, the AMO index also contains short-term fluctuations that can dominate the time series without reflecting changes in the underlying long cycle. The time period used here represents only part of one AMO oscillation so the short-term fluctuations are better represented than the long-term cycle, and the results must therefore be interpreted cautiously.

Trawl Data and Fishery Landings

In order to try to interpret our findings in the context of statewide commercial fishery landings, we requested monthly Georgia landings and effort data for blue crabs and the three shrimp species from the Atlantic Coastal Cooperative Statistics Program (ACCSP). Confidentiality rules prevented access to county-level data for all species, so data were only available for the entire state. Effort parameters included number of fishermen, number of dealers, and number of records per month. Confidentiality rules prevented access to monthly effort data for brown and pink shrimp, so we used monthly landings data (without effort) from the ACCSP website for these 2 species. Fishery data collection has changed in scope over time, from annual summaries (1950-1977) to monthly summaries (1978-1988) to mixed trip reports and monthly summaries (1989-2000) to entirely trip reports (2001-present). For both blue crabs and white shrimp, number of records per month increased dramatically starting in 1989 and fluctuated until the early 2000s before stabilizing into a more consistent pattern, consistent with these reporting changes. Therefore, we used pounds per record (roughly pounds per trip) as an estimate of commercial CPUE but only for the period 2001-2011. For correlation with trawl data, we eliminated months during which the food shrimp fishery is not usually fully open (January-May). We compared trawl catch in each sector and system with whole state gross landings for each species and with commercial CPUE for blue crabs and white shrimp.

Results

Trawl Catch Seasonality and Spatial Distributions

We first investigated the trawl data for seasonal and spatial characteristics of the catch per unit effort for each species.

Blue Crabs

Blue crabs were caught in trawls during all months of the year, with peak catches in spring and fall (Figure 2a). CPUE was much higher in upper and middle sectors in each system than in lower sectors, and catch rates were about the same across all three systems (Figure 2b).

White Shrimp

White shrimp were the most abundant of the three shrimp species and were caught in trawls during all months of the year, with a low catch period in June and July (Figure 2c). CPUE was much higher in upper and middle sectors in each system than in lower sectors. Catch rates were nearly the same across all three systems, with catch in the Ossabaw system being slightly lower than in the other two (Figure 2d).

Brown Shrimp

Brown shrimp were caught almost exclusively in June-August, and overall catch was only about 10% that of white shrimp (Figure 2e). More were caught in upper and middle sectors than in lower sectors, but the difference was not as great as for white shrimp. There was a slight decreasing trend in catch from Ossabaw to St. Andrew to Cumberland systems (Figure 2f).

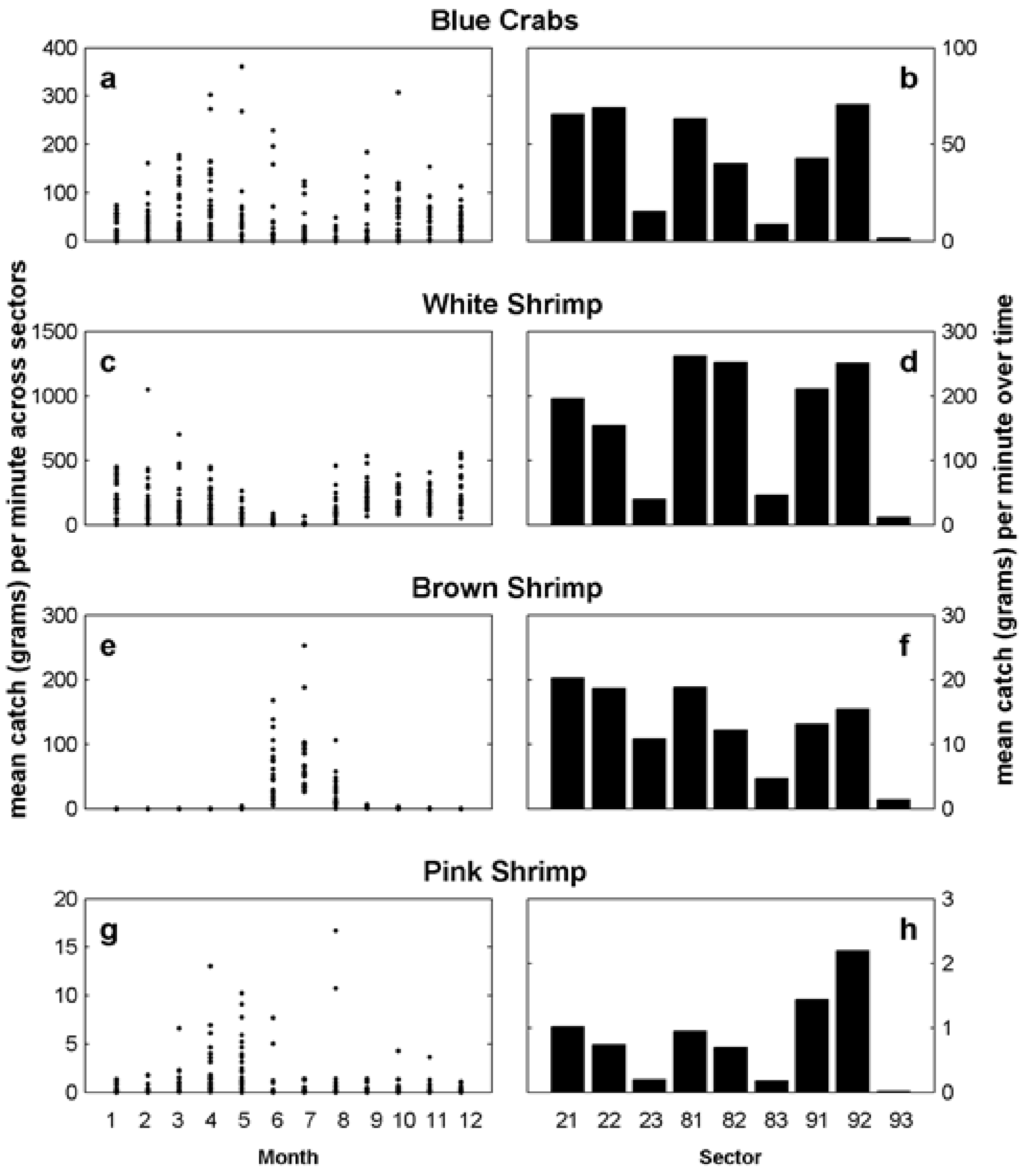

Figure 2. Mean catch (grams per minute) for each species (left) across all sectors for each month of the year and (right) over the analysis period for each sector.

Pink Shrimp

Pink shrimp were caught in trawls during all months of the year, with a peak in late spring (Figure 2g). Catch was only about 1% that of white shrimp. More were caught in upper and middle sectors than in lower sectors. In upper and middle sectors, catch was much higher in Cumberland than in Ossabaw and St. Andrew systems, but in lower sectors, catch in Cumberland was much lower than in the other two (Figure 2h).

River Discharge, Salinity and Tide

River discharge during the month of observation (lag = 0) and 1 month prior (lag = 1) was significantly and negatively related to site salinity at all but three sites: site 821 was related only at lag 0, and no significant relationships were found for sites 813 or 923, both of which had short time series. A significant 1-month lag is consistent with the long mixing time scales found for these slowly flushed coastal plain estuaries (Alber and Sheldon 1999). Tide stage was significantly related to salinity observations at all but one site (212) in the Ossabaw system. However, they were related at only three sites (812, 813, 831) in the St. Andrew system, and at no sites in the Cumberland system. Although tide stage likely affects salinity in estuaries, these results suggest that the variability in salinity due to river discharge overwhelms the variability due to tide stage at some sites.

Climate Signals, Salinity and Temperature

In phase one of this study, we found relationships between climate signals and watershed precipitation and river discharge. We presented the relationships as 2-dimensional graphics that showed the variable time lags involved by representing connections between individual months of climate signals and watershed precipitation (decomposed into principal components) and river discharge (e.g., see Sheldon and Alber 2013, Figure 3). Here we summarize those results by collapsing them to a single dimension, a line of boxes that represent connections from climate signals (at one or many months, lags not shown) to a given month of precipitation or river discharge. We then similarly represent the connections from climate signals to surface salinity and temperature, as our purpose in phase two was to see whether these relationships with freshwater inflow are reflected in water quality parameters (Figure 3).

In general, salinity correlation patterns with climate signals were comparable to river discharge correlation patterns: signals that showed positive relationships with river discharge tended to also be negatively related to salinity. The responses were often lagged an additional 1-2 months, especially during low-flow seasons. Correlation patterns were not as consistent across months as they were with precipitation and river discharge, which could be due to the shorter time series (fewer observations) used in this analysis, or to climate signal attenuation from precipitation through river discharge to salinity, especially given the additional effects of tide on salinity observations. The patterns shown in Figure 3 are a compilation from all sectors, but in general correlations were weaker and more sporadic at offshore sites. Correlations of climate signals with temperature were less frequent and not well related to the salinity correlation patterns.

Bermuda High Index (BHI)

Correlations between BHI and precipitation and river discharge are generally positive because an eastward position of the Bermuda High (positive sign convention) allows storms to enter the region. In phase one, we found that the BHI was moderate/strongly correlated with precipitation in each watershed from late spring through fall (with no lag) and with river discharge lagged approximately 1 month. Here, negative correlations with salinity were found in summer through early winter, lagged an additional 1-2 months in the Satilla and St. Marys river estuaries.

Given the dominance of the BHI in late spring-fall precipitation patterns in this region, it is surprising that temperature is not so strongly affected. There is evidence for a positive correlation only in late spring at the beginning of the Bermuda High season in all three estuaries, and near the end of the season (October) only in the Ogeechee/Ossabaw system.

El Niño / Southern Oscillation (ENSO/SOI)

Correlations between SOI and precipitation and river discharge are generally negative because of the sign convention of the SOI (negative for El Niño). In phase one, we found that SOI in summer-winter was weakly to moderately correlated with precipitation in each watershed in fall-winter. In the Ogeechee watershed, the fall-winter SOI was also moderately correlated with the second principal component of precipitation in winter, leading to an oscillation in precipitation between the upper and lower watershed.

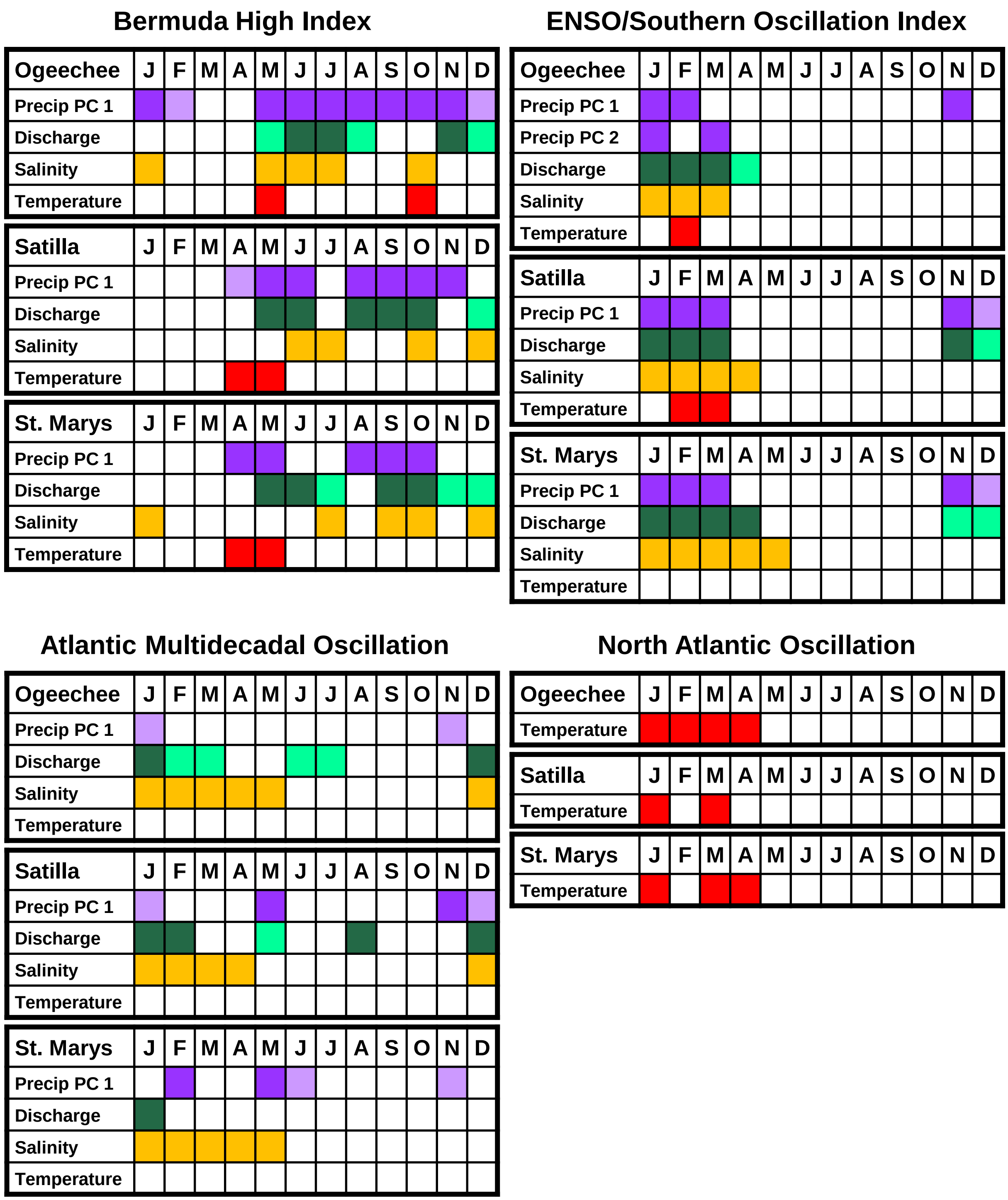

Figure 3. Correlations ($p<0.05$, lags not shown) between climate signals and watershed precipitation principal components (see Sheldon and Alber 2013), river discharge into the estuary, and surface salinity and temperature at GA DNR CRD trawl sampling sites for the Ogeechee/Ossabaw, Satilla/St. Andrew, and St. Marys/Cumberland river/sound systems. Lighter colors: $r^2<0.09$, Darker colors: $r^2>0.09$.

SOI correlations with river discharge resembled those with precipitation, with additional lags of about 1 month. Positive correlations with salinity were found in late winter-early spring.

There is very little evidence that the ENSO cycle affects estuarine water temperatures in these systems. Fall SOI was positively correlated with late winter temperatures in the Ogeechee/Ossabaw and Satilla/St. Andrew systems, but not in the St. Marys/Cumberland Sound.

Atlantic Multidecadal Oscillation (AMO)

In the Altamaha watershed, the AMO was most strongly correlated with a relatively minor modulation of precipitation patterns that tends to enhance seasonality differences in peak rainfall across the Altamaha watershed during AMO warm (positive) phases and to reduce seasonality differences during AMO cool phases (Sheldon and Burd 2014). The AMO correlation patterns are somewhat different in the three watersheds considered here, which may be due in part to poorer coverage of precipitation data across the watersheds (Sheldon and Alber 2013). Correlations of AMO with river discharge were generally stronger than with precipitation except in the St. Marys River where the most downstream gauge is relatively far upstream of the estuary mouth. Correlations with river discharge were generally negative (smaller discharge during AMO warm phases) and stronger in winter. Accordingly, we found positive correlations with salinity in winter-spring; however, these were not well corroborated by the ARMA model residuals and are difficult to distinguish from spurious correlations due to fluctuating time series.

We found positive correlations of AMO in many consecutive months with temperature in isolated months, at different lags in different sectors, and mostly not corroborated by ARMA model residuals. We interpreted these as spurious correlations not consistent with a real climate pattern, and they are not shown in Figure 3.

North Atlantic Oscillation (NAO)

In phase one, we found only sporadic, inconsistently signed, and likely spurious correlations (not shown) between NAO and precipitation and river discharge in each of these watersheds. Likewise, we found no evidence for any influence of NAO on estuarine salinity. However, the NAO was included in these analyses because it is an Atlantic Ocean signal known to affect temperature along the U.S. east coast (Rogers 1984; Hurrell and Van Loon 1997). Indeed, we found positive correlations with water temperature in winter-early spring at lag 1 month, with decreasing effect from north to south among the three estuaries.

River Discharge, Salinity, Temperature and Trawl Catch

Our evaluation of potential correlates with trawl catch yielded very few significant relationships, with weak evidence that winter river discharge, salinity and temperature may affect catch of some species. Below we briefly summarize the correlations that we did observe, although many may be statistical artifacts.

Blue Crabs

Correlations between crab trawl catch, discharge and salinity were not strong and were variable in terms of which months were affected in each sector, but taken together there is evidence that fall-winter river discharge (positively) and salinity (negatively) influenced blue crab catch with a 0-1 month lag. Only one sector (82) showed weak significant correlations with discharge and salinity during summer.

We found positive correlations of blue crab catch with temperature only in the coldest winter months in the upper and middle sectors, and no temperature influence on catch in lower (offshore) sectors. The latter is surprising given that the temperature distributions in the offshore sectors were very similar to those in the upper and middle sectors. The difference is probably not due to temperature but rather to the fact that trawl catch of blue crabs was much lower in the offshore sectors than in the upper and middle sectors. If warmer winters favor greater crab catch, it might be expected that amelioration of summer extreme temperatures might also be beneficial. Weak evidence for a negative effect of temperature during warm months was pervasive but statistically questionable due to the effects of outliers in the data.

White Shrimp

There was weak evidence suggesting that winter river discharge (positively) and salinity (negatively) influenced white shrimp catch, but the time lags were very different in different sectors so it seems likely that these are statistical artifacts and not real effects.

The few correlations that we found between temperature and white shrimp catch were questionable, with inconsistent long lags after winter temperature extremes and summer correlations that affected different isolated months in different sectors.

Brown Shrimp

We found potential positive correlations between river discharge and brown shrimp catch in June-August in two sectors: upper St. Marys (Sector 91) and middle Satilla (Sector 82). The only salinity correlation (negative) was in Sector 82 in August. It seems unlikely that flow and salinity effects on estuarine organisms would occur in a few isolated places, so these may again be statistical artifacts.

The brown shrimp catch is limited to summer months, and the few temperature correlations that we found in summer were influenced by outlier values and did not represent real trends.

Pink Shrimp

There was weak evidence in the Cumberland system only for positive correlations between river discharge and pink shrimp catch in winter, but the correlation is dependent on a few extreme values and the lack of correlation with salinity casts doubt on the significance of the flow correlation.

The few temperature correlations that we found with pink shrimp catch were influenced by outliers and inconsistent in direction (positive or negative), and did not appear to represent a true pattern with temperature.

Climate Signals and Trawl Catch

Our evaluation of potential climate signal correlations with trawl catch yielded no credible relationships. If climate signals were exerting a strong influence on catch, we would expect to see correlations across multiple sectors and contiguous months, which was not the case here. Below we briefly summarize the correlations that we did observe, although they again generally resembled statistical artifacts.

Blue Crabs

We found no credible evidence of correlations of blue crab catch with any of the four climate signals. The BHI and SOI showed no patterns at all. There were broad correlations of the AMO with single or nonadjacent months of catch that probably indicate outlier influences on the correlations, as it is not the seasonally consistent pattern that one would expect from a climate signal. The NAO also showed a few correlations in nonadjacent months with inconsistent lags that don't suggest a true climate pattern.

White Shrimp

There were widespread weak correlations of white shrimp catch with the SOI, but these were not corroborated by the ARMA model residuals and were mainly due to outlier values. The BHI and NAO each had a few isolated correlations influenced by outliers, often with changing directions of correlation, and these did not resemble true coherent climate patterns. Once again, the AMO correlations were in single or nonadjacent months, which were different in different sectors, and didn't resemble a climate pattern.

Brown Shrimp

We found weak evidence for positive correlations of brown shrimp catch with BHI primarily in middle sectors (sounds), but these appeared to be due to outliers rather than to real trends. The SOI and NAO showed no correlation patterns, and the AMO showed the inconsistent patterns in nonadjacent months that suggest statistical artifacts rather than climate influences.

Pink Shrimp

We found no evidence of correlations of pink shrimp catch with any of the four climate signals.

Trawl Data and Fishery Landings

We evaluated whether the GA DNR CRD trawl catch for any of the sectors and systems investigated in this report reflected the statewide commercial landings well enough to draw conclusions about climate effects on the fishery based on the findings of this study. Correspondence between the CRD trawl catch and the commercial landings was not strong enough to draw such conclusions. Below we describe these results in more detail.

Blue Crabs

Correlations between the monthly statewide commercial landings of blue crabs and the concurrent trawl catch rate in the sectors and systems investigated here were very poor. Half the cases showed no significant relationship at all ($p>0.05$), and those that did show a barely statistically significant trend had very weak correlations ($r^2<0.05$). Comparing the commercial CPUE instead of gross landings did not improve the relationships: three cases had no significant relationship and nine had $r^2<0.06$.

White Shrimp

Correlations between the monthly statewide commercial landings of white shrimp and the concurrent trawl catch rates during June-December were statistically significant ($p<0.05$) but not very strong ($r^2<0.09$ in upper sectors, 0.12-0.15 in middle sectors, 0.04-0.10 in lower sectors, and 0.11-0.16 in whole systems). Using commercial CPUE improved the correlations somewhat: in upper sectors, r^2 was insignificant in St. Andrew and Cumberland systems but 0.13 in Ossabaw; in middle sectors, r^2 was insignificant in Cumberland but 0.10-0.18 in Ossabaw and St. Andrew; in lower sectors r^2 was 0.11-0.30; and in whole systems r^2 was 0.09-0.21. Correlations with Ossabaw trawl catch were generally better than with catch in the other systems.

Brown Shrimp

Correlations between the monthly statewide commercial landings of brown shrimp and the concurrent trawl catch rates during June-December were better in the Ossabaw system (r^2=0.10-0.23 in sectors, 0.28 in system), worse in the St. Andrew system (r^2 was insignificant to 0.21 in sectors, 0.18 in system), and nonexistent in the Cumberland system.

Pink Shrimp

We found no significant correlations between monthly statewide commercial landings of pink shrimp and the concurrent trawl catch rates during June-December. This was a very limited data set because state landings data were missing after 1988, probably due to confidentiality limitations.

Discussion

During phase one of this study, we found broad regional climate signal patterns in the watershed precipitation and river discharge to three Georgia estuaries: the Ogeechee River/Ossabaw Sound system, the Satilla River/St. Andrew Sound system, and the St. Marys/Cumberland Sound system. In all three systems, the summer-early fall river discharge was correlated with the position of the Bermuda High, and the late fall-winter discharge was correlated with the ENSO cycle. The Atlantic Multidecadal Oscillation slightly modified the seasonality of the peak discharge, with effects that may weaken from north to south in Georgia (Sheldon and Alber 2013). These results were consistent with regional climate pattern studies. The BHI is the least well studied of the climate signals investigated here, but Henderson and Vega (1996) found significant correlations with southeast US coast precipitation, especially during spring and summer. ENSO is probably the most studied of all the known climate patterns, with warm phases (El Niño) usually associated with higher winter rainfall and cold phases (La Niña) usually associated with lower winter rainfall over the southeast (Ropelewski and Halpert 1986, 1996). Correlations between the AMO and rainfall are strongly positive in Florida and negative across much of the central US, with a change in direction near the Georgia-Florida border (Enfield et al. 2001). We failed to find any correlations of river discharge with the NAO, which has been linked to the flow of warm, moist air from the tropics into the southeastern US (Hurrell and Dickson 2004; Durkee et al. 2007).

It is not surprising that in the second phase of this study we found that the observed climate signal patterns extend to the salinity distributions in all three estuaries, as salinity in these riverine estuaries is strongly correlated with river discharge (Alber and Sheldon 1999; this study). The NAO signal, which did not correlate with river discharge, was the one signal that did not correlate with salinity. The relationships with salinity are likely even stronger than are indicated by these analyses, as the salinity observations in the GA DNR CRD data set occurred at various stages of the tide and it is difficult to account for that factor completely using semi-quantitative observations to the nearest quarter tide. We have thus established that climate signals do act through weather patterns to affect important habitat conditions in these estuaries, both seasonally and interannually.

The effects of climate signals on estuarine water temperatures were not as strong as the effects on salinity. Significant correlations were limited mainly to transitional months in the spring and, to a lesser extent, fall. These periods could still be ecologically important, however, as early spring warming could extend growing or breeding seasons for many organisms. Winter and early spring water temperatures were correlated with the NAO, corroborating other studies that have linked the NAO to temperature rather than rainfall in the southeast US (Rogers 1984; Henderson and Vega 1996; Hurrell and Van Loon 1997; Katz et al. 2003). The lack of correlations of temperature with the AMO is surprising, given that the AMO is an index of oceanic temperature. We would have expected to find correlations of AMO with water temperature especially in the lower estuarine sectors.

Correlations between trawl catch and the physical variables were few and generally weak. There was limited evidence for a positive effect of increased river discharge and decreased salinity on trawl catches of blue crabs, white shrimp, and pink shrimp only in winter. Individually, many of these correlations were statistically questionable and it is only the general agreement among them that lends weak support to the idea that river discharge and salinity may affect trawl catch rates. The only plausible correlation that we found for water temperature was with blue crab catch in the coldest winter months in upper and middle sectors. This suggests that either habitat choice or survival rate might be affected in the harshest winters, but otherwise blue crab catch in the trawl is not consistently related to water temperature.

Even though some climate signal patterns were found in estuarine salinity and temperature, we found that those physical variables affected trawl catch rates in only a few limited circumstances. This is consistent with the fact that we also found no credible links between climate signals and trawl catch of crabs and shrimp. There were cases in which large trawl catches of some species followed extreme weather events or climate signal extremes (e.g. strong El Niño) and those single values caused the correlation in that month to be statistically significant. It is certainly possible that catch rates could be affected by extreme events without being linearly related to more moderate changes in conditions. The reason that we are skeptical of these correlations representing true relationships between trawl catch and habitat parameters or climate signals is that generally there were also similar extreme events that were not followed by large catches, so the high values appeared to be outliers rather than evidence of a consistent nonlinear relationship between variables.

The lack of strong relationships between the trawl catches and other variables could be due to several factors. First, of course, is that these organisms may not be strongly affected by the climate signals investigated here. With seasonally changing dominance of climate signals, variable lag times, and effects from weather unrelated to these climate signals, overlaid by various ecological interactions (e.g. fluctuations in predation or disease), attenuation of the climate signals from precipitation to river discharge to estuarine conditions to fish catch is to be expected. The result that is more surprising is that trawl catches were not well related to physical variables (salinity, temperature) that are usually important components of estuarine habitats. Within estuarine sectors, concurrent stations generally had similar physical characteristics, yet trawl catches were highly variable. Thus other factors must have been affecting either abundances or preferred locations of organisms, resulting in patchy organism distributions that did not reflect the relatively consistent salinity and temperature conditions at the various sites. For example, we did not evaluate dissolved oxygen because of the more limited time series available. The fact that trawl collections at neighboring sites agreed so poorly suggests that sampling at two or three fixed sites per sector may not be adequate to characterize fluctuations in the organism abundances within the sectors.

Problems related to limited sampling of patchy organism distributions also raise the question of whether the climate relationships (or lack thereof) presented here reveal anything about effects on the populations of organisms that are susceptible to the commercial crab and shrimp fisheries. We investigated three riverine estuaries because we were able to find sufficient data for phase one to characterize watershed precipitation patterns and river discharge at gauged locations, and climate patterns were similar across all three as well as the Altamaha River estuary, indicating broad regional climate patterns. In general the trawl catches in these three estuaries were poor predictors of fishery landings in the same month. For white shrimp and brown shrimp, trawl catches in some individual sectors or systems explained at most 30% of the variability in the statewide commercial landings. The even poorer explanatory power for blue crabs may be attributable to gear differences (traps in the fishery vs. trawl for these monitoring surveys). Market forces and changing fishing effort may also alter the relationships between the populations that are susceptible to harvest and the actual landings. We have proceeded here with the assumption (not tested) that fishery landings generally reflect the availability of crabs and shrimp to the fishery. Nevertheless, since fluctuations in these trawl catches do not reflect fluctuations in the fishery, we must be cautious about extrapolating results from the trawl surveys to the fishery. GA DNR CRD also conducts trawl surveys in Wassaw, Sapelo, and St. Simons Sounds, where freshwater inflow to the estuaries is more difficult to characterize but crab and shrimp populations may vary differently than in the estuaries studied here, as estuaries with less direct riverine flow may offer different habitat conditions for crabs and shrimp. Thus in this study we cannot address whether the trawl catches in riverine estuaries are substantially different from the others, or whether the trawl surveys in the other estuaries, or all six estuaries taken together, might be better predictors of fishery landings. Although we found no evidence in this study for effects of four climate signals on trawl catches of crab and shrimp, we cannot say conclusively that these climate signals do not affect the larger populations that are susceptible to the statewide fisheries.

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Acknowledgments

This report was prepared by the Georgia Coastal Research Council under grant award #NA13NOS4190114 to the Georgia Department of Natural Resources from the Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of DNR, OCRM or NOAA.