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Oceanic-Atmospheric Modes of Variability and Their Effect on River Flow and Blue Crab (*Callinectes sapidus*) Abundance in the Northcentral Gulf of Mexico

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The University of Southern Mississippi

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by

Guillermo Humberto Sanchez Rubio

Abstract of a Dissertation
Submitted to the Graduate Studies Office
of The University of Southern Mississippi
in Partial Fulfillment of the Requirements
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ABSTRACT

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Oceanic-atmospheric modes of variability occur on interdecadal, multidecadal, decadal, and interannual timescales and their influence on climate around the world has been confirmed. The present study investigates Mississippi River and Pascagoula River flows in response to the influence of one or more of the four oceanic-atmospheric modes of variability: the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), and the El Nino Southern Oscillation (ENSO). These modes of variability are present in phases: PDO warm (PDOw) and cold (PDOc), AMO warm (AMOw) and cold (AMOc), NAO positive (NAOp) and negative (NAOn), and ENSO warm (ENSOw), neutral (ENSOn), and cold (ENSOc). High Mississippi River mean flow was associated with the PDOw, AMOc, and NAOp phases, with low river flow linked to their opposite phases. High Pascagoula River mean flow was related to the AMOc and NAOp phases, with low river flow linked to their opposite phases. Pascagoula River flow was significantly higher during the ENSOw than ENSOc events, within PDOw/AMOw/NAOp and NAOn phase.

Blue crab data on abundance were taken from fishery-independent trawl survey programs conducted by the Gulf Coast Research Laboratory, Ocean Springs, Mississippi and the Louisiana Department of Wildlife and Fisheries in coastal waters of Mississippi and Louisiana, respectively. Four long-term climatic phases (PDOc/AMOc/NAOn, PDOc/AMOc/NAOp, PDOw/AMOc/NAOp, and PDOw/AMOw/NAOp and NAOn) overlapped with four distinct periods of annual blue crab abundance that were identified using hierarchical agglomerative clustering and non-metric, non-parametric multi-dimensional scaling techniques. The following abundance periods were delineated: period I (1967-1970), period II (1971-1980), period III (1981-1998), and period IV (1999-2004). For all but three years (1991, 1995, 2005) the overall abundance of blue crabs fell into chronological sequences under climatic phases. A single year (1990) did not group with any of the four abundance periods. Periods II and III were characterized by high numbers of crabs and increased river flow, whereas Period IV was distinguished by low numbers of crabs and decreased river flow. Years of lowest abundance (period IV) occurred at a time of unprecedented change in habitat associated with catastrophic storms, the cumulative consequences of man-made alterations to coastal wetlands, and an unfavorable climatic regime. Whether a shift to a more favorable climatic regime would increase abundance is unknown.

Blue crab abundance was related to long-term hydrological conditions across the Mississippi River and Pascagoula River basins with 23% of the variability explained by oceanic-atmospheric modes of variability (AMO, NAO), salinity, and frequency of southeast winds. These factors may favor blue crab productivity by increasing marsh edge habitat, decreasing predation, and facilitating shoreward transport of megalopae. The importance of biotic factors associated with quality of habitat as refuge has been emphasized by recent studies. Because climate operates on an ever-changing coastal environment and because of the inability to quantify sources of natural mortality of

young crabs, prediction of blue crab abundance is difficult when current knowledge is coupled solely with the influence of climatic factors.

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CHAPTER I

INFLUENCE OF OCEANIC-ATMOSPHERIC MODES OF VARIABILITY ON MISSISSIPPI RIVER AND PASCAGOULA RIVER FLOWS

Introduction

Climate in the northern hemisphere is influenced by oceanic-atmospheric modes of variability occurring on interdecadal (Trenberth 1990), multidecadal (Delworth and Mann 2000; Sutton and Hodson 2005), decadal (Mehta et al. 2000), and interannual (Wang and Fu 2000) timescales. In the continental United States, climatological studies (e.g., Rogers and Coleman 2003; McCabe et al. 2004; Tootle and Piechota 2006) have provided information that could, in the near future, aid in the development of long lead-time forecasts of streamflow. The regions of these modes of variability and the stations of river flow are illustrated in Fig. 1.

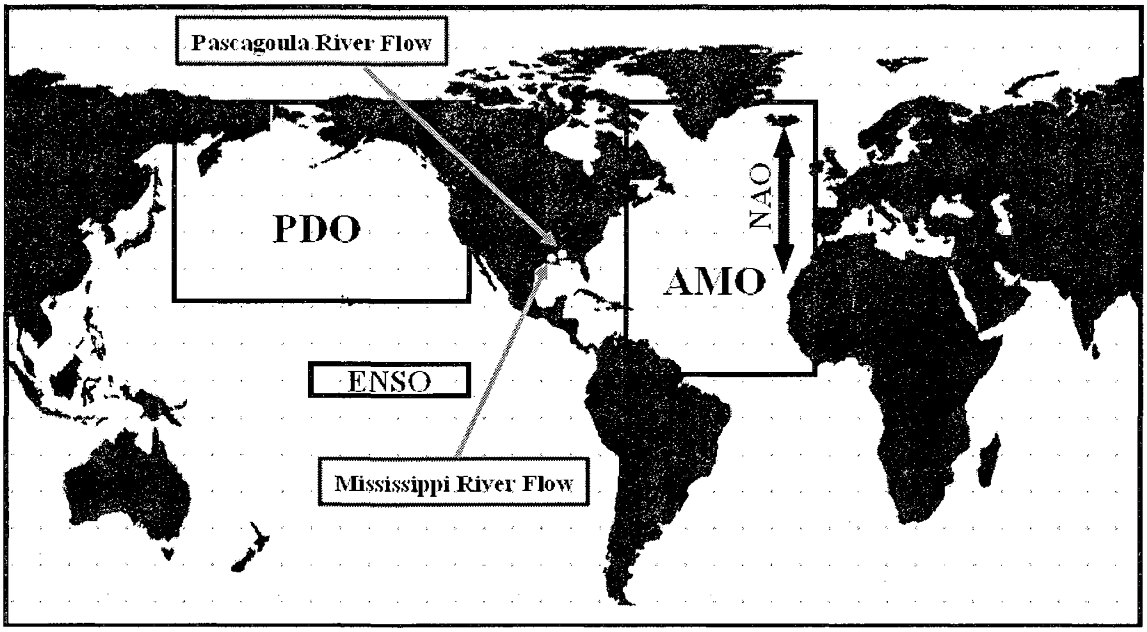

FIG. 1. General areas where the oceanic-atmospheric indices (PDO, Pacific Decadal Oscillation; AMO, Atlantic Multidecadal Oscillation; NAO, North Atlantic Oscillation; ENSO, El Niño Southern Oscillation) were calculated and Mississippi River and Pascagoula River flows data were acquired.

The PDO (Pacific Decadal Oscillation) is an oceanic-atmospheric phenomenon associated with the periodic (25-50 years) warming (PDOw) or cooling (PDOc) of the eastern North Pacific Ocean (poleward of 20° north) (Mantua et al. 1997; Mantua and Hare 2002). The AMO (Atlantic Multidecadal Oscillation) represents below (AMOc) and above (AMOw) normal sea surface temperature (SST) across the North Atlantic from 0 to 70° N latitude (Enfield et al. 2001), with a periodicity of 65-80 years (Kerr 2000; Gray et al. 2004). The NAO (North Atlantic Oscillation) is associated with a meridional oscillation in sea level pressure (SLP) between Iceland and the Azores (Hurrell and Van Loon 1997). The NAO has displayed quasi-biennial and quasi-decadal negative (NAOn) and positive (NAOp) phases since the late 1800s (Hurrell and Van Loon 1997) and its behavior is generally referred to as decadal. ENSO (El Niño Southern Oscillation) refers to the periodic (2-7 years) warming or cooling of the eastern equatorial Pacific Ocean (Lighthill 1969; Godfrey 1975; McCreary 1976) with the shift of southeast trades over the central and western Pacific (Wyrtki 1975; Krueger and Winston 1975; McPhaden 1999). The warm phase of ENSO (ENSOw) is referred to as El Niño; the cool phase (ENSOc) is referred to as La Niña; and the phase between them is referred to as neutral (ENSOn). The ENSO phases are identified using the SST anomaly from the NIÑO3.4 region (5°S-5°N and 120°W-170°W) in the equatorial Pacific Ocean.

Oceanic-atmospheric modes of variability have been associated with the hydrology and meteorology of the continental United States. Streamflows were related to the PDO (Cayan et al. 2001; Tootle et al. 2005; Tootle and Piechota 2006), the AMO (Tootle et al. 2005; Tootle and Piechota 2006), the NAO (Tootle et al. 2005), and ENSO (McCabe and Jackson 1984; Tootle et al. 2005). Changes in air temperature and precipitation were associated with the shift of the PDO phase (Cayan et al. 2001) whereas spatial and temporal variance in drought frequency was related to the PDO and AMO (Hidalgo 2004; McCabe et al. 2004). Precipitation was linked to the AMO (Enfield et al. 2001) whereas temperature and conditions of humidity were associated with the NAO (Visbeck et al. 2001). Precipitation (Douglas and Englehart 1981; Ropelewski and Halpert 1986; Ropelewski and Halpert 1987; Enfield 1996; Darby and Sondag 1998; Gershunov and Barnett 1998a; Enfield et al. 2001), temperature (Ropelewski and Halpert 1986), and the probability of hurricane landings (Bove et al. 1998; Pielke and Landsea 1999) were related to ENSO.

Long-term oceanic-atmospheric modes of variability were found to modulate the influence of ENSO in the hydrology and meteorology of the continental United States. An increase in the frequency of ENSO events (Trenberth and Hoar 1997) was noted with the shift of the PDO phase from cold to warm in 1977 (Trenberth and Hurrell 1994; Mantua et al. 1997; Minobe 1997; Zhang et al. 1997; Chao et al. 2000; Dettinger et al. 2001; Mantua and Hare 2002). The PDO was found to modulate the influence of ENSO on precipitation (Gershunov and Barnett 1998b), streamflow (Hamlet and Lettenmaier 1999; Harshburger et al. 2002; Beebee and Manga 2004; Tootle et al. 2005; Tootle and Piechota 2006), and flood potential (Pizarro and Lall 2002). The AMO modulated the influence of ENSO on precipitation (Enfield et al. 2001) whereas the AMO and NAO were found to modulate the influence of ENSO on streamflow (Tootle et al. 2005). Neither the PDO nor the NAO enhanced (or dampened) the effect of ENSO on the Palmer Drought Severity Index (Rajagopalan et al. 2000).

Recent studies have focused on the role played by the combined effect of multidecadal oceanic-atmospheric modes of variability on ENSO-related hydrology of the continental United States. Hidalgo and Dracup (2001, 2003) acknowledged a possible strong influence of the AMO in the precipitation generated by ENSO and modulated by the PDO. Also, McCabe et al. (2004) found that the wetness of ENSO was modulated by the PDO and those coupled conditions were regulated by the AMO. The ENSO-related drought frequency appears to be modulated in complicated ways by the PDO and AMO (McCabe et al. 2004) whereas streamflow is influenced by the AMO, ENSO, and the Pacific-North American (PNA) teleconnection (Rogers and Coleman 2003). The PNA teleconnection patterns are manifested as anomalies in the 700 or 500 mb (mid-troposphere) geopotential height field in the northern hemisphere winter (Horel and Wallace 1981; Wallace and Gutzler 1981; Yarnal and Diaz 1986).

The present study investigates flows of both the Mississippi River at Vicksburg, Mississippi, USA and the Pascagoula River at Merrill, Mississippi, USA in response to the influence of one or more of the four oceanic-atmospheric modes of variability: the PDO, the AMO, the NAO, and the ENSO.

Data and Methods

The responses of Mississippi River and Pascagoula River flows to phases of one or more of the oceanic-atmospheric modes of variability were examined using both parametric and nonparametric techniques. Major data sets used to establish the relationships between oceanic-atmospheric modes of variability and river flow were the oceanic-atmospheric data for the Pacific and Atlantic Oceans and river flow data for the lower Mississippi River and Pascagoula River Basins.

The PDO and AMO index values were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (2007). For the period 1945 to 2004, the cold phase (1945-1976) of the PDO index was a negative numerical index value whereas the warm phase (1977 to 2004) was a positive numerical value (Mantua et al. 1997; Hare and Mantua 2000). McCabe et al. (2004) evaluated coupled effects of the PDO and the AMO for four periods: PDO warm and AMO warm (1926-1943), PDO cold and AMO warm (1944-1963), PDO cold and AMO cold (1964-1976), and PDO warm and AMO cold (1977-1994). The PDO and AMO phases used by McCabe et al. (2004) were adopted for the period 1950-1994. For the present study, the PDO warm phase was extended to 2004, even though there was a drop in the index for the years 2000 to 2003, and the warm phase of AMO (1995-2004) was included in the analyses. A review of the PDO and AMO indices since 1948 is found in Figs. 2 and 3 and Table 1.

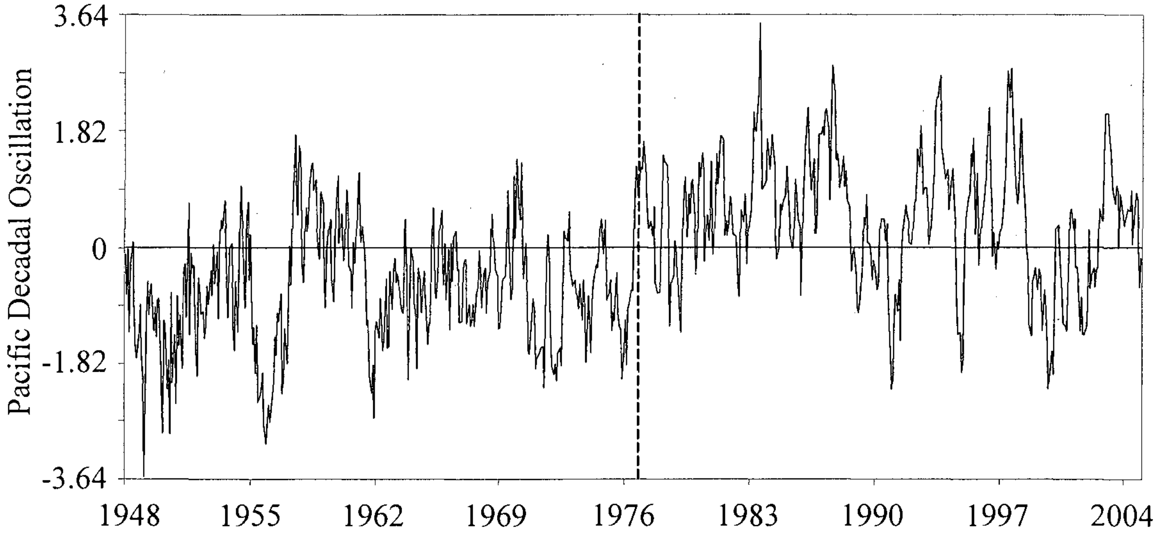

FIG. 2. PDO cold (1948-1976) and warm (1977-2004) phases are separated by the dashed vertical line.

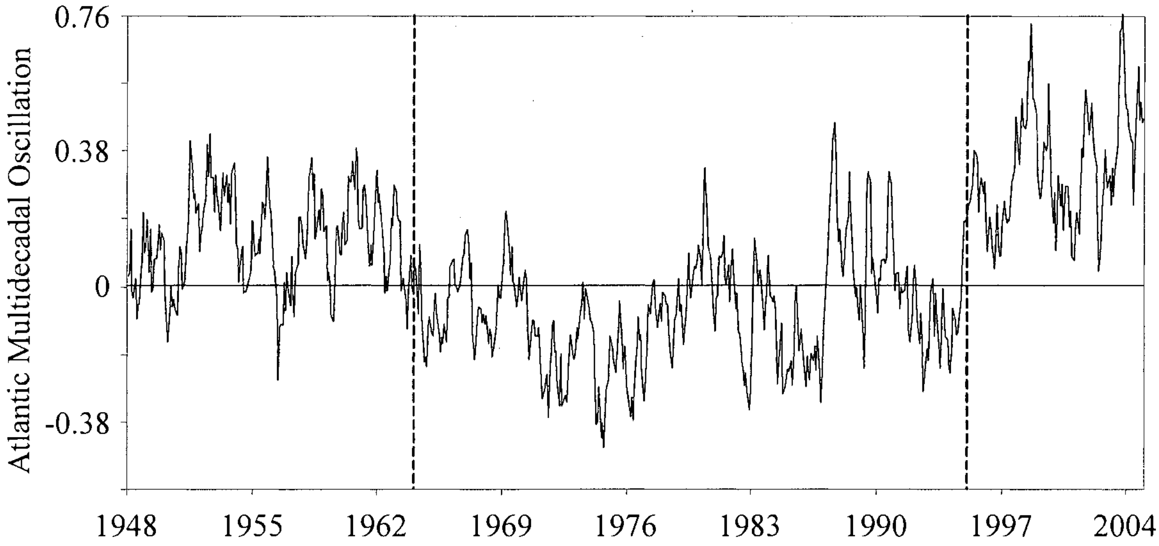

FIG. 3. AMO cold (1964-1994) and warm (1948-1963 and 1995-2004) phases are separated by the dashed vertical lines.

TABLE 1. Years identified as cold/negative, warm/positive, or neutral for the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and El Niño Southern Oscillation (ENSO).

	PDO	AMO	NAO	ENSO
COLD/ NEGATIVE	1945-1976	1964-1994	1950-1972 1997-2004	1950, 1954-1956, 1964 1970-1971, 1973-1975, 1983-1984, 1988, 1995, 1998-2000
NEUTRAL				1952-1953, 1958-1962 1966-1967, 1978-1981, 1985, 1989-1990, 1996, 2001, 2003
WARM/ POSITIVE	1977-2004	1948-1963 1995-2004	1973–1996	1951, 1957, 1963, 1965, 1968-1969, 1972, 1976-1977, 1982, 1986-1987, 1991-1994, 1997, 2002, 2004

The NAO index was taken from the NOAA Climate Prediction Center (2007a). Hurrell and Van Loon (1997) applied a low pass filter to the yearly NAO index values to remove fluctuations of fewer than four years. This resulted in a negative phase from the early 1950s to 1970s, a positive/negative fluctuation from the 1970s to early 1980s, and a positive phase from the early 1980s to mid-1990s. When applying a three year moving average to the NAO index, the NAO showed negative (1950-1972 and 1997-2007) and positive (1973-1996) phases (Fig. 4, Table 1).

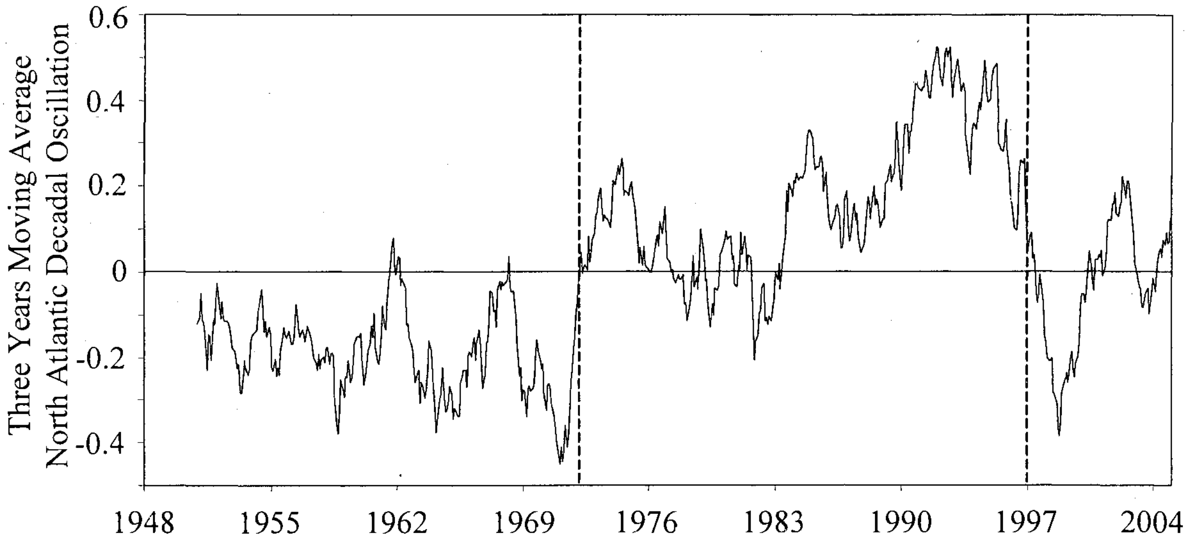

FIG. 4. NAO negative (1950-1972 and 1997-2004) and positive (1973-1996) phases are separated by the dashed vertical lines.

The NIÑO3.4 index was retrieved from the NOAA Climate Prediction Center (2007b). Although there is considerable variation among events, ENSOw and ENSOc events typically develop between April and June, and the largest (positive and negative) values of the NIÑO3.4 index tend to be observed from December to February (International Research Institute for Climate and Society 2007) Various techniques have been developed to identify ENSO events. For the present study, the approach of Rogers and Coleman (2003) was used. These authors identified ENSOw and ENSOc events as extreme when the NIÑO3.4 SST anomaly exceeded absolute 0.75°C. When there was an apparent short term event, three or more monthly values from May to February were averaged to determine the kind of event for which that year was classified. Table 1 and Fig. 5 summarize the ENSO events used in the present study.

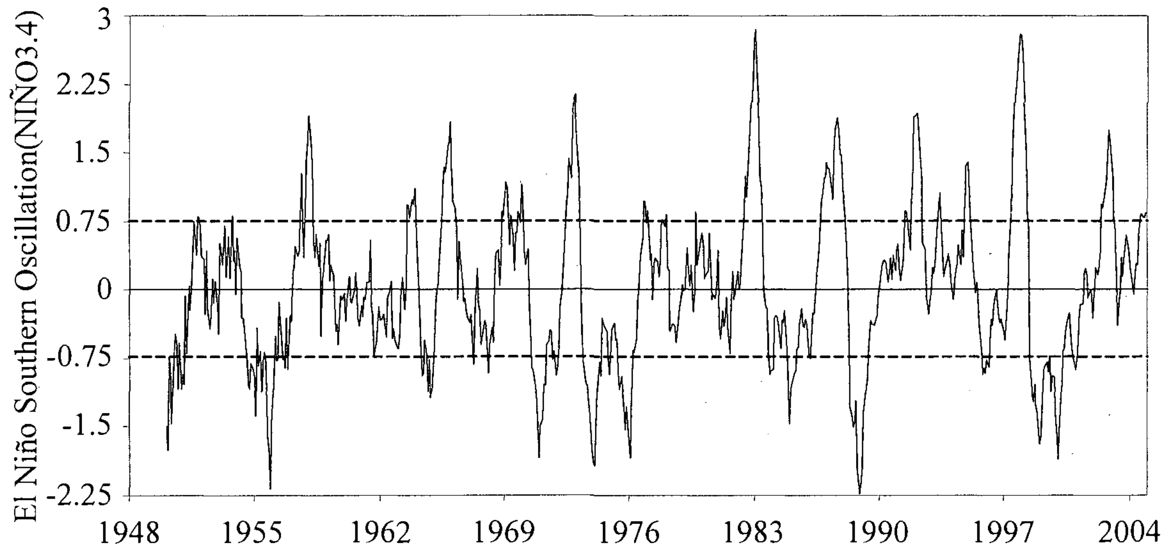

FIG. 5. NIÑO3.4 sea surface temperature index (1950-2004). Extreme ENSO warm and cold phases exceeded absolute ±0.75°C (dashed horizontal lines).

The Mississippi River flow data set was taken from the U.S. Geological Survey station at Vicksburg, Mississippi, USA (USGS National Water Information System 2007a) and the U.S. Army Corps of Engineers station at Tarbert Landing, Mississippi, USA (USCOE 2007). The USGS data extends from 1931 to 1999 and the USCOE data from 1961 to 2004. For years in which river flow data are available at both stations, a Pearson Correlation test was conducted to determine the relationship between flows. Flows were highly correlated (r= 0.978, p< 0.0001) between the two stations. To determine river flow at Vicksburg from the missing period (2000 to 2004), flow data from Talbert Landing were divided by the data from the Vicksburg station and the resulting quotient was multiplied by Talbert Landing values from 2000 to 2004. This provided a continuous data set for the Mississippi River from 1950 to 2004. The Pascagoula River flow data set was retrieved from the USGS station at Merrill, Mississippi, USA (USGS National Water Information System 2007b); data used covered the period from 1950 to 2004. Mississippi River data were converted from daily to monthly means; Pascagoula River data were available by month. Anomalies were calculated for both rivers by determining the overall monthly mean flow for each individual month over all years. The overall monthly values were then subtracted from individual monthly values to determine the anomaly. The yearly river flow anomaly was calculated from September to August of each study year. River flow data covering the period from 1950 to 2004 (55 years) were then analyzed under phases and/or events of individual and combined oceanic-atmospheric indices. River flow data are reported in cubic feet per second (cfs).

Mississippi River and Pascagoula River flows were compared within phases (cold/negative or warm/positive) of one or more of the PDO, AMO, and NAO indices. River flows, within phases of one or more long-term indices, were then evaluated under interannual ENSO events (cold, warm, and neutral). Any significant differences (greater than 95%) in river flow means or medians were reported (Tables 2 and 3, Figs. 6 and 7). A parametric t-test was performed on the response of river flow means to changes in phases or/and events of oceanic-atmospheric indices. For phases and/or events of limited duration, a nonparametric rank-sum test (Mann-Whitney U Test) was performed on the response of river flow medians to changes in phases or/and events of oceanic-atmospheric indices.

Although the river flow analysis, within climatic phases and/or events, is limited by the short-term (55 years) instrumental records of sea surface temperature, the available datasets do provide an adequate number of PDO, AMO, and NAO phases and ENSO events to evaluate their single and combined impacts on river flows in the study area.

While longer records of SST (PDO, AMO, and ENSO) have been primarially reconstructed using paleotemperature proxies (Evans et al. 1999; Linsley et al. 2000a; Linsley et al. 2000b; Evans et al. 2001; Wilson et al. 2006; Hetzinger et al. 2008) and tree rings (Biondi et al. 2001; Gray et al. 2004; Gergis 2006), their resolution is limited to the tropical location where corals develop and to the annual period of tree growth.

Results and Discussion

Climatic phases that showed significant differences in Mississippi River and Pascagoula River flows are shown in Tables 2 and 3 for individual and coupled phases and Tables 4 and 5 for three and four phases. Time series histograms representing significant differences (> 95%) in Mississippi River and Pascagoula River flows under different climatic phases are shown in Figs. 6 and 7. Differences in temporal, spatial, and analytical approaches complicated data comparisons and may be responsible in part for contradictory results among published studies. Data for this study are specific to the lower basins of the two rivers, whereas much of the published literature covers broader geographic areas.

TABLE 2. Climatic phases that showed significant differences (greater than 95%) in Mississippi River flow means (t-test). "c" indicates the cold phase of the index; "w" indicates the warm phase of the index; "n" indicates either the neutral phase of ENSO index or the negative phase of NAO index; and "p" indicates the positive phase of the index. PDO, Pacific Decadal Oscillation; AMO, Atlantic Multidecadal Oscillation; NAO, North Atlantic Oscillation; ENSO, El Niño Southern Oscillation.

Phase (% of Years Below Normal River Flow)	Yearly River Mean Flow (cfs)	Phase (% of Years Above Normal River Flow)	Yearly River Mean Flow (cfs)
PDOc (70)	-31,051	PDOw (79)	54,316
NAOn (61)	-27,450	NAOp (75)	63,893
PDOc/AMOw (71)	-67,477	PDOw/AMOc (83)	68,254
PDOc/NAOn (74)	-43,622	PDOw/NAOp (80)	68,425
AMOw/NAOn (55)	-36,015	AMOc/NAOp (77)	63,342
PDOc/ENSOn (89)	-97,416	PDOw/ENSOw (82)	73,628
		PDOw/ENSOn (90)	66,204
NAOn/ENSOc (80)	-52,487	NAOp/ENSOc (71)	88,379
		NAOp/ENSOn (87)	64,320
NAOn/ENSOn (73)	-66,297	NAOp/ENSOc (71)	64,320
		NAOp/ENSOn (87)	88,379

TABLE 3. Climatic phases that showed significant (greater than 95%) differences in Pascagoula River flow means (t-test) and medians (Mann-Whitney Test). "c" indicates the cold phase of the index; "w" indicates the warm phase of the index; "n" indicates the neutral phase of ENSO index or the negative phase of NAO index; and "p" indicates the positive phase of the index. PDO, Pacific Decadal Oscillation; AMO, Atlantic Multidecadal Oscillation; NAO, North Atlantic Oscillation; ENSO, El Niño Southern Oscillation.

Phase (% of Years Below Normal River Flow)	Yearly River Mean Flow (cfs)	Phase (% of Years Above Normal River Flow)	Yearly River Mean Flow (cfs)
NAOn (65)	-1151	NAOp (58)	1364
PDOc/NAOn (70)	-1442	PDOc/NAOp (100)*	2935
		PDOw/NAOp (50)	1049
AMOw/NAOn (68)	-1099	AMOc/NAOp (64)	1607
PDOw/ENSOc (86)	-2193	PDOw/ENSOw (73)	1709
AMOw/ENSOc (100)	-3768	AMOc/ENSOc (67)	1012
		AMOc/ENSOw (62)	529
		AMOc/ENSOn (44)	875
		AMOw/ENSOw (67)	1287
		AMOw/ENSOn (30)	-439
NAOn/ENSOc (80)	-2910	NAOn/ENSOw (60)	586
		NAOp/ENSOc (57)	1152
		NAOp/ENSOw (67)	971
		NAOp/ENSOn (50)	1991

* Nonparametric Test.

Test of River Flow within Phases/Events of Single Oceanic-Atmospheric Indices

The phases or events of a single index were evaluated by examining their influence on Mississippi River and Pascagoula River flow (Fig. 6a-c).

PDO. Mississippi River flow was significantly lower during the PDO cold (PDOc) phase than during the PDO warm (PDOw) phase (Table 2, Fig. 6a). During the PDOc phase, 70% of the years were below normal river flow whereas during the PDOw phase, 79% of the years were above normal river flow. These results were consistent with prior studies of the association between Mississippi River basin hydrology and the PDO. Tootle et al. (2005) found higher streamflows in the upper/middle basin during the PDOw phase than during the PDOc phase. McCabe et al. (2004) calculated drought frequency for 20-year moving periods for the contiguous states, data that included areas within the Mississippi and Pascagoula River basins. They found that the warm phase of the PDO was associated with a low drought frequency with the inverse for the cold phase within the Mississippi River basin. Tootle and Piechota (2006) found a positive correlation between streamflows and a specific area within the Pacific Ocean, the Northeastern Pacific SST, a correlation not found during PDOc years.

In the present study, there was no difference in Pascagoula River flow between the PDOc and PDOw phases, a finding also reported by Tootle et al. (2005). Other hydrological studies that include the region influenced by the Pascagoula River are contradictory. McCabe et al. (2004) found that the warm phase of the PDO was associated with a low drought frequency, with the inverse for the cold phase within the region of the Pascagoula River. As with the Mississippi River region, Tootle and Piechota (2006) found a positive relationship between streamflows in the area of the

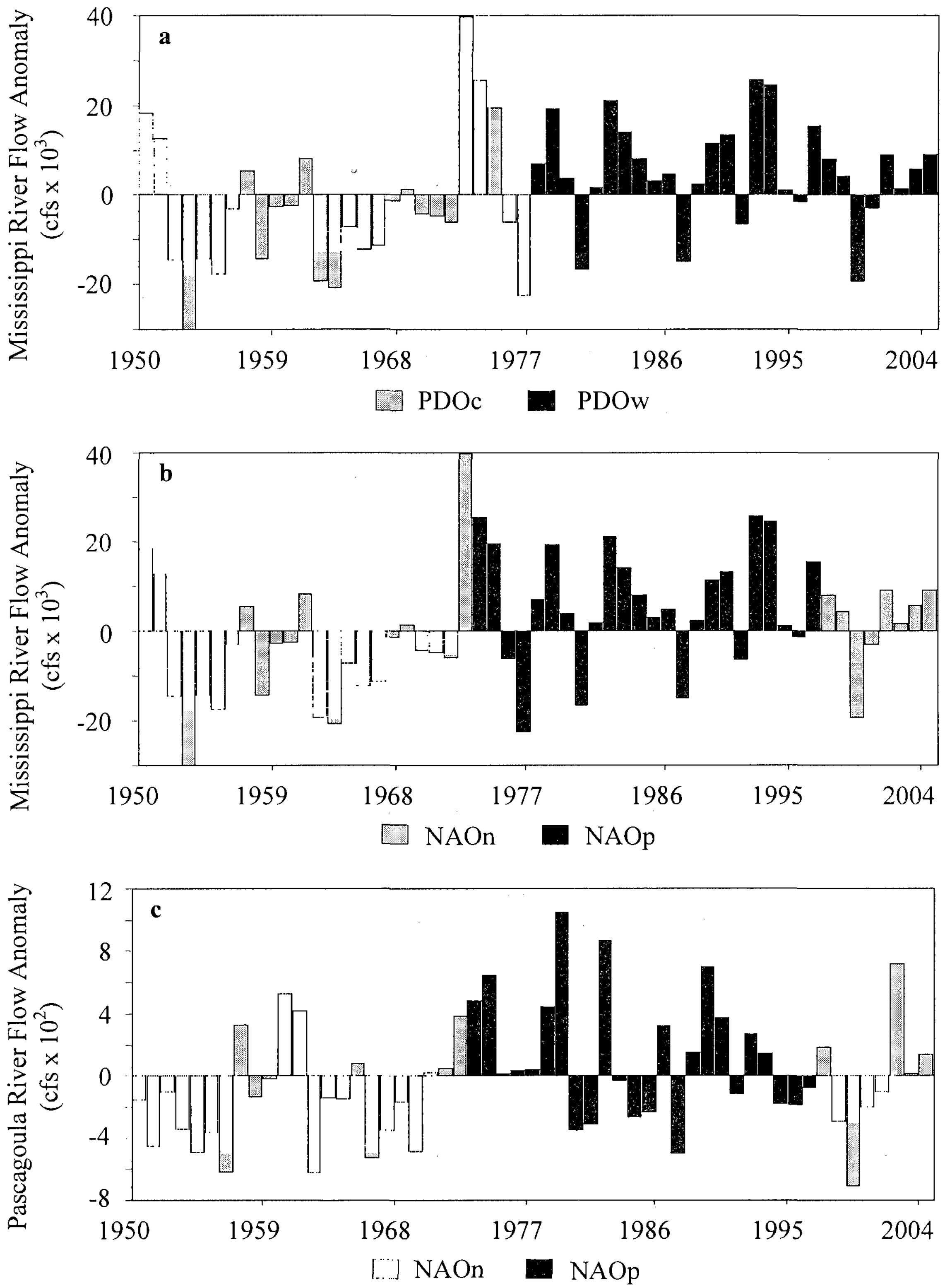

FIG. 6. Yearly (September to August) flow of Mississippi River at Vicksburg, Mississippi and Pascagoula River at Merril, Mississippi within the phases of a single index. Climatic phases with significantly different (> 95%) river flows are represented by black and gray bars for phases with high and low river mean flows, respectively.

Pascagoula River and Northeastern Pacific SST regions during PDOw years; there was no significant correlation during the PDOc years.

AMO. There were no differences in Mississippi River and Pascagoula River flows between the AMO cold (AMOc) and AMO warm (AMOw) phases; however, there was a tendency towards higher river flows during the AMOc phase. This observed tendency for higher flow during the cold phase was found to be significant in previous hydrological studies. For the region of the Mississippi River, McCabe et al. (2004) found that drought frequency was below and above normal during AMOc and AMOw phases, respectively. These data were consistent with the lowered precipitation found in some areas of the region during the AMOw phase (Enfield et al. 2001). In the upper/middle basin, Tootle et al. (2005) also found streamflows higher during the AMOc phase than during the AMOw phase. A positive correlation between streamflow and sea surface temperature in the North-central Atlantic was found during the AMOc years (Tootle and Piechota 2006).

In contrast to the present study, Enfield et al. (2001) found a significantly higher rainfall during the AMOw in the Pascagoula River area; McCabe et al. (2004) noted that drought frequency was low during that phase. Tootle et al. (2005), however, found that streamflows were higher during AMOc phase than during the AMOw phase. A positive correlation between streamflow and sea surface temperature in the North-central Atlantic was found during the AMOc years (Tootle and Piechota 2006).

NAO. Mississippi River and Pascagoula River flows were significantly lower during the NAO negative (NAOn) phase than during the NAO positive (NAOp) phase (Tables 2 and 3, Fig. 6b-c). For the Mississippi River, 61% of the years were below normal river flow during the

NAOn phase, whereas 75% of the years were above normal river flow during the NAOp phase. For the Pascagoula River, 65% of the years were below normal river flow during the NAOn phase, whereas 58% of the years were above normal river flow during the NAOp phase. These results were consistent with Tootle et al. (2005) who found a higher streamflow during the NAOp phase than during the NAOn phase in the upper/middle Mississippi River basin and with Visbeck et al. (2001) who noted that the NAOp phase was associated with warmer and wetter conditions than average in the Mississippi River and Pascagoula River areas.

ENSO. In the present study, Mississippi River and Pascagoula River flows were not different among ENSO events, although the influence of ENSO tended to be higher in the Pascagoula River area. For the Mississippi River region, Ropelewski and Halpert (1987) and Enfield (1996) found no relationship between ENSO and precipitation and Tootle et al. (2005) found no influence of ENSO on streamflow. Gershunov and Barnett (1998a), however, found that the frequency of winter precipitation was lower under ENSOw event than under the ENSOc event in part of the basin (the Mississippi-Ohio River valleys).

Based on other studies, the influence of ENSO events along the Gulf Coast appears to be significant. In Louisiana, ENSO was found to positively influence streamflow (McCabe and Jackson 1984). Tootle et al. (2005) noted that the entire southeast was affected. Using an index of sea level pressure from the equatorial Pacific (Southern Oscillation Index, SOI: Tahiti - Darwin sea level pressure), Ropelewski and Halpert (1987) found that a negative SOI was associated with increased precipitation in the northcentral Gulf Coast. Separating data by season, Douglas and Englehart (1981) and Ropelewski and Halpert (1986) observed that during ENSOw events, there is substantially increased winter precipitation on the Gulf Coast whereas during ENSOc events, winter precipitation decreased. Other indices (SST from the equatorial Pacific: NIÑO3, ±6°, 90°-150°W; PAC3, ±5°, 170°-120°W) show positive relationships to rainfall along the Gulf Coast (Enfield 1996; Gershunov and Barnett 1998a). Using an index developed from many different variables, (Multi-variate ENSO Index, MEI), Darby and Sondag (1998) found similar results.

Test of River Flow within Phases/Events of Coupled Oceanic-Atmospheric Indices

The coupling of indices was evaluated by examining the Mississippi River and Pascagoula River flows in every combination of phases/events. Differences in yearly mean river flow from the Mississippi River and Pascagoula Rivers are shown in Figs. 7 and 8.

PDO and AMO. There was a significantly lower Mississippi River flow during the PDOc/AMOw phase when compared to the PDOw/AMOc phase (Table 2, Fig. 7a), a result that corresponded to the river flow variation found under both phases of each individual index (PDO and AMO). River flow tendency under the AMO phases was enhanced by the coupling with the dominant PDO. These results were consistent with hydrological studies in the continental U.S. McCabe et al. (2004) found that the PDOc/AMOw phase produced above normal drought frequency in wider areas of the Mississippi River basin than did the PDOw/AMOc phase. In addition, PDOw and AMOc years were linked to streamflow stations from the middle Mississippi River basin and Gulf Coast, whereas AMOw years were associated with streamflow stations from the upper Mississippi River basin; the PDOc was not related to any streamflow station in those areas (Tootle and Piechota 2006). Pascagoula River flow was not significantly different between PDOc/AMOw and PDOw/AMOc phases.

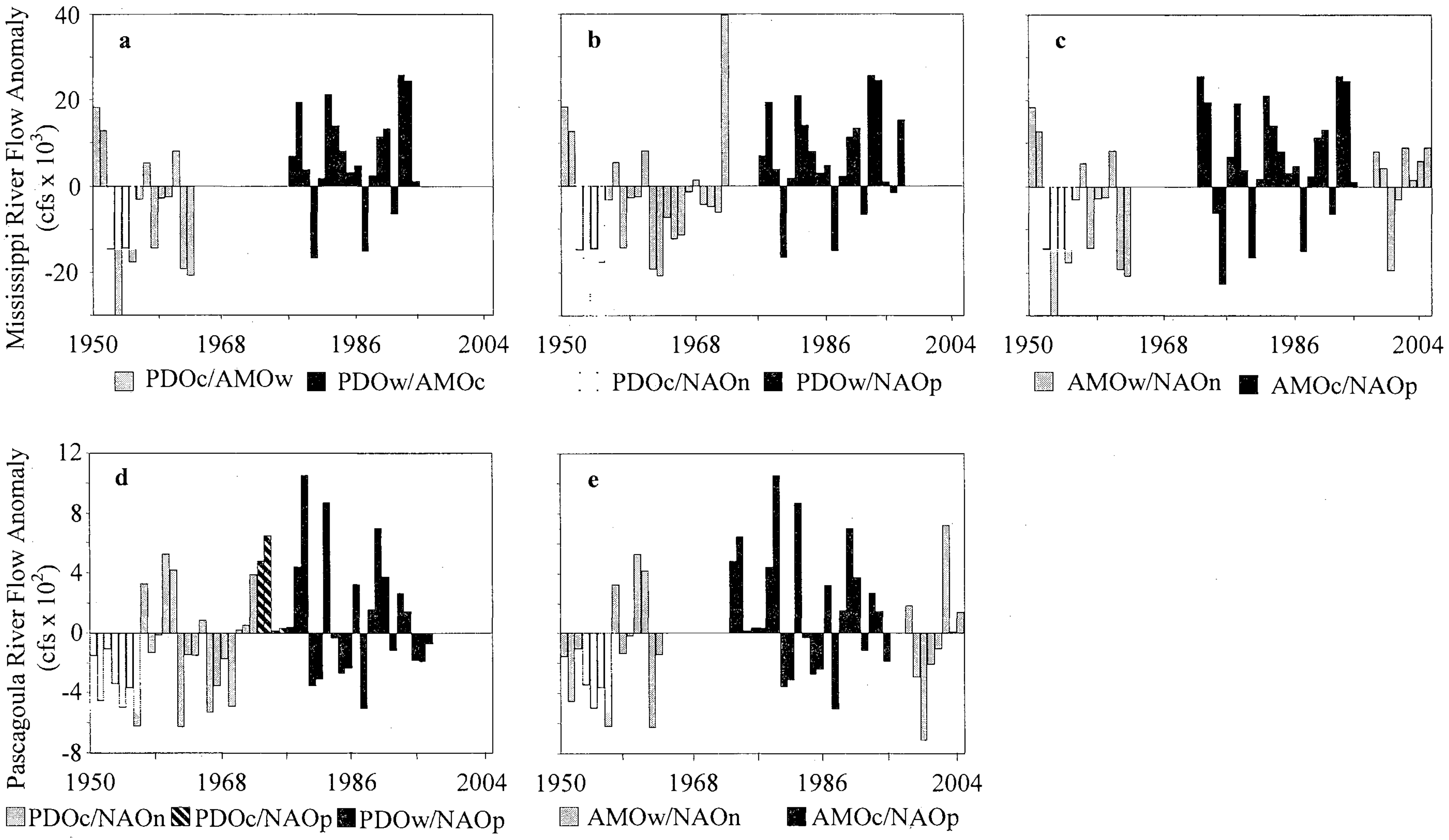

FIG. 7. Yearly (September to August) flow of Mississippi River at Vicksburg, Mississippi and Pascagoula River at Merril, Mississippi within the phases of two combined indices. Climatic phases with significantly different (>95%) river flows are represented by patterns of black and gray bars for phases with high and low river mean or median flows, respectively.

PDO and NAO. In the Mississippi River, the PDOc/NAOn phase was associated with significantly lower river flow when compared to the PDOw/NAOp phase (Table 2, Fig. 7b), a result that corresponded to the river flow variation produced by the same phases of both indices individually. The PDO and NAO were linked to similar streamflow stations in the Mississippi River basin where, when considered individually, the PDOw and NAOp phases produced higher streamflows than did PDOc and NAOn phases (Tootle et al. 2005).

In the lower Pascagoula River, the PDOc/NAOn phase resulted in significantly lower river flow when compared to PDOc/NAOp and PDOw/NAOp phases (Table 3, Fig. 7d). This was equivalent to the results found for each individual index where the PDO showed no influence and the NAO was extremely influential in Pascagoula River flow.

AMO and NAO. During the AMOw/NAOn phase, the flow in the Mississippi River (Table 2, Fig. 7c) and Pascagoula River (Table 3, Fig. 7e) was significantly lower than during the AMOc/NAOp phase. Similar results occurred when the AMO and NAO phases were tested individually.

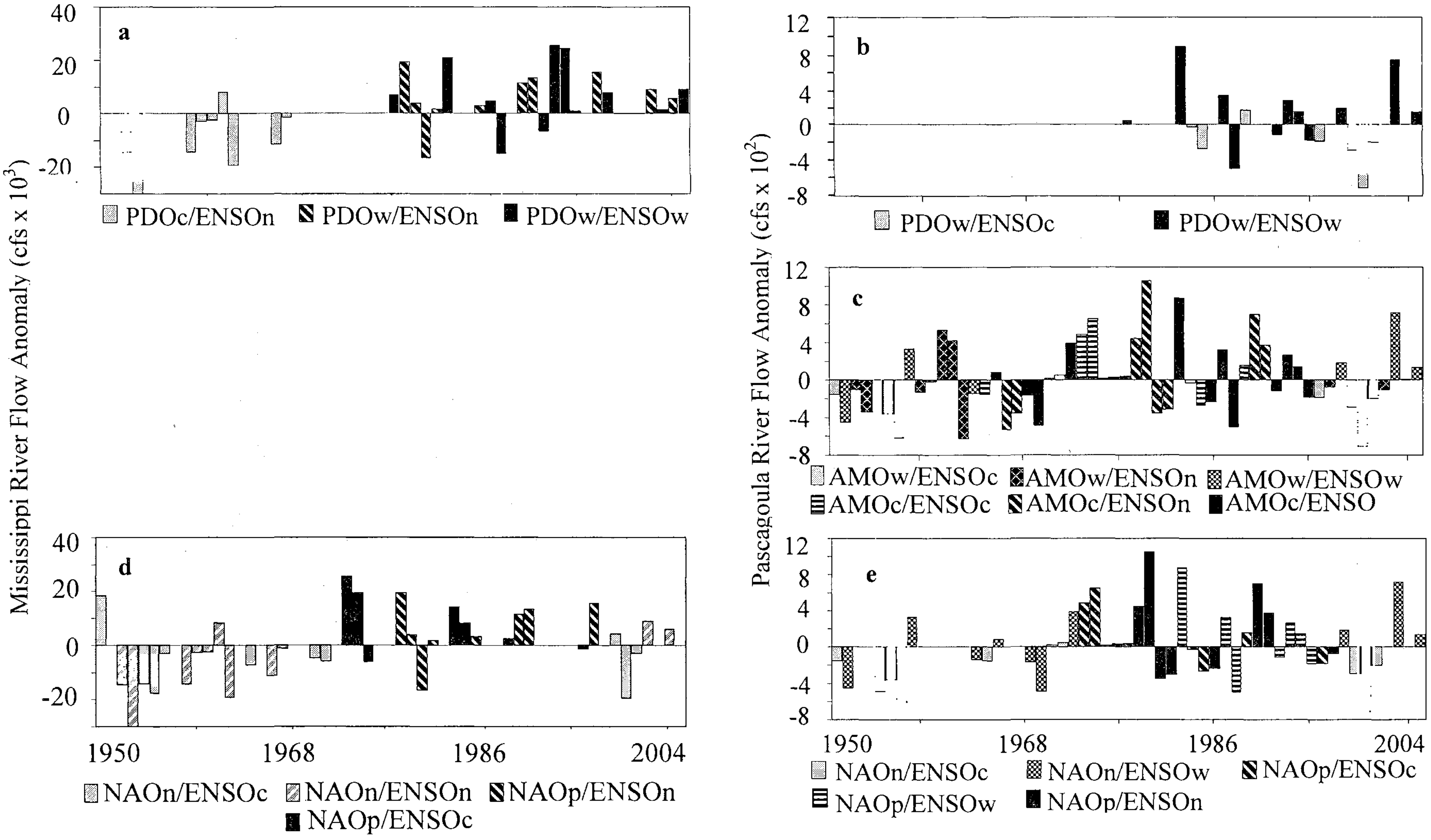

FIG. 8. Yearly (September to August) flow of Mississippi River at Vicksburg, Mississippi and Pascagoula River at Merril, Mississippi within the phases of two combined indices. Climatic phases with significantly different (>95%) river flows are represented by patterns of black and gray bars for phases with high and low river mean flows, respectively.

PDO and ENSO. In the Mississippi River, the PDOc/ENSOn phase produced significantly lower river flow than did the PDOw/ENSOw and PDOw/ENSOn phases (Table 2, Fig. 8a). As with the individual indices, river flow was more influenced by the PDO than ENSO. Results from other studies vary. Rajagopalan et al. (2000) found that the PDO did not enhance or dampen the ENSO effect on summer Palmer Drought Severity Index and Tootle et al. (2005) observed that the PDO did not impact ENSO streamflow patterns in the continental U.S. In contrast, Gershunov and Barnett (1998b) found that ENSOw (ENSOc) SLP and precipitation patterns tend to be stronger and more stable during PDOw (PDOc) phases. Pacific Ocean SSTs influenced non-ENSO streamflow regions (middle Mississippi River basin) during PDOw phase and ENSO streamflow regions (southeast, northwest, northeast, southwest of the U.S.) during PDOc phase (Tootle and Piechota 2006).

In the Pascagoula River, the PDOw/ENSOc phase produced significantly lower river flow than did the PDOw/ENSOw phase (Table 3, Fig. 8b). Although individual phases of the PDO and ENSO showed no influence on Pascagoula River flow, the PDOw phase seemed to enhance the opposing signals of ENSOw and ENSOc phases. Similar results were found in other studies. The PDO was shown to modulate the influence of ENSO on SLP and precipitation (Gershunov and Barnett 1998b), streamflow (Hamlet and Lettenmaier 1999; Harshburger et al. 2002; Beebee and Manga 2004), and flood potential (Pizarro and Lall 2002). Tootle and Piechota (2006) considered that depending on the interdecadal phenomenon (PDO), the interannual signal (ENSO) is either enhanced or dampened. The Pacific Ocean SSTs were associated with non-ENSO streamflow regions (Pascagoula River basin) during the PDOw phase and with ENSO streamflow regions under the PDOc phase. In the continental United States, Gershunov and Barnett (1998b) found that the ENSOw signal (SLP and heavy daily precipitation) under the PDOw phase was amplified and completely opposite to the ENSOc signal under the PDOc phase. In contrast to these studies, Rajagopalan et al. (2000) noted that the effect of ENSO on the Palmer Drought Severity Index (PDSI) was not enhanced or dampened by the PDO and Tootle et al. (2005) observed that there was no response in streamflow when the PDO was combined with ENSO.

AMO and ENSO. In the area of the Mississippi River under study, individual phases of AMO and ENSO and their coupling showed no influence on river flow, a result inconsistent with prior studies of hydrological factors related to streamflow. Enfield et al. (2001) found that during the AMOw phase, an extensive area of precipitation in the eastern Mississippi Basin was negatively correlated with ENSO3.4 whereas an area confined to a small region in the Great Plains was positively correlated. During the AMOc phase, the coverage of the area negatively correlated was decreased by half that of the warm phase, whereas the area positively correlated showed a substantial increase in coverage. As a result, winter precipitation accumulation in the Mississippi River Basin was reduced more during the AMOw/ENSOw phase than during the AMOc/ENSOw phase.

Although the comparison of phases of each individual index (AMO and ENSO) showed no effect on Pascagoula River flow, their combined effect resulted in significantly lower river flow during the AMOw/ENSOc phase than during AMOc/ENSOc, AMOc/ENSOw, AMOc/ENSOn, AMOw/ENSOw, and AMOw/ENSOn phases (Table 3, Fig. 8c). During the AMOw/ENSOc phase, all eight yearly river flows were below normal, whereas during AMOw/ENSOn and AMOw/ENSOw phases, three of ten and four of six years were above normal, respectively. The mean river flows were -3768 cfs (AMOw/ENSOc), -439 cfs (AMOw/ENSOn), and 1287 cfs (AMOw/ENSOw). The AMOw phase appeared to be dominated by ENSO with river flow increasing steadily from ENSOc to ENSOn to ENSOw. During AMOc/ENSOc, AMOc/ENSOn, and AMOc/ENSOw phases, six of nine, four of nine, and eight of thirteen years were above normal, respectively. The mean river flows were 1012 cfs (AMOc/ENSOc), 875 cfs (AMOc/ENSOn), and 529 cfs (AMOc/ENSOw). The AMOc phase appeared to dominate and reverse the influence of ENSO such that river flow was above normal and decreased steadily from ENSOc to ENSOn to ENSOw. Tootle et al. (2005) found streamflows higher during the AMOc/ENSOc phase than during the AMOw/ENSOc phase in the Pascagoula River basin and observed that AMOc phase appears to dominate ENSOc phase such that streamflow was above normal when typically ENSOc results in below normal streamflow. In contrast, Enfield et al. (2001) found that the correlation between the ENSO3.4 SST anomaly and precipitation over the Mississippi Basin during AMOc phase was insignificant although the same correlation was significant and negative under the AMOw phase.

NAO and ENSO. During the NAOn/ENSOc phase and the NAOn/ENSOn phase (Table 2, Fig. 8d), Mississippi River flow was significantly lower than during NAOp/ENSOc and NAOp/ENSOn phases. For the period of record, eight of ten (NAOn/ENSOc phase) and eight of eleven (NAOn/ENSOn phase) years were below normal river flow with means of -52487 cfs and -66297 cfs, respectively. During the other two phases, five of seven (NAOp/ENSOc phase) and seven of eight

(NAOp/ENSOn phase) years were above normal with mean river flows of 88379 cfs and 64320 cfs, respectively. Mississippi River flow was determined by NAO and not by ENSO, which was similar to the results found with individual indices in the present study and in the study of Tootle et al. (2005). These latter authors noted that the NAOp/ENSOc phase resulted in significantly more streamflow than the NAOn/ENSOc phase in the Midwestern region. The effect of ENSO on the Palmer Drought Severity Index, however, was not enhanced or dampened by the NAO (Rajagopalan et al. 2000).

During the NAOn/ENSOc phase, Pascagoula River flow was significantly lower than during NAOn/ENSOw, NAOp/ENSOc, NAOp/ENSOw, and NAOp/ENSOn phases (Table 3, Fig. 8e). For the NAOn/ENSOc phase, eight of ten years were below normal river flow with a mean of -2910 cfs. During the other four phases, six of ten (NAOn/ENSOw phase), four of seven (NAOp/ENSOc phase), six of nine (NAOp/ENSOw phase), and four of eight (NAOp/ENSOn phase) years were above normal with means of 586, 1152, 971, and 1991 cfs, respectively. Although the NAOp phase appeared to dominate ENSO events, some influence of ENSO on river flow was evident: a gradual reduction of river flow occurred with ENSOn, continued with ENSOc, and ended with ENSOw. During the NAOn phase, river flow was determined by ENSO and the ENSOw phase produced a higher river flow than did the ENSOc phase. These results were consistent with the AMO/ENSO coupled test and with the study of Tootle et al. (2005).

Tests of River Flow within Phases/Events of Multiple Oceanic-Atmospheric Indices

River flow responses were evaluated by the influence of the phases/events using a combination of three and four indices (Tables 4 and 5). These analyses confirmed test results of river flow within phases/events of single and coupled oceanic-atmospheric indices. Mississippi River flow responded to the physical mechanisms (see following section) imposed by individual and/or combined long-term modes of variability (PDO, AMO, and NAO). Phases of those mechanisms determined the frequency, intensity, and spatial coverage of precipitation/runoff events across the Mississippi River basin. High river flow was determined primarily by the individual and/or combined PDOw and NAOp phases, whereas low river flow was determined by their opposite phases. The individual or combined PDOw and NAOp phases enhanced the tendency of the AMOc phase to increase river flow, whereas the opposite phases of both indices (PDO and NAO) dampened the tendency of the AMOw phase in decreasing river flow. High river flow was associated with individual and/or combined PDOw, AMOc, and NAOp phases, whereas low river flow was associated with individual and/or combined opposite phases of the same indices.

Long-term Mississippi River flow fluctuated according to the interannual influence of the physical mechanisms imposed by ENSO. During the PDOw/AMOw phase, river flow was significantly higher under ENSOn (100656 cfs) than under ENSOc (-48659 cfs) events. Interdecadal/multidecadal/decadal climatic phases determined periods of long-term Mississippi River flow, whereas interannual events produced fluctuations within those periods.

TABLE 4. Climatic phases that showed significant differences (greater than 95%) in Mississippi River flow means (t-test) and medians (Mann-Whitney Test). "c" indicates the cold phase of the index; "w" indicates the warm phase of the index; "n" indicates either the neutral phase of ENSO index or the negative phase of NAO index; and "p" indicates the positive phase of the index. PDO, Pacific Decadal Oscillation; AMO, Atlantic Multidecadal Oscillation; NAO, North Atlantic Oscillation; ENSO, El Niño Southern Oscillation.

Phase (% of Years Below Normal River Flow)	Yearly River Mean Flow (cfs)	Phase (% of Years Above Normal River Flow)	Yearly River Mean Flow (cfs)
PDOc/AMOc/NAOn (78)*	-6514	PDOw/AMOc/NAOp (83)	68,254
PDOc/AMOw/NAOn (71)	-67,477		
PDOc/AMOw/ENSOn (86)	-107,329	PDOw/AMOc/ENSOw (75)	78,122
		PDOw/AMOc/ENSOn (86)	51,438
		PDOw/AMOw/ENSOn (100)*	100,656
PDOw/AMOw/ENSOc (75)	-48,659	PDOw/AMOw/ENSOn (100)*	100,656
PDOc/NAOn/ENSOn (89)	-97,416	PDOw/NAOn/ENSOw (100)*	61,644
		PDOw/NAOp/ENSOc (75)*	57,240
		PDOw/NAOp/ENSOw (75)	78,122
		PDOw/NAOp/ENSOn (88)	64,320
AMOw/NAOn/ENSOc (71)	-49,483	AMOc/NAOp/ENSOc (83)	105,538
AMOw/NAOn/ENSOn (67)	-67,091		
PDOc/AMOc/NAOn/ENSOc (67)	-59,496	PDOw/AMOc/NAOp/ENSOc (100)*	81,179
		PDOw/AMOw/NAOn/ENSOw (100)*	61,644
PDOc/AMOw/NAOn/ENSOn (86)	-107,329	PDOw/AMOc/NAOp/ENSOw (75)	78,122
		PDOw/AMOc/NAOp/ENSOn (86)	51,438

* Nonparametric Test.

TABLE 5. Climatic phases that showed significant (greater than 95%) differences in Pascagoula River flow means (t-test) and medians (Mann-Whitney Test). "c" indicates the cold phase of the index; "w" indicates the warm phase of the index; "n" indicates the neutral phase of ENSO index or the negative phase of NAO index; and "p" indicates the positive phase of the index. PDO, Pacific Decadal Oscillation; AMO, Atlantic Multidecadal Oscillation; NAO, North Atlantic Oscillation; ENSO, El Niño Southern Oscillation.

Phase (% of Years Below Normal River Flow)	Yearly River Mean Flow (cfs)	Phase (% of Years Above Normal River Flow)	Yearly River Mean Flow (cfs)
PDOw/AMOw/ENSOc (100)	-3468	PDOc/AMOc/ENSOc (83)*	1764
		PDOw/AMOc/ENSOw (62)*	1052
		PDOw/AMOw/ENSOw (100)*	3462
		PDOw/AMOw/ENSOn (33)*	-553
PDOc/AMOw/ENSOc (100)	-4068	PDOc/AMOc/ENSOc (83)*	1764
		PDOw/AMOc/ENSOw (62)*	1052
		PDOw/AMOc/ENSOn (57)*	2383
		PDOw/AMOw/ENSOw (100)*	3462
		PDOw/AMOw/ENSOn (33)*	-553
PDOw/AMOw/ENSOn (67)	-553	PDOw/AMOw/ENSOw (100)*	3462
PDOw/NAOn/ENSOc (100)	-3998	PDOc/NAOp/ENSOc (100)*	3807
		PDOw/NAOn/ENSOw (100)*	3462
		PDOw/NAOp/ENSOw (62)*	1052
PDOc/NAOn/ENSOc (71)	-2444	PDOw/NAOn/ENSOw (100)*	3462
AMOw/NAOn/ENSOc (100)	-4038	AMOc/NAOn/ENSOc (67)*	-279
		AMOc/NAOp/ENSOc (67)	1657
		AMOc/NAOp/ENSOw (67)	971
		AMOc/NAOp/ENSOn (57)	2383
		AMOw/NAOn/ENSOw (67)	1287
		AMOw/NAOn/ENSOn (33)	-404

(continued on next page)

Table 5 (*continued*)

Phase (% of Years Below Normal River Flow)	Yearly River Mean Flow (cfs)	Phase (% of Years Above Normal River Flow)	Yearly River Mean Flow (cfs)
PDOc/AMOw/NAOn (79)	-1548	PDOc/AMOc/NAOp (100)*	2935
PDOc/AMOw/NAOn/ENSOc (100)	-4068	PDOc/AMOc/NAOn/ENSOc (67) *	-279
PDOw/AMOw/NAOn/ENSOc (100)	-3998		
PDOc/AMOc/NAOn/ENSOc (67)	-279	PDOw/AMOw/NAOn/ENSOw (100)*	3462
PDOw/AMOw/NAOn/ENSOc (100)	-3998	PDOc/AMOc/NAOp/ENSOc (100)*	3807
		PDOw/AMOc/NAOp/ENSOw (62)*	1052
		PDOw/AMOw/NAOn/ENSOw (100)*	3462
PDOc/AMOw/NAOn/ENSOc (100)	-4068	PDOc/AMOc/NAOp/ENSOc (100)*	3807
		PDOw/AMOc/NAOp/ENSOw (62)*	1052
		PDOw/AMOc/NAOp/ENSOn (57)*	2383
		PDOw/AMOw/NAOn/ENSOw (100)*	3462

* Nonparametric Test.

Pascagoula River flow responded primarily to NAO in such a way as to make AMO tendencies on river flow significant. When opposite phases of both indices were coupled, the physical mechanisms of both indices determine the frequency, intensity, and spatial coverage of precipitation/runoff events across the Pascagoula River basin. The PDO long-term influence in river flow is concealed by the basin size and proximity to the source of the Atlantic modes of variability. High river flow was related to NAOp and AMOc/NAOp phases, whereas low river flow was associated with the NAOn and AMOw/NAOn phases.

Long-term Pascagoula River flow fluctuated according to the interannual influence of the physical mechanisms imposed by ENSO. Those long-term river flow ENSO fluctuations were significantly different within individual and/or combined PDOw, AMOw and NAOn phases. During individual and/or any combination of the PDOw, AMOw, and NAOn phases, river flows were significantly lower under ENSOc events than under ENSOw events. During the AMOw phase or when AMOw was coupled with the PDOw or NAOn phases, river flow was significantly lower under ENSOc events than under ENSOn events. During the PDOw/AMOw phase, river flow was significantly lower under the ENSOn event than under the ENSOw event. Each of the ENSO events was determinant in the Pascagoula River flow variation during the PDOw/AMOw phase. A steady significant reduction of mean river flow was found during ENSOw (3462 cfs), ENSOn (-553 cfs), and ENSOc (-3468 cfs) phases. Multidecadal/decadal climatic phases determined periods of long-term Pascagoula River flow, whereas interannual events produced fluctuations within those periods.

Physical Explanation for the Association between Climatic Phases/Events and River Flow

Long-term climatic phases and Mississippi River flow. The physical explanation for the long-term association found between the combined PDO, AMO, and NAO phases and Mississippi River flow is as follows: the PDO patterns determine the jet stream fluctuations in position and direction (Jacobs et al. 1994), whereas the coupled AMO and NAO long-term patterns (D'Aleo and Taylor 2007) determine the development, location, and orientation of the eastern trough in the jet stream (Bradbury et al. 2002) and the strength and position of the Bermuda High (Elsner et al. 2001). Those conditions determine the frequency, trajectory, spatial coverage, and intensity of the western (Jacobs et al. 1994) and eastern (Jones and Davis 1995) storms across the continental U.S. During the PDOw/AMOc/NAOp phase, the southern shift of the jet stream with north-south meanders (Jacobs et al. 1994), a rudimentary eastern trough (Bradbury et al. 2002), and a strong northeast Bermuda High (Elsner et al. 2001) allow frequent intrusions of Arctic air to the lower basin and marine moist air to the upper basin. The Gulf of Mexico and Atlantic Ocean moisture is transported into the continental U.S. (Hurrell et al. 2001), where it collides further north with Arctic air, producing western and eastern storms across extensive areas of the Mississippi River basin. Those storms produce frequent, intense, and wide-spread precipitation events, increasing streamflows across the basin. During the PDOc/AMOw/NAOn phase, a northern shift of the jet stream with west-east direction, a well-developed eastern trough, and a weak southwest Bermuda High are associated with sporadic western and frequent eastern storms across the Mississippi River basin. In addition, the well-developed eastern trough and the weak Bermuda High prevent the transport of high amounts of moisture from the Atlantic Ocean into the upper Mississippi River basin. Those conditions produce a reduction in the frequency, intensity, and spatial coverage of precipitation events which in turn decrease streamflows across the Mississippi River basin.

Long-term climatic phases and Pascagoula River flow. The physical explanation for the long-term association found between the coupled AMO and NAO patterns (D'Aleo and Taylor 2007) and Pascagoula River flow is as follows: winter weather patterns throughout the North Atlantic basin have historically been affected by changes in the NAO (Rogers and Van Loon 1979; Hurrell and Van Loon 1997) and AMO (McCabe et al. 2004). The eastern trough development, location, and orientation in the jet stream (Bradbury et al. 2002) and the strength and position of the Bermuda High (Elsner et al. 2001) are determined by the combined NAO and AMO phases. Those physical mechanisms establish the frequency, trajectory, and spatial coverage of the eastern storms (Jones and Davis 1995) and the amount of moisture across the continental U.S. During the AMOc/NAOp phase, the rudimentary eastern trough allows sporadic southern intrusions of Arctic air (Bradbury et al. 2001) whereas the strong northeastern Bermuda High transports frequently high amounts of moisture into the continental U.S. (Elsner et al. 2001). Gulf of Mexico and Atlantic Ocean moisture is transported into the continental U.S. (Hurrell et al. 2001) becoming the source of high precipitation events under any western cold front regimes within the Pascagoula River basin. Those mechanisms contribute to high streamflows within the Pascagoula River basin. During the AMOw/NAOn phase, the well-developed eastern trough allows frequent southern intrusions of Arctic air, reducing the transport of Atlantic Ocean moisture to the continental U.S. Moisture transport is further reduced by the weakening of the southwestern Bermuda High. Under those mechanisms, precipitation events and streamflows are reduced in western cold front regimes within the Pascagoula River basin. The influence of the PDO on Pascagoula River flow is concealed by the proximity of the basin to the waters of the Gulf of Mexico and the Atlantic Ocean where physical mechanisms of the AMO and NAO are more influential.

Interannual ENSO events and Mississippi River and Pascagoula River flows within long-term climatic phases. The physical explanation for the ENSO association with the Mississippi River and Pascagoula River flows, under individual and/or combined the PDOw, AMOw, and NAOn phases, is as follows: during the PDOw phase, there is a southern shift of the jet stream with north-south meanders (Jacobs et al. 1994) whereas during the NAOn/AMOw coupled phase (D'Aleo and Taylor 2007) there are frequent intrusions of Arctic air (Jones and Davis 1995) from a well-developed eastern trough (Bradbury et al. 2002), a weak southwestern Bermuda High (Elsner et al. 2001), and low turbulence and evaporation rates in the Atlantic Ocean (Hastenrath and Greischar 2001). These physical mechanisms contribute to frequent intrusions of Arctic air across the continental U.S. and transport of moisture to the lower Mississippi River basin and the entire Pascagoula River basin. During boreal winter, the Aleutian low deepens by the coupled ENSOw event (Jacobs et al. 1994) and the PDOw phase (Mantua et al. 1997), which are responsible for the southern shift of the jet stream. In addition, the ENSOw event increases the warming of the Tropical North Atlantic (TNA) and increases the Western Hemisphere Warm Pool (WHWP) to twice its average size (Wang and Enfield 2003). The WHWP, defined by Wang and Enfield (2001) as the ocean region covered by water warmer than 28.5°C, is composed of the eastern North Pacific west of Central America, the Gulf of Mexico and the Caribbean, and the western tropical North Atlantic. ENSO events not only control the frequency of the intrusion of Arctic air but also the potential amount of moist air that could be transported across the Mississippi River and Pascagoula River basins. During the PDOw/AMOw/NAOn phase, the entire Pascagoula River basin is under a continuous source of moist air and frequent intrusion of Arctic air whereas only the lower Mississippi River basin is under the same regime of moist air and Arctic air. These may be the reasons why Pascagoula River flow reacts more to the changes of ENSO events. The influence of ENSO, within a long-term climatic phase, is related to the difference between the basins size and location within the continental U.S.

Summary and Conclusions

The present study examined the individual and combined influences of four oceanic-atmospheric modes of variability (PDO, AMO, NAO, and ENSO) on Mississippi River and Pascagoula River flows. Their influence on river flows was determined by the duration of the modes of variability, their source area, and spatial relation to the river basins. The phases of those modes of variability were associated with the physical mechanisms that determine the frequency, intensity, and spatial coverage of precipitation/runoff events across the basins. The Mississippi River basin covers an extensive area of the continental U.S. and its long-term river flow variability was primarily associated with interdecadal (PDO), multidecadal (AMO), and decadal (NAO) oceanic-atmospheric forces. Higher Mississippi River flow was found during the AMOc phase when it was accompanied by the influential PDOw and/or NAOp phases. In contrast, the Pascagoula River basin covers a small area in the northcentral Gulf Coast and the long-term Pascagoula River flow was primarily associated with the multidecadal (AMO) and decadal (NAO) oceanic-atmospheric forces. Higher Pascagoula River flow was found under AMOc phase when it was accompanied by the influential NAOp phase. During opposite phases of the oceanic-atmospheric forces mentioned above, Mississippi River and Pascagoula River flows were lower. The results of the current study are consistent with, and complement, previous studies that associated those modes of variability with the physical mechanisms responsible for hydrological variability in the continental U.S.

Interdecadal/multidecadal/decadal climatic phases determined periods of long-term Mississippi River flow whereas interannual events produced fluctuations within those periods. During the PDOw/AMOw phase, ENSO influenced Mississippi River flow whereas during individual and/or combined PDOw, AMOw, and NAOn phases, ENSO influenced Pascagoula River flow. The ENSO events showed less influence on the Mississippi River flow than on the Pascagoula River flow. The ENSO signal is not evident within the Mississippi River basin; however, the PDOw/AMOw phase enhanced the ENSO signal on river flow. A significantly lower Mississippi River flow was found during ENSOc events than during ENSOn events. During the same PDOw/AMOw phase, ENSO strongly influenced the Pascagoula River basin, producing a significantly steady reduction of Pascagoula River flow from ENSOw to ENSOn to ENSOc phases. These results are consistent with a prior study that showed interannual ENSO teleconnections were modulated by long-term modes of variability.

Inconsistencies with the present data and other published research may be related to differences in temporal and spatial components among studies and the varying analytical approaches used. Although much of the published literature covers streamflows from broad geographic areas, data for the present study are specific to the lower basins of the Mississippi and Pascagoula Rivers. Some relationships that were significant in the published literature were noted only as tendencies in this study due to limited river flow data. However, an adequate number of oceanic-atmospheric modes of variability were available to evaluate their single and combined impacts on river flows.

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CHAPTER II

OCEANIC-ATMOSPHERIC MODES OF VARIABILITY AND THEIR EFFECTS ON RECRUITMENT OF BLUE CRABS (*CALLINECTES SAPIDUS*) IN NORTHCENTRAL GULF OF MEXICO

Introduction

Non-linear oceanic-atmospheric modes of variability, such as the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and El Nino Southern Oscillation (ENSO), determine the spatial and temporal development of storm fronts through the Mississippi River and Pascagoula River basins. These storm fronts are formed by the collision of moist warm air from the Gulf of Mexico (GOM), Caribbean Sea, and Atlantic Ocean with dry polar air. Interactions among non-linear oceanic-atmospheric modes of variability have been shown to modulate precipitation/runoff across both river basins (Douglas and Englehart 1981; Ropelewski and Halper 1986; Gershunov and Barnett 1998; Cayan et al. 2001; Enfield et al. 2001; McCabe et al. 2004).

In microtidal Louisiana estuaries, climate-related factors strongly influence water level patterns in short periods (days) to long periods (decades) (Conner and Day 1987; Turner 1987). Childers et al. (1990) found that high (or low) rates of local precipitation and Mississippi River discharge were generally associated with anomalously high (or low) marsh inundation regimes, respectively, that coincide with ENSO warm (or ENSO cold) events (interannual oceanic-atmospheric mode of variability). The frequency and duration of flooding events as well as the extension of marsh/water edge are determined by river discharge (Walker et al. 1987), daily tides (Reed 1989; Rey et al. 1990; Rogers et al. 1994; Rozas and Minello 1999), southerly wind-driven waters (Reed 1989), winter storms (Baumann 1980; Cahoon and Turner 1987), tropical storms and hurricanes (Baumann 1980), sea level rise (Penland et al. 1987), and coastal subsidence (Mitsch and Gosselink 1986; Turner and Boesch 1987). Flooding events directly influence the degree of marsh habitat accessibility (Rozas and Reed 1993; Minello and Webb 1997; Whaley 1997; Rozas and Minello 1998; Castellanos and Rozas 2001), which in turn has been found to increase inshore secondary productivity (Zimmerman et al. 2000). Interannual climatological variation in the Mississippi River basin affects recruitment (Childers et al. 1990), overall productivity of fisheries (Day et al. 1973), and the make-up of biological communities (Twilley et al. 2001).

Discharge from the Mississippi River and Atchafalaya River represents over 90% of the total river discharge in Louisiana (Perret et al. 1971); high discharge rates increase water levels (Bauman 1987) and dilute salinities (Barrett and Gillespie 1973; Bauman 1987) along the Louisiana coast. The Pascagoula River and Pearl River account for more than 90% of the freshwater discharge into the Mississippi Sound (Eleuterius 1978). Annual river discharge is tightly linked to environmental factors that are known to influence coastal shelf and inshore productivity in the northcentral GOM. The timing of Mississippi River discharge, wind-driven upwelling, incident light, vertical mixing, nutrient flux, phytoplankton and microzooplankton production, and oxygen depletion are all strongly correlated on the coastal shelf (Everett 1971; Walsh 1988; Muller-Karger et al. 1991; Gardner et al. 1994; Justic et al. 1997; Lohrenz et al. 1997). In coastal Louisiana west of the Mississippi River, nutrient-rich riverine waters and meteorological conditions contribute to the development of a strong seasonal thermocline during the summer between highly productive surface waters and less productive bottom waters. Excess primary production sinks to the bottom, where decomposition of organic material takes place, generating, in some cases, oxygen concentrations below 2 mg/l. When oxygen depletion is severe, hypoxia blocks movement of migrating organisms (Gazey et al. 1982) and reduces species richness, abundance, and biomass of infauna (Pavela et al. 1983; Gaston 1985; Rabalais et al. 1995), finfish, and shrimp (Leming and Stuntz 1984; Renaud 1986).

The blue crab, *Callinectes sapidus*, 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 al. 2001). Louisiana and Mississippi account for ~70% (Guillory and Perret 1998) and 1% (Guillory et al. 2001), respectively, of blue crab production in the GOM. Despite its commercial, recreational and ecological value, there have been few studies conducted on the influence of climatic factors on blue crab production; most research has focused on examining the link between quality and quantity of habitat as a determinant of population size.

Guillory (2000) used fishery independent data from selected Louisiana estuaries to calculate a recruitment index (catch per unit effort, CPUE, of blue crabs less than 40 mm carapace width collected during January and February). He found that the index was positively correlated with Mississippi River discharge during the late summer/early fall and attributed that correlation to a reduction in blue crab predator-prey interactions due to dispersal or emigration of marine predators in expanded low salinity habitats. Other studies have also linked high survival rates of blue crabs through the juvenile stages to the extension of nursery areas and to availability of structured habitats. River discharge enhances wetland nursery areas not only by increasing geographic extent of favorable habitat but also by providing nutrients that facilitate growth of emergent and submergent vegetation. Vegetated nursery habitats provide chemical cues for settlement, food, and refuge to juvenile crabs (Everett 1971; Fucik 1974; Williams et al. 1990; Heck and Spitzer 2001; Heck et al. 2001; Rakocinski et al. 2003). Attached or mat-forming algae in addition to ephemeral habitats such as detrital matter, drift algae, and bryozoans (Rakocinski et al. 2003; Spitzer et al. 2003) also provide structure and support high densities of post-settlement blue crab stages (Rakocinski et al. 2003). Although unvegetated habitats have lower densities of juveniles than do structured habitats (Rakocinski et al. 2003), extensive areas of unvegetated soft sediment bottoms in the northern GOM also provide important refuge for small crabs.

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 non-linear oceanic-atmospheric modes of variability themselves are not readily predictable, propagation of modes of variability from their source area would provide lead time for prediction of the impact of climate on local populations. Although interactions of phases/events among non-linear oceanic-atmospheric modes of variability have been associated with Mississippi River and Pascagoula River discharge (Chapter I), 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 non-linear oceanic-atmospheric modes of variability and blue crab recruitment in the northcentral GOM and to elucidate underlying mechanisms involved in that association. My hypothesis is as follows:

> Climate-related factors responsible for the long-lasting hydrological regimes across the Mississippi River and Pascagoula River basins are linked to long-term periods of blue crab abundance in the northcentral GOM.

Methodology

The interactions among phases/events of non-linear interdecadal (the PDO mode), multidecadal (the AMO mode), decadal (the NAO mode), and interannual (the ENSO mode) oceanic-atmospheric modes of variability were used to determine climatic phases influencing GOM estuaries over the period 1967 – 2005. The acquisition and methodology employed in determining those climatic phases are described in detail in Chapter I. In the same chapter, a detailed description of acquisition and processing of Mississippi River and Pascagoula River flow data is presented. Table 1 summarizes the data acquired for the present study.

Monthly Palmer Drought Severity Index (PDSI) for the Mississippi River basin was calculated from the monthly PDSI values of four U.S. regions that encompass the basin. The proportion of each regional PDSI value that contributes to the PDSI value for the Mississippi River basin is calculated by the weight to surface area relationship of images from the sections of the basin and their correspondent regions. An image of all four U.S. regions, each of the four regions, and each of the four sections of the Mississippi River basin were weighed to 0.001g. The weight of a section of the basin was divided by the weight of its region to determine the proportion of the basin within a region. These proportions were used to multiply their regional PDSI values to obtain the

TABLE 1. Climatological, meteorological, and hydrological parameters (1967-2003) and blue crab abundance (1967-2005) used in data analysis.

Parameter	Annual	Source	Range of Values
Pacific Decadal Oscillation (PDO)	Jan.-Dec.	NOAA: Earth System Research Laboratory (2008a)	-1.29 to 1.82
Atlantic Multidecadal Oscillation (AMO)	Jan.-Dec.	NOAA: Earth System Research Laboratory (2008b)	-0.31 to 0.53
North Atlantic Oscillation (NAO)	Jan.-Dec.	NOAA: Climate Prediction Center (2008)	-0.94 to 0.70
Equatorial Pacific NINO3.4 Index	May-Feb.	NOAA: Climate Prediction Center (2007)	-1.65 to 2.15
Kessler Southeasterly Wind, % h	Sep.-Aug.	NOAA: National Climatic Data Center (2007a)	14 to 33
Kessler Northwesterly Wind, % h	Sep.-Aug.	NOAA: National Climatic Data Center (2007a)	15 to 25
Mississippi Basin Palmer Drought Severity Index	Sep.-Aug.	NOAA: National Climatic Data Center (2007b)	-1.88 to 3.75
Mississippi River Discharge, ft^3/s	Sep.-Aug.	U. S. Geological Survey: National Water Information System (2007a) and U.S. Army Corps of Engineers (2007)	-224751 to 397007
Pascagoula River Discharge, ft^3/s	Sep.-Aug.	U. S. Geological Survey: National Water Information System (2007b)	-7073 to 10511
Louisiana Coastal Sea Level Anomaly, ft	Sep.-Aug.	U.S. Army Corps of Engineers (2008)	-0.47 to 0.56
Trawl Sampling Salinity, ppt	Sep.-Aug.	Louisiana Department of Wildlife and Fisheries and Gulf Coast Research Laboratory	9.75 to 20.21
Crab Abundance per Trawl	Jan.-Dec.	Louisiana Department of Wildlife and Fisheries and Gulf Coast Research Laboratory	2.49 to 12.08

PDSI values for each section of the basin. The weight of each basin section was divided by their combined weight, obtaining a new quotient value. This quotient indicates the contribution of each PDSI value from each section of the basin to the total PDSI value of the Mississippi River basin. The PDSI values from September of the previous year to August of the following year were averaged to obtain an annual PDSI value for the Mississippi River basin.

Daily coastal sea level was obtained from six U.S. Army Corps of Engineers gauges along the Louisiana coast (Fig. 1: Hackberry, 1966-2003; Cocodrie, 1969-2003; Grand Isle, 1984-2003; Rigolets, 1966-2003; Bancker, 1966-2003; and Delacroix, 1975-2003). Daily sea level values were averaged to obtain monthly sea level values for each gauge. Monthly sea level values were highly correlated among the six gauges ($r > 0.241$, $p < 0.001$) allowing a regional sea level data set to be calculated from the average of the six individual data sets. Regional monthly sea level anomaly was calculated by subtracting the average value of sea level by month from the monthly value per year of the regional sea level data set (1966-2003). The sea level anomaly values from September of the previous year to August of the following year were averaged to obtain an annual sea level anomaly for the northcentral GOM. Hourly wind data were obtained from the National Climatic Data Center, Ashville, North Carolina. Wind measurements were taken at the Kessler airport, Biloxi, Mississippi with an anemometer mounted at 10 m height. To identify wind directions (angle with respect to the coast) influencing sea level in the northcentral GOM, PV-Wave 6.21 (Visual Numerics Inc., Boulder, Colorado) software was used to correlate the Kessler airport wind direction (vector) and sea level from two gauges west (Grand Island and Cocodrie) and two gauges east (Delacroix and

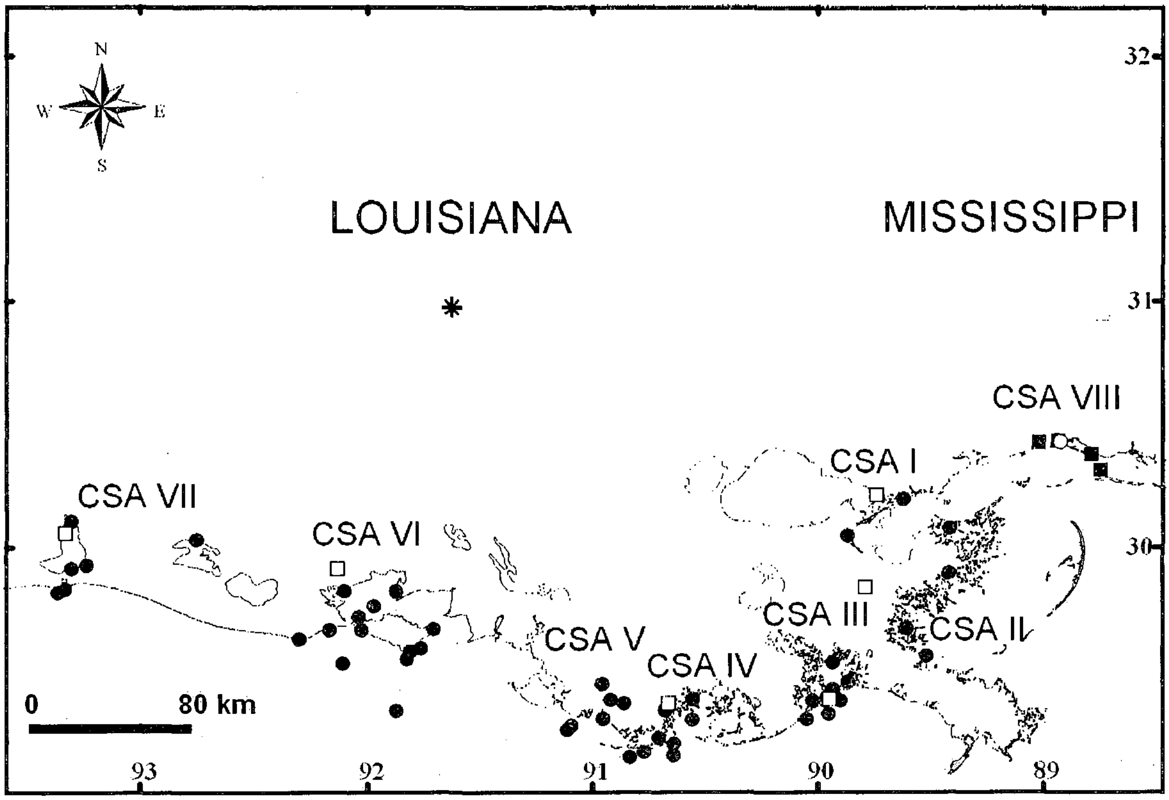

FIG. 1. Trawl stations surveyed by Louisiana Department of Wildlife and Fisheries (47 solid circles) and Gulf Coast Research Laboratory (4 solid squares), stations from the U.S. Army Corps of Engineers (6 sea level gauges: open squares and 1 river flow station: asterisk), river flow stations from the U.S. Geological Survey (2 open triangles), and wind station from the National Climatic Data Center (open circle). Coastal Study Areas: 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.

Rigolets) of the Mississippi River Delta. The wind directions identified in these analyses were used to subdivide the Kessler airport wind data into a monthly data set of the frequency (number of hours) of wind directions that increased and decreased sea level. Monthly number of hours of influential winds from September of the previous year to August of the following year were added and divided by the annual (September to August) number of hours sampled. Two data sets were generated showing the proportion of hours per year that influential winds increased and decreased sea level in the study area.

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; Fig.1). The study area is divided into eight 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. Since 1967, Louisiana sampling (CSAs I-VII) is conducted weekly from March to October and biweekly from November to February, whereas since 1973 Mississippi stations (CSA VIII) have been surveyed monthly. Both states, by agreement, use standard gear and sampling protocols: a 4.9 m otter trawl with 1.9 cm bar mesh and a 6.35 mm mesh liner. Trawls are pulled for 10 min and samples are iced in the field. Data are available on juvenile, late-stage juvenile, subadult, and adult blue crabs collected in inshore waters of both states. During the acquisition of biological data, Louisiana Department of Wildlife and Fisheries and Gulf Coast Research Laboratory personnel recorded surface and bottom salinities for each of the trawl sampling tows. Monthly surface salinities from trawl stations within each CSA were averaged to obtain a single data set of salinity by CSA. The monthly CSA salinities were highly correlated ($r>0.169$, $p<0.002$) and were averaged to obtain a single regional data set of monthly salinity. Regional salinities from September of the previous year to August of the following year were averaged to obtain a single annual salinity data set.

Although Louisiana biological data cover the period 1967 to 2005, sampling effort and areal coverage among and within CSAs were variable from 1967-1981 and more equally distributed beginning in 1982. Trawl stations sampled within each study area varied and not all stations within a CSA were sampled each month. Disparity in trawl survey periods, fishing effort, and coverage complicated comparisons of abundance among study areas within climatic phases in the Louisiana data. A regional analysis was conducted after finding that hydrological parameters such as river flow (Chapter I), salinity, and sea level reacted in a similar manner within the study area. A regional length frequency analysis showed that blue crabs collected by trawl ranged from 2.5 to 305.0 mm CW (Fig. 2). Crabs less than 50.0 mm CW comprised 61.7% of the catch with crabs below 90.0 mm comprising 82.0%. Crabs began recruiting to trawls at 20.0 mm CW with full recruitment at 30.0 mm CW. Legal-sized crabs (127 mm CW) made up ~10% of the catch.

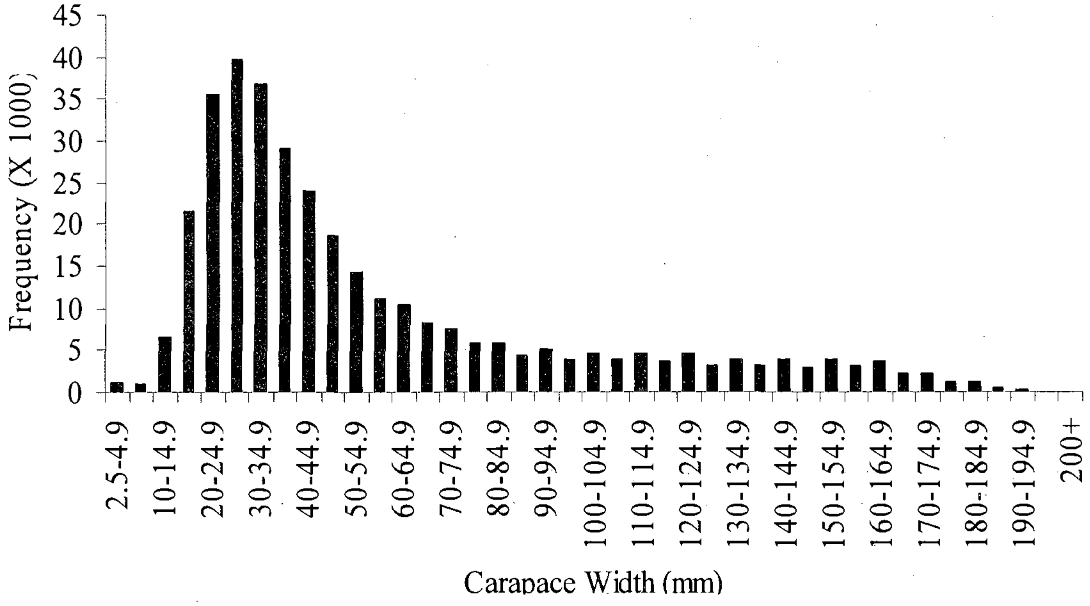

FIG. 2. Size-frequency of blue crabs in 4.9 m beam otter trawls from the northcentral Gulf of Mexico.

Mississippi and Louisiana data sets were simplified to eight CSAs and a regional data set of yearly (January-December) overall (all size classes) abundance (CPUE). All size classes in the trawl data were used in analyses to obtain maximum sample size. To obtain a yearly 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 eight yearly CSA CPUEs. The CPUE for each study area was added and then divided by the number of study areas to produce an additional yearly regional CPUE. Data were analyzed regionally in a manner that ensured equality across each study area (giving the same weight to each station and each study area). Data for years 1967 to 1972 represent Louisiana only; sampling in Mississippi did not begin until 1973.

Periods of Overall Blue Crab Abundance and Long-term Climatic Phases

Multivariate analyses were used to examine biological data (PRIMER 6, Plymouth Routines in Multivariate Ecological Research). Missing values were replaced by zero according to the stipulation on biotic data in PRIMER 6. Bray-Curtis similarities (Bray and Curtis 1957) were calculated among years on non-transformed CPUE data from the eight coastal study areas. The Bray-Curtis similarity matrix was used to perform hierarchical agglomerative clustering using a group-average linkage method (Kaufman and Rousseeuw 1990) and non-metric multi-dimensional scaling (MDS). The multivariate analyses were used to determine the sequence of overall blue crab CPUE in the northcentral GOM. This sequence was compared with the series of climatic phases created by the combination of phases from the interdecadal mode (PDO), the multidecadal mode (AMO), and the decadal mode (NAO) of climatic variability.

The null hypothesis, that there was no difference in blue crab CPUE within the identified sequences of abundance, was tested by analysis of similarity (ANOSIM; Clarke and Green 1988), a non-parametric permutation procedure that was applied to the ranked Bray-Curtis similarity matrix. The procedure involved three main steps: computation of a test statistic (R) reflecting the differences in abundance between periods, contrasted with differences among replicates within those periods; recomputation of the test statistic for 999 permutations in which annual abundances were randomly reassigned to various periods; and calculation of the significance level by referring the observed value of R to its permutation distribution. Under the null hypothesis, arbitrarily reassigning annual abundances to different periods had little effect on the value of R. For pairwise comparisons of blue crab CPUE between periods, the Bonferroni correction was applied. Pairwise R values (0 to 1) were more indicative of CPUE relationships among periods than were the significance values. There were large differences in R values, with the periods being either well separated ($R \approx 0.75$), overlapping but clearly different ($R \approx 0.5$), or barely separable at all ($R \approx 0.25$; Clarke and Gorley 2001).

A one-way ANOVA (SPSS 13) was used to examine periods of blue crab abundance. When significant differences in blue crab CPUE among periods were detected ($P \leq 0.05$), pairwise comparisons of abundance were conducted using Hochberg, Games-Howell, and Gabriel post hoc tests. Yearly CPUEs, within long-term crab abundance periods, were further examined under the inter-annual influence of ENSO events using ANOSIM and a one-way ANOVA test.

Crab Abundance, Oceanic-Atmospheric Modes of Variability, and Meteorological and Hydrological Parameters

Correlation analysis (SPSS 13) was used to determine the relationship among regional crab abundance, modes of variability (PDO, AMO, NAO, and ENSO), and meteorological (southeasterly and northwesterly winds) and hydrological (Mississippi River and Pascagoula River flows, Mississippi Basin Palmer Drought Severity Index, Louisiana coastal sea level, and salinity) parameters. To cross validate the relationships found in the correlation analysis between crab abundance and other parameters, multiple linear regression analysis (Statistical Package R 2.7.0 2008) was used. Regression analysis was used to identify models of oceanic-atmospheric modes of variability and meteorological and hydrological parameters that contribute to the variability in blue crab abundance in the northcentral GOM. To find the best-fitting model, an Akaike's Information Criterion (AIC; Akaike 1973) and Bayesian Information Criterion (BIC; Raftery 1996) were calculated for each model. The AIC and BIC estimate the amount of information a model explains from its residual sums of squares (RSS, related to the amount of the variance left unexplained) and penalizes models for the number of parameters used (Burnham and Anderson 1998). The BIC was used in addition to the AIC to provide further support for model choice. The BIC uses maximized likelihood as a measure of information content. To select the best model, competing models were compared based on BIC and AIC values after correction for small sample size (McQuarrie and Tsai 1998). The criteria are such that the lower the values, the better fitting the model. The AIC technique was run forward, backwards, and forward/backwards to determine the best model for each method. To check the reliability of the final model, three AIC models were compared with models from BIC. The final two models were then run on SPSS multiple linear regression analysis to determine the R^2 of the final model.

Results

Periods of crab abundance and long-term climatic phases

The cluster analysis (Fig. 3) revealed four distinct periods of annual blue crab abundance: period I, 1967-1970; period II, 1971-1980; period III, 1981-1998; and period IV, 1999-2005. Three years did not follow in chronological sequence; 1991 grouped in period II, 2005 grouped in period III, and 1995 grouped in period IV. High CPUE in 1990 did not cluster with any of the four periods. The four periods of abundance were also separated in the MDS mapping (Fig. 4). As occurred in the cluster analysis, period I was far removed from the other periods of crab abundance. The beginning years (1967-1970) were characterized by low sampling effort, limited coverage within a CSA, and lack of samples from some study areas and for these reasons, data from period I should be interpreted with caution. Each data point in Fig. 4 represents an annual CPUE and the distances between points indicate their relative similarity to each other. Among the 39 years, crab abundances gathered from the same period were generally more similar to each other than those collected from different periods. A tight grouping of annual crab abundances was found during periods I, III, and IV whereas annual abundances were more distant in periods II. One-way analysis of similarity (ANOSIM) revealed that crab abundances were distinct among the four abundance periods (global R= 0.701, p, 0.001). The pairwise ANOSIM test showed overlap, but periods were clearly different (R>0.57, p=0.001, in 999 permutations). Although the comparison between periods I and II exhibited a high R value (R=1, p=0.003, in 330 permutations), the low number of permutations may preclude meaningful results.

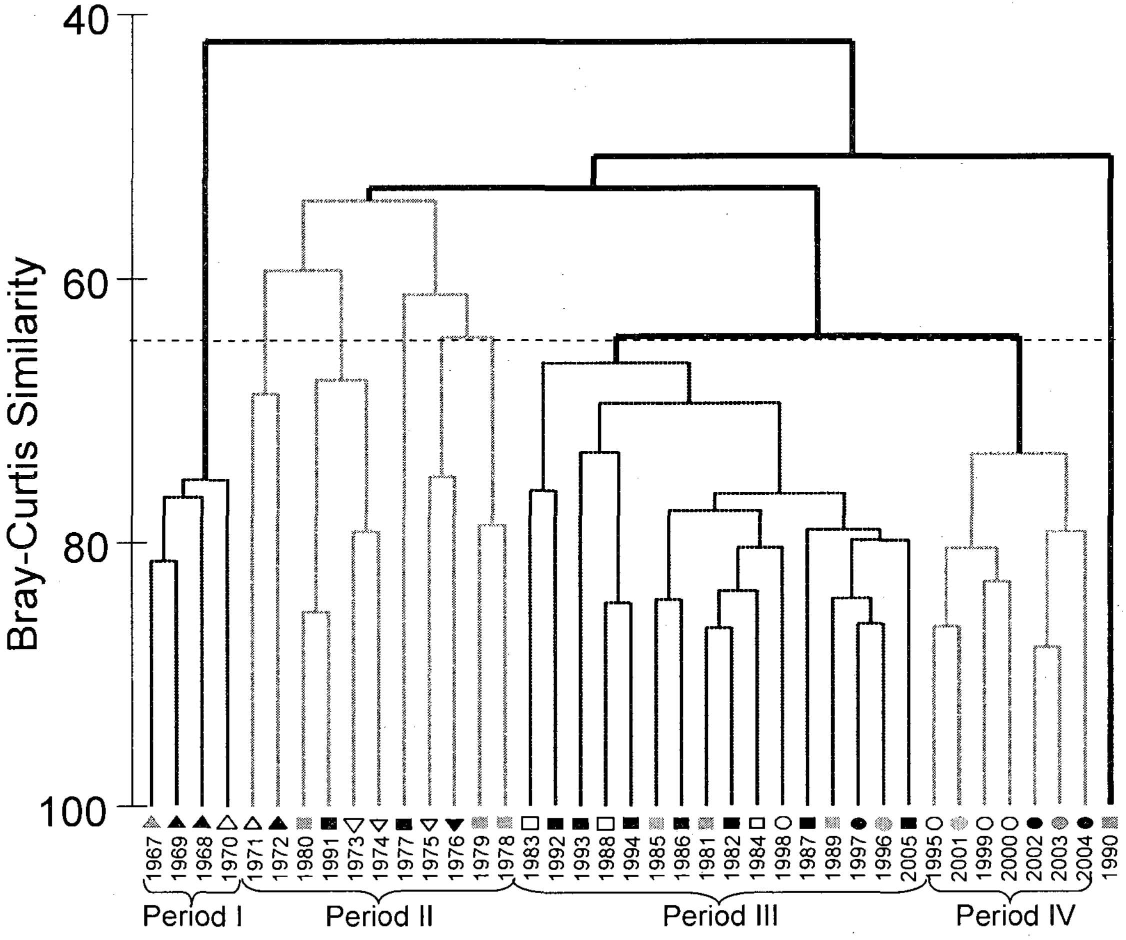

FIG. 3. Dendrogram for hierarchical clustering (using group-average linking) from Bray-Curtis similarities on 39 years of untransformed annual blue crab abundance from the northcentral Gulf of Mexico estuaries. The last two periods (III and IV) of blue crab abundance were separated at a 64.5% similarity threshold (dotted line). Labels along x-axis represent years. Symbols represent multidecadal/decadal climatic phases (triangle=PDOc/AMOc/NAOn, inverted triangle =PDOc/AMOc/NAOp, square =PDOw/AMOc/NAOp, circle =PDOw/AMOw/NAO[1]) and their shading represent interannual climatic phases (black=ENSOw, gray=ENSOn, white=ENSOc).

[1] During this climatic phase NAO was positive (NAOp: 1995-1996) and negative (NAOn: 1997-2005).

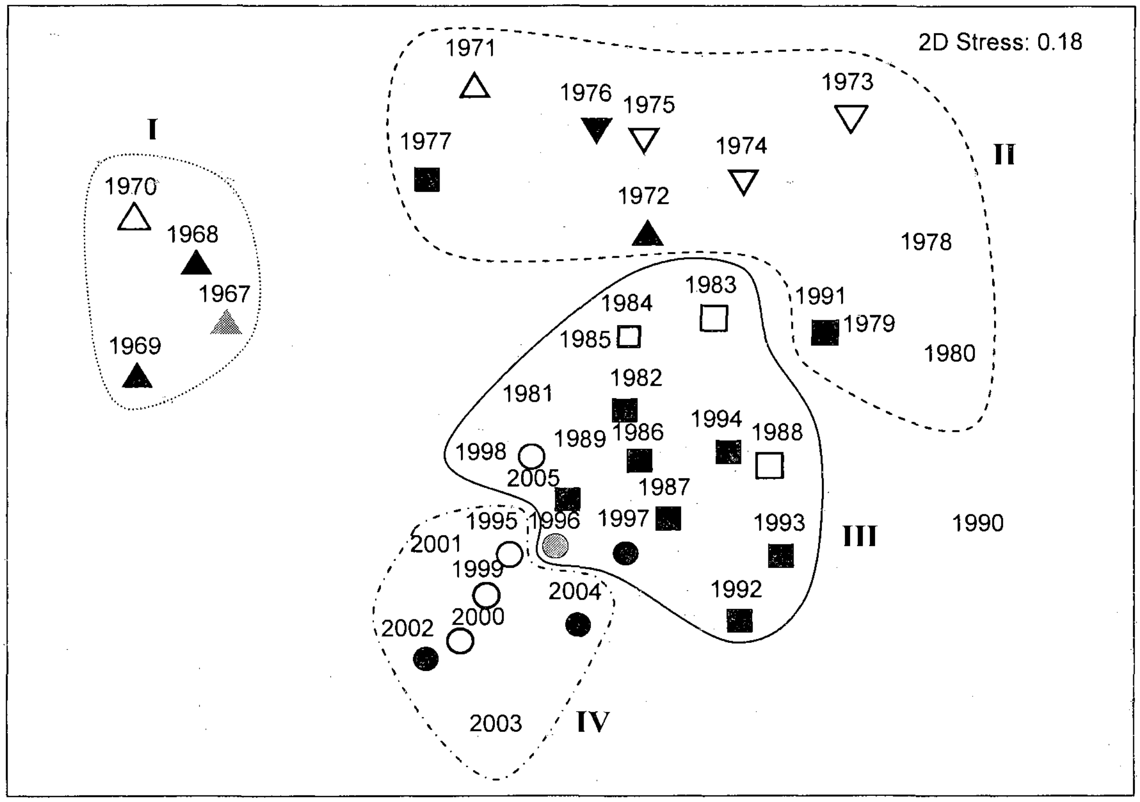

FIG. 4. Multi-dimensional scaling of blue crab abundance in the northcentral Gulf of Mexico from three different interannual climatic events within four multidecadal/decadal climatic phases, based on Bray-Curtis similarities from untransformed data. Numbers represent years. Symbols represent long-term climatic phases (triangle= PDOc/AMOc/NAOn, inverted triangle= PDOc/AMOc/NAOp, square= PDOw/AMOc/NAOp, circle= PDOw/AMOw/NAO[1]) and their shading represent interannual climatic events (black= ENSOw, gray= ENSOn, white= ENSOc). Lines represent long-term periods of abundance: square dot line= period I, dash line= period II, solid line= period III, and dash dot line= period IV.
[1]During this climatic phase NAO was positive (NAOp: 1995-1996) and negative (NAOn: 1997-2005).

Chronological similarity between four multidecadal/decadal climatic phases (PDOc/AMOc/NAOn, 1967-1972; PDOc/AMOc/NAOp, 1973-1976; PDOw/AMOc/NAOp, 1977-1994; PDOw/AMOw/NAO[1], 1995-2005) and four abundance periods (I, 1967-1970; II, 1971-1980; III, 1981-1998; IV, 1999-2004) are

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[1] During this climatic phase NAO was positive (NAOp: 1995-1996) and negative (NAOn: 1997-2005).

clearly seen in Fig. 5. The overlap of abundance periods between climatic phases showed a lag in biotic response to the transition from one climatic phase to another.

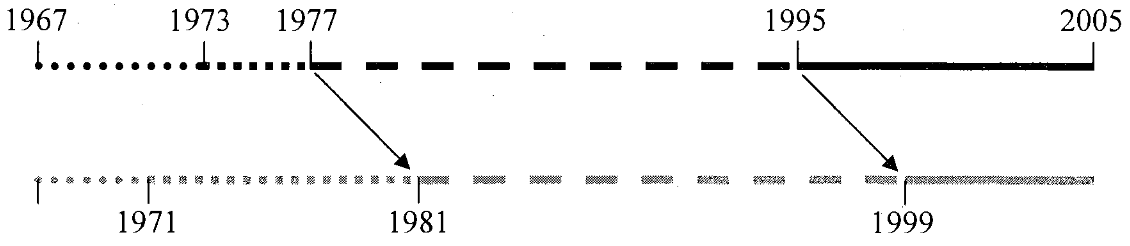

FIG. 5. Climate-related river flow regimes (black line) and periods of blue crab abundance (gray line) in the northcentral Gulf of Mexico. The PDOc/AMOc/NAOp regime and period I (round dotted line), the PDOc/AMOc/NAOp regime and period II (square dotted line), the PDOw/AMOc/NAOp regime and period III (dashed line), and the PDOw/AMOw/NAO[1] regime and period IV (solid line). Arrows show the four years lag in biological response to changes in climate phases.

[1] During this climatic phase NAO was positive (NAOp: 1995-1996) and negative (NAOn: 1997-2005).

A comparison among climate phases, river flow regimes, and the actual number of crabs per trawl are shown in Fig. 6. The first climate phase shows low Pascagoula River and high Mississippi River flows linked to intermediate crab abundance. The second and third climate phases are characterized by high river flows and high crab abundances, whereas the fourth climate phase of low river flows exhibit low blue crab abundance. The one-way ANOVA test showed significant differences among periods of blue crab abundance ($F=16.018$, $p<0.001$, $df=3$, $r^2=0.549$, Fig. 6). During periods II and III, there was higher crab abundance than in periods I and IV ($p<0.037$). There was also higher crab abundance in period I than in period IV ($p=0.001$). The pairwise test showed no significant difference between periods II and III ($p=0.099$).

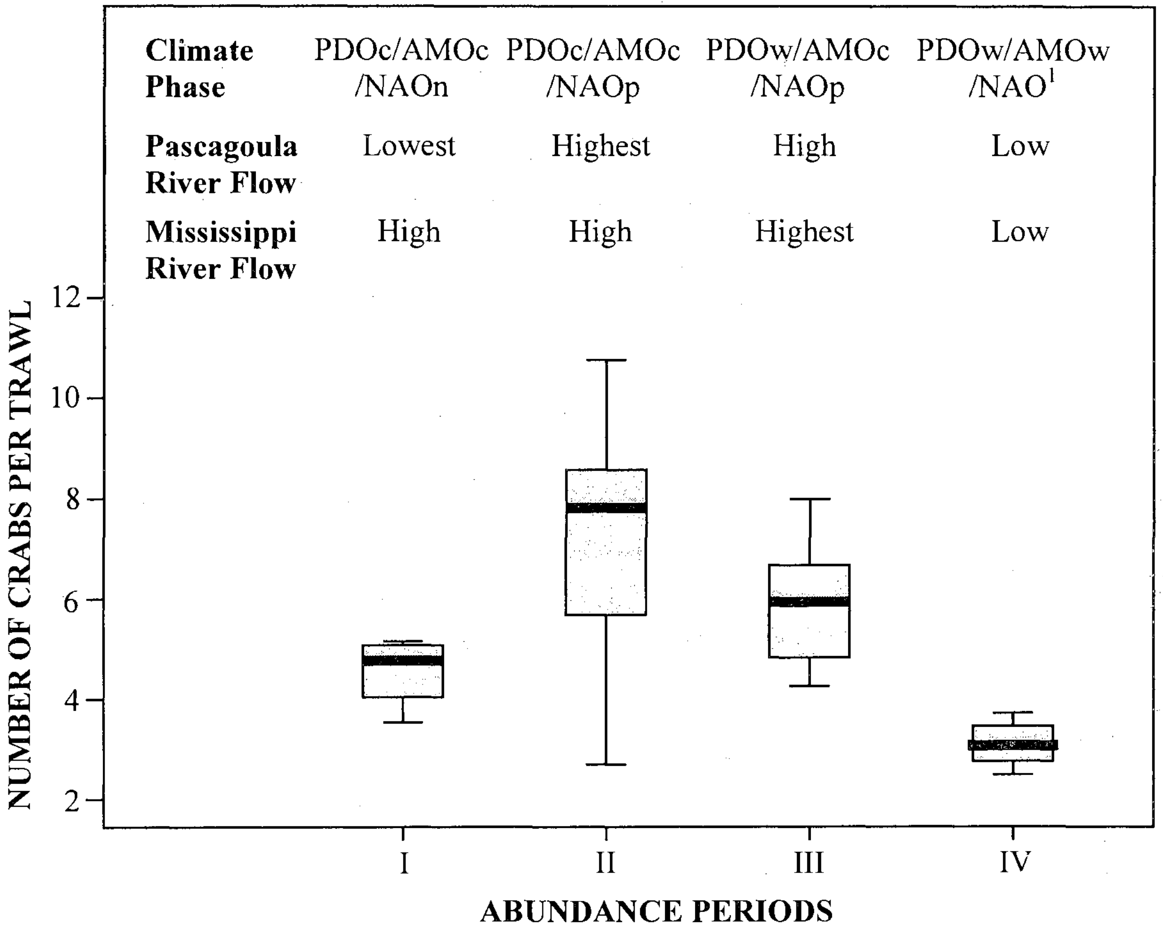

FIG. 6. Long-term climate phases and river flow regimes in relation to the number of blue crabs per trawl during four periods of abundance (I, 1967-1970; II, 1971-1980; III, 1981-1998; IV, 1999-2004) in the northcentral Gulf of Mexico. Box plots indicate 5th, 25th, 50th (median), 75th, and 95th percentiles as horizontal lines.

[1] During this climatic phase NAO was positive (NAOp: 1995-1996) and negative (NAOn: 1997-2005).

Periods of Crab Abundance and Interannual ENSO Events

The influence of ENSO events on annual crab abundance were analyzed within the four long-term periods of abundance (Figs. 3 and 4). Each type of ENSO event (warm, cold, neutral) occurred in each period of abundance with one exception; period I lacked an ENSOc event. The MDS mapping (Fig. 4) showed annual fluctuations within the periods of abundance according to the ENSO event in place. To compare crab abundance during ENSO events within each of the four periods of abundance, an ANOSIM and a one-way ANOVA were carried out. Numbers of replicate ENSO events within each period of abundance varied. Significant differences in crab abundance using ANOSIM (global $R = 0.625$, $p=0.001$) and a one-way ANOVA ($p<0.001$) were found; however, pairwise comparisons showed that those differences were more related to climatic phases than to the actual influence of ENSO events.

Crab Abundance, Oceanic-atmospheric Modes of Variability, and Meteorological and Hydrological Parameters

Significant correlations ($r>0.321$, $p<0.047$) were found among oceanic-atmospheric modes of variability, hydrological and meteorological parameters, and blue crab abundances (Fig. 7). Those relationships were consistent with the mechanisms that were found to be responsible for the hydrological conditions across the Mississippi River and Pascagoula River basins (Chapter I). Correlation and multiple regression analysis showed that crab abundance was closely related to the same factors. The AIC and BIC produced similar models. One model contained the AMO and salinity (AIC value of 59.8 and BIC of value 1.7), the other model contained NAO and the frequency of southeast winds (AIC value of 60.3 and BIC of value 2.3). Both models had an r^2 of 23%. Modes of variability (AMO or NAO) included in the linear regression models were strongly related to hydrological conditions in the Mississippi River and Pascagoula River basins (Chapter I). The other two parameters (southeast winds and salinity) emphasized the importance of hydrological conditions (sea level and low salinity) in determining the variability of blue crab abundance in the northcentral GOM.

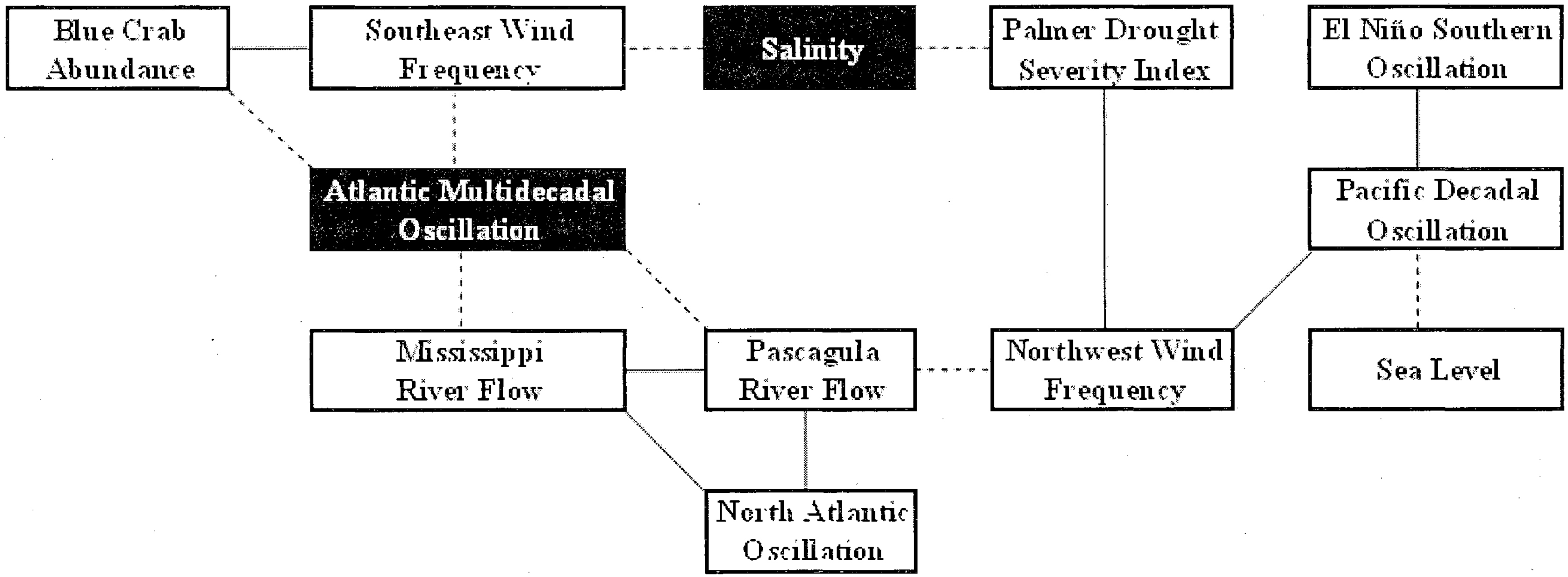

FIG. 7. Flow chart of significant correlations among oceanic-atmospheric modes of variability, hydrological and meteorological parameters, and blue crab abundances (CPUE) in the northcentral Gulf of Mexico. Positive correlations are indicated by solid lines and negative correlations by dotted lines. Gray and black rectangles show the two sets of variables included in the regression models that explain 23% of the variability in blue crab abundance. White rectangles represent the variables non-included in the regression models.

Discussion

Population levels of juvenile blue crabs in northcentral GOM estuaries were linked to climate-related hydrological regimes associated with long-term atmospheric and oceanic modes of variability. Over the study period (1967-2005), four long-term climatic phases were found to overlap chronologically with four periods of blue crab abundance identified by cluster analysis and MDS. During the periods of overlap, a slowed biotic response to the change in climatic phase was observed. For all but three years, the abundance of blue crabs fell into chronological sequences under climatic phases. The years 1991, 2005, and 1995, however, were non-chronological, occurring in periods II, III, and IV, respectively. The 1991 abundance followed the largest annual (1990) CPUE of the study period. The 1990 abundance did not group with any of the climate periods. Period IV was characterized by low abundance and 1995, with its low CPUE, clustered with that group. Catch was higher and more variable in period III and CPUE in 2005 clustered in that period. Those years (1995 and 2005) were characterized by high numbers of hurricanes and tropical storms in the northcentral GOM. There were significant differences in abundance between periods with one exception: periods II and III. High variation in period II and the climatological similarity between the periods may have accounted for the lack of significance in post-hoc tests. Blue crab abundance was highest in period II with numbers decreasing through period IV. Periods of elevated crab abundance (II and III) were associated with high river flow, low salinity, and an increased frequency of southeast winds. River flow (More 1969; Wilber 1994; Guillory 2000) and salinity (Guillory 2000) have been linked to blue crab abundances. Early investigations into factors affecting population dynamics of blue crabs related fluctuations in abundance to physiological tolerances to temperature and salinity (intrinsic effect). Livingston (1976) was among the first to suggest that the influence of salinity may be operating extrinsically by structuring the surrounding biotic community.

Recent research suggests that predation is the component of the biotic community affecting abundance. Studies on predator/prey interactions (Heck and Coen 1995; Heck et al. 2001; Guillory and Prejean 2001; Moksnes and Heck 2006) and habitat selection/utilization (Williams et al. 1990; Morgan et al. 1996; Heck and Spitzer 2001; Rakocinski et al. 2003) suggest that factors that increase or decrease refuge availability are determinant in the establishment of population levels. Both inter- and intra-specific predation operate to regulate abundance of juvenile blue crabs in the GOM (Guillory et al. 2001). Greater diversity of predators, fewer predation-free refuges, and lack of seasonality in predation activity all contribute to the high 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, abundance of juveniles differed among climatic phases with the period of greatest crab abundance associated with high river flow, an increased frequency of southeast winds, and low salinity. Lowest abundances were associated with reduced river flow, low frequency of occurrence of southeast winds, and high salinity. The AMO and NAO were found to be important drivers of climate-related factors influencing long-term hydrological conditions across the Mississippi and Pascagoula River basins (Chapter I). Mississippi and Pascagoula river flows and blue crab abundance were higher during the AMO cold and NAO positive phases than during the AMO warm and NAO negative phases. Regression models that included the AMO and salinity and the NAO and southeast winds were found to explain 23% of the variability in blue crab abundance in the northcentral GOM. 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 Wilber (1994) in Apalachicola Bay, Florida, Guillory (2000) in Louisiana estuaries, and More (1969) in Texas bays.

Although long-term climatological patterns influence abundance of estuarine organisms, there is also evidence that shorter climatic events can affect population levels. In micro-tidal Louisiana estuaries, inter-annual climate-related factors were found to influence water level patterns over limited time periods. Childers et al. (1990) found that high (or low) rates of local precipitation and Mississippi River discharge were generally associated with anomalously high (or low) marsh inundation regimes, respectively, that coincided with ENSO warm (or ENSO cold) events (inter-annual oceanic-atmospheric mode of variability). The frequency and duration of inter-annual flooding events as well as the extension of marsh/water edge are determined by river discharge (Walker et al. 1987), daily tides (Reed 1989; Rey et al. 1990; Rogers et al. 1994; Rozas and Minello 1999), southerly wind-driven waters (Reed 1989), winter storms (Baumann 1980; Cahoon and Turner 1987), and tropical storms/ hurricanes (Baumann 1980). Flooding events not only influence the degree of marsh habitat accessibility (Rozas and Reed 1993; Minello and Webb 1997; Whaley 1997; Rozas and Minello 1998; Castellanos and Rozas 2001), they also increase the areal extent of non-vegetated habitats. Although unvegetated habitats have lower densities of juveniles than do structured habitats (Rakocinski et al. 2003), extensive areas of unvegetated soft sediment bottoms in the northern GOM provide important refuge for small crabs. In the current study, all ENSO events (warm, cold, neutral) occurred in all periods of abundance. The MDS mapping of blue crab abundances within ENSO events by climatic phase showed annual variations in abundance by ENSO event; however, those differences were not significant and appeared to be overshadowed by the stronger influence of the long-term climatic phases. The effect of ENSO events on river discharge was more evident in the last climatic phase, a time of drought, thus ENSO events were more influential locally. During the last climatic phase, Pascagoula River flow was significantly higher during ENSOw events than during ENSOc events. Previous studies linking abundance of estuarine organisms to ENSO events were generally conducted in small areas over a limited time frame (Childers et al. 1990). While interannual events associated with increased local rainfall and river flow influence distribution and abundance of organisms on small-scale, long-term climatic phases dominate hydrological conditions in GOM estuaries.

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 megalopal settlement) was found to be dependent on inter-annual 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 circulation patterns that transported larvae offshore initially, but then acted to return them to shore at the appropriate stage. Annual temporal periodicity of settlement is similar; however, settlement is highly episodic and there are large annual variations in numbers of megalopae (Perry et al. 1995; Perry et al. 2003). Regardless of the level of recruitment, by the time crabs reach ~30 mm CW, populations begin to level off and then decrease at a gradual rate (Perry et al. 1998). In their study, Perry et al. (1998) noted that high numbers of megalopae and early crabs did not result in proportionally elevated numbers of late stage juveniles as high and low recruitment years had similar population levels. They concluded that the GOM blue crab fishery was not recruitment limited and that year-class strength was dependent on juvenile survival. Recent analysis of data from fishery-independent, long-term monitoring studies in Alabama, Mississippi, and Louisiana confirm those findings. In those states, there have been significant declines in numbers of later stage juveniles in trawl surveys; however, early life history stages collected in beam plankton trawls and seines do not exhibit similar trends (Perry et al. 2008).

Climate interacts with an ever-changing physiographic landscape world-wide. In the northern GOM, detrimental changes in habitat brought about by the cumulative impacts of human activities have been exacerbated by a series of catastrophic events in recent years. All life history stages of the blue crab are affected to some degree by climate and the hydrology associated with the differing climatic phases. Recruitment, while physically mediated, has been adequate and numbers of megalopae and early juveniles do not exhibit declines. There is strong evidence that fisheries sustainability is dependent upon juvenile survival. In the present study and others, the quantity and quality of coastal marsh habitat have been linked to the successful production of blue crabs. There is a minimum amount of quality habitat necessary to support fishery production but it is not clear what this minimum may be or how to classify the quality of a particular piece of marsh in order to prioritize the most important pieces for protection or restoration. Development of quantitative tools that can be used to plan and prioritize protection and restoration of coastal habitat is critical and should be a priority for future research. It is incumbent on resource managers to address issues associated with preservation of habitat.

Conclusions

Four distinct periods of blue crab abundance were related to four long-term climate-related hydrological regimes in the northcentral GOM. Flood-related factors (river flow, frequency of southeast winds, and salinity) were associated with elevated catches of juveniles (periods II and III) whereas lowest numbers were collected in drought years (period IV). Yearclass success appears to be established in juveniles ~ 30.0 mm CW and larger; recruitment is not a limiting factor. The current study examined data on a regional scale, and this may have masked the influence of more local ENSO events on population levels. Twenty-three percent of the variability in blue crab abundance was explained by the couplings of the AMO and salinity or the NAO and frequency of southeast winds. The inability to quantify parameters associated with habitat alteration and loss makes prediction of recovery based on current knowledge difficult. Significant downward trends in abundance of juvenile blue crabs across the northern GOM have occurred over a time period characterized by unprecedented changes in habitat associated with catastrophic storms and the cumulative consequences of man-made alterations to coastal wetlands. Whether the shift to a more favorable climate phase would reverse declining trends is unknown as it is currently impossible to quantitatively factor in the influence of changing habitats. The results of this work are a starting point toward understanding the complex relationship between habitat, climate, and fisheries productivity.

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