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Climate-Related Hydrological Regimes And Their Effects On Abundance Of Juvenile Blue Crabs (Callinectes Sapidus) In The Northcentral Gulf Of Mexico

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Abstract—The abundance of juvenile blue crabs (*Callinectes sapidus*) in the northcentral Gulf of Mexico was investigated in response to climate-related hydrological regimes. Two distinct periods of blue crab abundance (1, 1973–94 and 2, 1997–2005) were associated with two opposite climate-related hydrological regimes. Period 1 was characterized by high numbers of crabs, whereas period 2 was characterized by low numbers of crabs. The cold phase of the Atlantic Multidecadal Oscillation (AMO) and high north-south wind momentum were associated with period 1. Hydrological conditions associated with phases of the AMO and North Atlantic Oscillation (NAO) in conjunction with the north-south wind momentum may favor blue crab productivity by influencing blue crab predation dynamics through the exclusion of predators. About 25% (22–28%) of the variability in blue crab abundance was explained by a north–south wind momentum in concert with either salinity, precipitation, or the Palmer drought severity index, or by a combination of the NAO and precipitation.

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Nonlinear oceanic-atmospheric oscillations have been linked to hydrological conditions in the continental United States. Individual and combined nonlinear oceanic-atmospheric oscillations, such as the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and El Niño Southern Oscillation (ENSO) have been shown to modulate Mississippi, Atchafalaya, Pearl, and Pascagoula river flows in their lower basins (Sanchez-Rubio et al., 2011). Discharge from the Mississippi and Atchafalaya rivers represents over 90% of the total river discharge in Louisiana (Perret et al., 1971). The Pascagoula and Pearl rivers account for more than 90% of the freshwater discharge into the Mississippi Sound (Eleuterius, 1978). High river flows in northern Gulf of Mexico (GOM) estuaries have been linked to increased commercial landings of blue crabs (*Callinectes sapidus*) in Texas (More, 1969) and Florida (Wilber, 1994) and to both commercial landings and abundance of juvenile crabs (<40 mm carapace width [CW]) in Louisiana (Guillory, 2000). River discharge enhances wetland nursery areas by increasing the geographic extent of marsh-edge habitat and by providing nutrients that facilitate growth of vegetation. The quantity and quality of coastal marsh habitat have been linked to the successful production of blue crabs. Flooding events directly influence the degree of accessibility of marsh habitats (Rozas and Reed, 1993; Minello and Webb, 1997; Castellanos and Rozas, 2001). Vegetated and ephemeral structured habitats provide chemical cues for settlement, food, and refuge to juvenile crabs (Williams et al., 1990; Heck et al., 2001; Rakocinski et al., 2003).

The blue crab is a conspicuous member of coastal ecosystems along the Atlantic and Gulf coasts and the species supports important recreational and commercial fisheries for both hard and soft crabs (Guillory et

Table 1

Meteorological and hydrological parameters and sources for juvenile blue crab (*Callinectes sapidus*) abundance data used in data analyses. Data for climate-related hydrological regimes, oceanic-atmospheric indices, and Mississippi and Pascagoula river flows were adopted from Sanchez-Rubio et al. (2011).

Parameter	Annual period	Source
Kessler east-west and north-south wind momentum, (dynes/cm^2)h	Sep–Aug	http://cdo.ncdc.noaa.gov/qclcd/QCLCD?prior=N&state=MS&wban=13820 (accessed Mar 2007).
Coastal Louisiana and Mississippi Palmer drought severity index and precipitation, mm		http://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp (accessed Mar 2008).
Louisiana coastal water level, m		http://www.mvn.usace.army.mil/eng/edhd/watercon.htm (accessed Feb 2008).
Trawl sampling salinity, ppt		Louisiana Department of Wildlife and Fisheries, Gulf Coast Research Laboratory-Mississippi Department of Marine Resources
Catch per unit of effort	Jan–Dec	

al., 2001). The ability to predict adult population size and thus annual available harvest has been limited by an incomplete understanding of the impact of biotic and abiotic variables as they relate to recruitment and survival of juvenile blue crabs. Although the oceanic-atmospheric oscillations have been associated with the amount of Mississippi River and Pascagoula River discharge (Sanchez-Rubio et al., 2011), they have not been related to the periodicity of blue crab population levels in the northcentral GOM. The purpose of the present study is to examine the relationship between nonlinear oceanic-atmospheric oscillations and juvenile blue crab abundance in the northcentral GOM and to elucidate underlying mechanisms involved in that association. This article also addresses the relevance of this study for the management of blue crab in the northcentral GOM.

Materials and methods

Data acquisition

Sanchez-Rubio et al. (2011) examined combinations of oceanic-atmospheric oscillations related to river flow in the northcentral GOM and determined that two regime occurred during the period covered in this study: I) the AMO (cold)–NAO (positive[=high water flow]) and II) the AMO (warm)–NAO (negative[=low water flow]). These regimes were used to examine the relationship between climate and juvenile blue crab abundance. Individual oceanic-atmospheric indices and river-flow anomalies were also adopted from that study. Other meteorological (wind momentum) and hydrological (precipitation, Palmer drought severity index [PDSI], water level, and salinity) data and the biological data (crab abundance) used in the present study are described and illustrated in Table 1 and Figure 1, respectively. The annual environmental data were calculated from September to August because that period incorporates the time of peak settlement of megalopae in the northern GOM and these megalopae are an important link in determining early year-class strength. Perry and Stuck (1982) noted that the large catches of blue crab megalopae in August and September were followed by an increased catch of juvenile crabs (10.0 to 19.9 mm) in October or November in Mississippi estuaries. Thus the chosen period for examination follows the dominant modal group responsible for year-class strength. Blue crabs recruit to trawls at ~30 mm CW and are abundant at this size in the winter. The January to December time frame covers the period of juvenile development and it is this period when year-class success is established.

Daily coastal water-level data were obtained from two U.S. Army Corps of Engineers gauges along the Louisiana coast (Fig. 1: see Cocodrie [1969–2000], and Rigolets [1966–2005]). Daily water-level data from the Rigolets gauge were averaged to obtain monthly water-level values. The monthly water-level values were averaged to obtain an annual water-level data set for the years 1973–2005. An annual water level anomaly was calculated by subtracting the average value by year from the yearly values of water level. Hourly wind data were obtained from the National Climatic Data Center, Ashville, NC. Hourly records of wind speed and direction were taken from the Kessler Airport, Biloxi, MS, with an anemometer mounted at 10 m height. The direction of the winds was subdivided into winds from the east (67.5–112.5°), west (247.5–292.5°), north (337.5–22.5°), and south (157.5–202.5°). Wind stress values were calculated for the four directions in dynes/cm^2. For each direction of the winds, the monthly average of wind stress was multiplied by the number of hours (wind momentum = [dynes/cm^2]h) and then, annual values of wind momentum were calculated from 1973 through 2003. To compare climate-related periods of blue crab

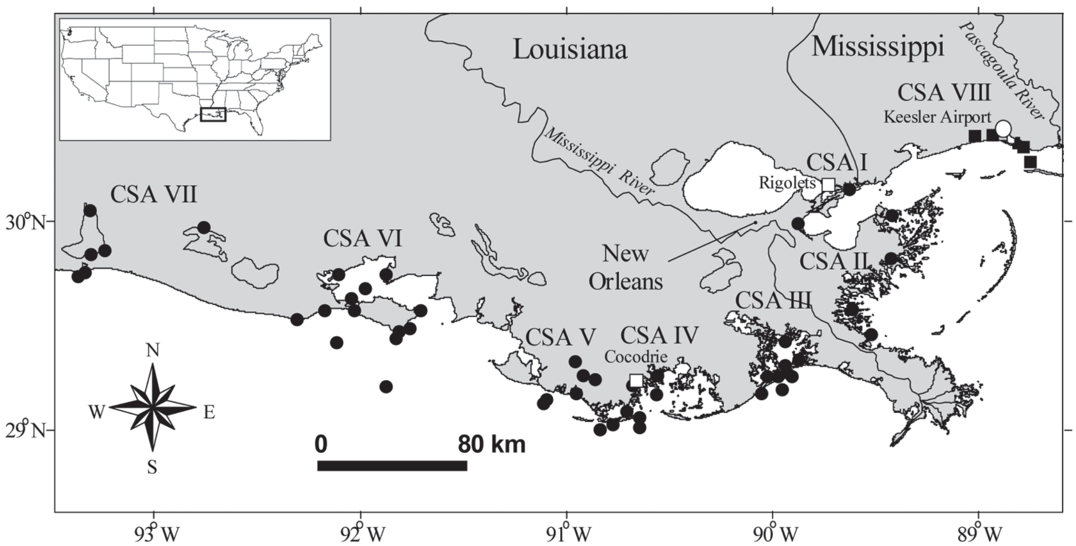

Figure 1

Trawl stations surveyed by Louisiana Department of Wildlife and Fisheries (47 solid circles) and Gulf Coast Research Laboratory (four solid squares), stations from the U.S. Army Corps of Engineers (two sea level gauges: open squares), and the wind station from the National Climatic Data Center (open circle). Coastal study areas (CSAs): I=Lake Borgne-Chandeleur Sound estuary; II=Breton Sound estuary; III=Barataria Bay estuary; IV=Terrebonne-Timbalier Bay estuary; V=Lake Mechant-Caillou Lake estuary; VI=Vermilion Bay estuary; VII=Calcasieu Lake estuary; and VIII=Biloxi estuary.

abundance, a wind momentum time series was formed by year from the difference between east and west and north and south winds. Two data sets were generated showing the east-west and north-south wind momentum values. To identify wind directions (angle with respect to the coast) influencing water level in the northcentral GOM, PV-Wave, vers. 6.21 (Visual Numerics Inc., Boulder, CO) software was used to correlate the Kessler Airport wind direction (vector) and water level from one gauge west (Cocodrie) and one gauge east (Rigolets) of the Mississippi River Delta.

Annual PDSI and precipitation values were calculated for each of the four divisions (southwest, southcentral, and southeast Louisiana, and coastal Mississippi) in the northcentral GOM. For each of the four divisions, an annual precipitation anomaly was calculated by subtracting the average value by year from the yearly values of precipitation. Annual PDSI (Pearson $r>0.649$, $P<0.001$) and precipitation (Pearson $r>0.646$, $P<0.001$) values were highly correlated among the four divisions and thus allowed calculation of regional annual (1967–2005) data for both variables.

Long-term, fishery-independent, biological data were acquired from 47 stations in Louisiana (Louisiana Department of Wildlife and Fisheries) and four stations in Mississippi (Gulf Coast Research Laboratory and Mississippi Department of Marine Resources). This region was divided into eight coastal study areas (CSAs): seven in Louisiana and one in Mississippi (Fig. 1). Louisiana data (CSAs I–VII) cover the period 1967 to 2005 and samples were collected weekly from March to October and biweekly from November to February. Mississippi data (CSA VIII) extended from 1973 to 2005 and samples were taken monthly. Both states, by agreement, use standard gear and sampling protocols: a 4.9-m otter trawl (1.9-cm bar mesh with a 6.35-mm mesh liner in the codend) pulled for 10 minutes. Crabs were counted and measured to the nearest carapace width (mm). Monthly surface salinities were calculated from trawl stations west (CSA III, V–VII) and east (CSA I and VIII) of the Mississippi River Delta. Monthly salinities were averaged to obtain single data sets of annual (1973–2004) salinity for each CSA. The annual salinity of each CSA was multiplied by the number of samples taken annually and the products for all CSAs were added and then divided by the total number of samples collected in the eight CSAs. The yearly regional salinity was a weighted average by sample size, which gives to the CSAs where few samples were collected less weight than those where large numbers of samples were taken in the calculation of the regional salinity data set. An annual weighted salinity anomaly was calculated by subtracting the average value by year from the yearly values of weighted salinity. The variability of salinity can be considered regionally, because two major rivers in the west (Mississippi and Atchafalaya rivers) and two in the east (Pearl and Pascagoula rivers) of the Mississippi River Delta are responsible for 90% of freshwater discharge to the northern GOM (Eleuterius, 1978; Perret et al., 1971).

Although the biological data for Louisiana cover the period 1967 to 2005, trawl sampling effort and areal coverage among and within CSAs were variable from 1967 through 1981 and more equally distributed beginning in 1982. A regional data set of yearly overall abundance (all size classes) was constructed. The vast majority of the crabs collected were less than one year old. Crabs <50 mm CW represented 61.7% of the catch and crabs <90 mm CW represented 82%. To obtain a yearly catch per unit of effort (CPUE), the average catch by station in each study area was calculated by dividing the total catch by the total number of samples. The annual CPUE for each station within a study area was added and then divided by the number of stations to obtain a yearly CPUE for each of the eight CSAs. The annual CPUE of each CSA was multiplied by the number of samples taken annually and the products for all CSAs were added and then divided by the total number of samples collected in the eight CSAs. The yearly regional CPUE was a weighted average by sample size, which gives the CSAs with few collected samples less weight than those with a large number of samples in the calculation of the regional CPUE.

Climate-related hydrological regimes and crab abundance

Over the period of the biological surveys (1967–2005), two climate-related hydrological regimes (1973–94 and 1997–2005) were identified (Sanchez-Rubio et al., 2011). To evaluate the response of blue crab abundance to these hydrological regimes, a *t*-test was used. Relationships among crab abundance and oceanic-atmospheric oscillations and hydrological and meteorological parameters were determined by using correlation analysis. To identify models of oceanic-atmospheric oscillations and meteorological and hydrological parameters that contribute to the variability in blue crab abundance in the northcentral GOM, multiple linear regression analysis (Statistical Package R, vers. 2.7.0, http://www.r-project.org/) was used. To find the best-fitting model, an Akaike's information criterion (AIC; Akaike, 1981) and Bayesian information criterion (BIC; Raftery, 1996) were calculated for each model. To check model reliability, the models with the lowest BIC and AIC values were compared after having been corrected for small sample size (McQuarrie and Tsai, 1998). Multiple linear regression in SPSS (IBM, Somers, NY) was used on the selected models to determine their r^2 values.

Results

Climate-related hydrological regimes and crab abundance

Two long-term climate-influenced hydrological regimes were found to be related to two distinct periods of blue crab abundance in the northcentral GOM. Significance differences in blue crab mean abundance (t=3.196, P=0.003; Fig. 2) were found within regimes that were associated by Sanchez-Rubio et al. (2011) with wet and dry conditions. During regime I (wet), there were higher catches of juvenile crabs than during regime II (dry). The regime with the highest blue crab abundances had a significantly higher mean of the north-south wind momentum (t=2.187, P=0.038) and a lower mean of AMO (t=–7.276, P<0.001) than did the regime with low crab abundance (Table 2).

Correlation analysis showed that blue crab abundance was positively correlated with the north-south wind momentum (Pearson r=0.406, P=0.023) and PDSI (Pearson r=0.356, P=0.042) and was negatively related to salinity (Pearson r=0.345, P=0.053). According to the regression models developed from AIC and BIC, the north-south wind momentum in concert with either salinity, precipitation, or the Palmer drought severity index, or the combination of the NAO and precipitation were influential in determining 22% to 28% of the variability in blue crab abundance (Table 3). Figure 3 shows histograms of the variables that were associated with blue crab abundance by year.

Discussion

Early investigations into factors affecting population dynamics of blue crabs attempted to relate fluctuations in abundance to physiological tolerances to temperature and salinity. Livingston (1976) was among the first to

Table 2

Juvenile blue crab (*Callinectes sapidus*) weighted catch-per-unit-of-effort data and climatological factors showing significant differences in mean values during two hydrological regimes in the northcentral Gulf of Mexico. AMO: Atlantic Multidecadal Oscillation and NAO: North Atlantic Oscillation.

	Climate-related hydrological regimes	
Average values	AMO cold–NAO positive 1973–94	AMO warm–NAO negative 1997–2005
Weighted catch per unit of effort	7.207	4.395
AMO	–0.147	0.201
North–south wind momentum, (dynes/cm^2)h	0.083	–0.082

Table 3

Model results determined with Akaike's information criterion (AIC) and Bayesian information criterion (BIC) used to describe annual variability of the weighted catch per unit of effort (CPUE=average crab catch per ten minute trawl) of juvenile blue crabs (*Callinectes sapidus*) in the northcentral Gulf of Mexico.

Model	Response variables	Explanatory variables	df	Sum of squares	*F* value	$P(>F)$	Coeff.	AIC	BIC	r^2
1	Weighted CPUE	North–south wind momentum	1	32.261	6.8453	0.01438	5.477	51.8	0.38	0.28
		North Atlantic Oscillation	1	12.550	2.6629	0.11432	2.278			
		Precipitation	1	23.697	5.0282	0.03335	1.058			
		Intercept					5.616			
2		North–south wind momentum	1	32.261	6.3966	0.01735	5.049	53.0	0.18	0.23
		Weighted salinity	1	22.277	4.4169	0.04471	–0.3328			
		Intercept					6.0473			
3		North–south wind momentum	1	32.261	6.3389	0.01781	5.5061	53.3	0.46	0.22
		Precipitation	1	20.992	4.1248	0.05185	0.9928			
		Intercept					5.8755			
4		North–south wind momentum	1	32.261	6.3234	0.01794	4.7625	53.4	0.54	0.22
		Palmer drought severity index	1	20.642	4.0460	0.05399	0.5745			
		Intercept					5.8365			

suggest that the influence of salinity might be operating extrinsically by structuring the surrounding biotic community. Recent research indicates that predation affects abundance in the northern GOM. Studies on predator-prey interactions (Heck and Coen, 1995; Guillory and Prejean, 2001; Moksnes and Heck, 2006) and habitat selection and utilization (Williams et al., 1990; Morgan et al., 1996; Rakocinski et al., 2003) indicate that factors that increase or decrease refuge availability are also determinant in the establishment of population levels. Both inter- and intraspecific predation, operate to regulate abundance of juvenile blue crabs in the GOM (Guillory et al., 2001). A high diversity of predators, few predation-free refuges, and year round predation activity (i.e., a lack of seasonality in predation) all contribute to the high regional mortality of juvenile crabs (Heck and Coen, 1995). If predation is the primary determinant of population levels, then those factors that influence available refuge may ultimately control abundance.

In the current study, the period of greatest crab abundance (climate-related hydrological regime I) was associated with a mean positive north–south wind momentum and a mean low value of AMO. Blue crab abundance was also positively correlated with the north–south component of wind momentum and PDSI and was negatively related to salinity. About 25% (22–28%) of the variability in blue crab abundance was explained by a north–south wind momentum in concert with either salinity, precipitation, or PDSI, or by the combination of NAO and precipitation. The AMO and NAO were found to be important drivers of climate-related features influencing long-term hydrological conditions across coastal Louisiana and Mississippi

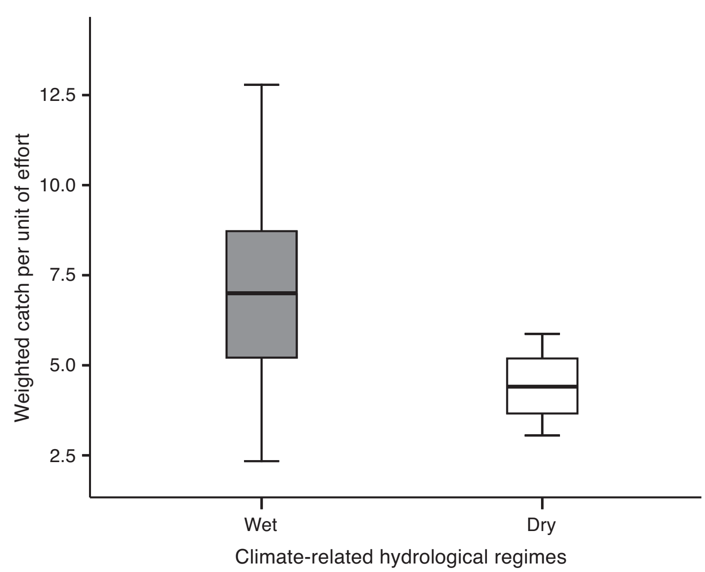

Figure 2

Weighted catch per unit of effort (CPUE=average crab catch per ten-minute trawl) of juvenile blue crabs (*Callinectes sapidus*) related to the two dominant climate-related hydrological regimes in the northcentral Gulf of Mexico between 1973 and 1994 (AMO cold–NAO positive: gray bar) and 1997–2005 (AMO warm–NAO negative: white bar). AMO=Atlantic Multidecadal Oscillation and NAO=North Atlantic Oscillation. Horizontal lines for each box plot indicate 5th, 25th, 50th (median), 75th, and 95th percentiles.

(Sanchez-Rubio et al., 2011). Mississippi, Atchafalaya, Pearl, and Pascagoula river flows and blue crab abundance were higher during AMO cold and NAO positive phases than during AMO warm and NAO negative phases. Other studies have linked blue crab abundance to river flow and salinity. Guillory (2000) noted juvenile blue crab abundance was positively related to river flow and negatively related to salinity in fishery-independent (crabs <40 mm CW) trawl survey data for Louisiana. High commercial landings of blue crabs were associated with increased river flow by More (1969) in Texas bays, Wilber (1994) in Apalachicola Bay, Florida, and Guillory (2000) in Louisiana estuaries. Hydrological conditions associated with phases of AMO and NAO in conjunction with the north–south wind may influence blue crab predation dynamics through predator exclusion. Under an annual positive north–south wind regime with flooding rain events, greater availability of low-salinity habitats increases the survival of juvenile crabs by diminishing intra- and interspecific predation. Under an annual negative north–south wind regime (inshore water movement), low-salinity habitats are reduced and there is a greater suite of predators and an increased opportunity for predation.

Although long-term climatological patterns influence the abundance of estuarine organisms, there is also evidence that an interannual oceanic-atmospheric oscillation (ENSO) can affect population levels. In microtidal Louisiana estuaries, ENSO-related hydrological conditions were found to influence the abundance of estuarine organisms over limited time periods (Childers et al., 1990). High (or low) rates of local precipitation and Mississippi River discharge were generally associated with anomalously high (or low) marsh inundation, respectively, that coincided with ENSO warm (or ENSO cold) phases. The ENSO warm and cold phases generally coincided with the lowest abundance of organisms, and the ENSO neutral phase was related to high abundance. Sanchez-Rubio et al. (2011) found that the effect of ENSO phases on river discharge was most evident in the last climate-related hydrological regime (drought) in the Pascagoula River and flow from this river was significantly higher during ENSO warm and ENSO neutral phases than during the ENSO cold phase. Although the ENSO was found to affect river flow, the limited number of ENSO phases (warm, cold, neutral) occurring during the last hydrological regime precluded any meaningful analysis of the abundance of crabs in relation to ENSO events.

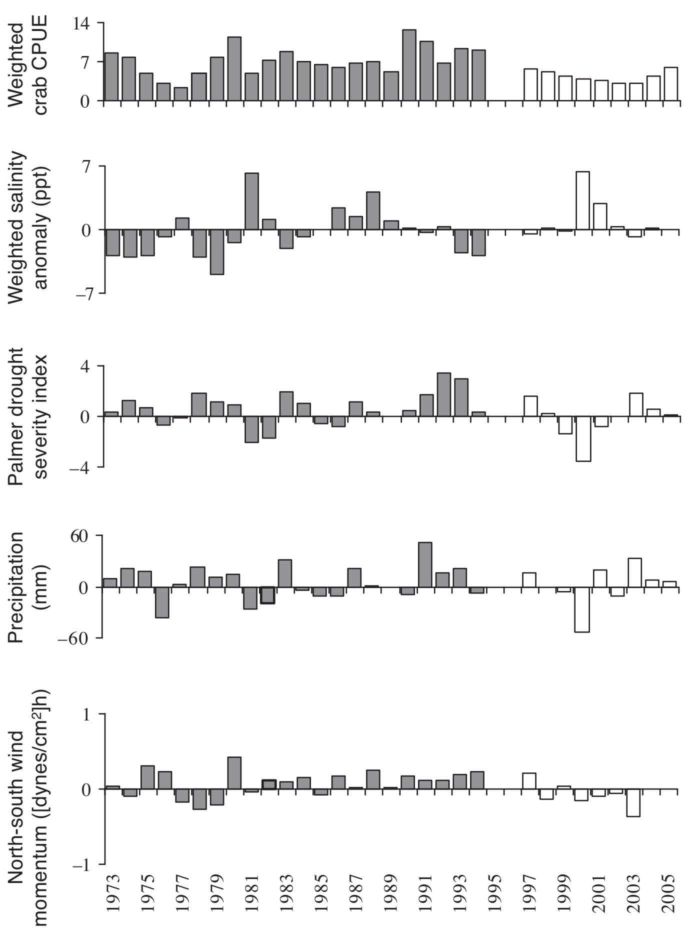

Figure 3

Weighted catch per unit of effort (CPUE=average crab catch per ten minute trawl) of juvenile blue crabs (*Callinectes sapidus*) related to highly influential hydrological and meteorological factors (salinity, PDSI, precipitation, and north–south wind momentum) in the northcentral Gulf of Mexico within two climate-related hydrological regimes (AMO cold–NAO positive: gray bars, and AMO warm–NAO negative: white bars). AMO=Atlantic Multidecadal Oscillation and NAO=North Atlantic Oscillation.

Implications for management

Management of any fishery requires some knowledge of the factors that contribute to year-class strength. Initial population levels are established by recruitment. In the northern GOM, recruitment success (measured as the number of megalopae at settlement) was found to be dependent on interannual variations in wind stress patterns coupled with basin-scale events, such as Loop Current spin-off eddies, generated during critical periods of larval development (Johnson and Perry, 1999; Perry et al., 2003). Seasonality of spawning coincided with climatological inner shelf water circulation patterns that transported larvae offshore initially but then acted to return them to shore at the appropriate developmental stage. Although annual temporal periodicity of settlement was similar, settlement was highly episodic and there were large annual variations in numbers of megalopae (Perry et al., 1995; Perry et al., 2003). Perry et al. (1998) noted that regardless of the level of recruitment, by the time crabs reach ~30 mm CW, population abundance begins to level off and then decreases at a gradual rate. In that study, high numbers of megalopae and early-stage crabs did not result in proportionally elevated numbers of late-stage juveniles; instead, high and low recruitment years had similar population levels. They concluded that the northcentral GOM blue crab fishery was not recruitment limited and that year-class strength was dependent on juvenile survival. In the northcentral GOM, there have been significant declines in numbers of later stage juveniles in trawl surveys; however, blue crabs at early life history stages collected in beam plankton trawls and seines do not exhibit similar trends (Riedel et al., 2010).

Climate interacts with an ever-changing physiographic landscape world-wide. Significant downward trends in abundance of juvenile blue crabs across the northern GOM have occurred over a period characterized by drought and unprecedented changes in habitat associated with catastrophic storms and the cumulative consequences of man-made alterations to coastal wetlands (Riedel et al., 2010). Recruitment has been adequate and numbers of megalopae and early juveniles do not exhibit declines. Unlike the fishery in Chesapeake Bay, the fishery in the GOM does not suffer from overharvesting (Riedel et al., 2010). There is strong evidence that fishery sustainability is dependent upon juvenile survival. In the northcentral GOM, climate and hydrological features operate to structure available habitat in ways that affect juvenile survival of blue crabs. Whether the shift to a more favorable climate phase would reverse declining trends is unknown because it is currently impossible to quantitatively account for the influence of changing habitats. The results of this work are a starting point toward understanding the complex relationship between climate, habitat, and fisheries productivity.

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