The Influence of Circulation Variability on Postlarval Brown Shrimp (*Penaeus aztecus*) Recruitment

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ABSTRACT

The Influence of Circulation Variability on Postlarval Brown Shrimp (*Penaeus aztecus*) Recruitment. Heather M. Manitzas (Andrew Vastano), Life Sciences, Texas A&M University.

A parametric study with a calibrated and verified computer model has shown that changes in the direction of seaward atmospheric frontal passages as slight as ten degrees can significantly influence the nature of surface flow off Sabine Pass and Galveston Entrance. These computations and an array of interdisciplinary field observations reveal the sensitivity of the shelf's nearshore waters to external forcing. Abrupt restriction of transport into Sabine Lake and Galveston Bay by the development of seaward plumes is possible during several day episodes whose timing can influence recruitment of brown shrimp (*Penaeus aztecus*) postlarvae. Postlarvae attempt to enter estuaries from the shelf over a late March--early April spring tide interval each year in order to reach an environment necessary for their development into adults. Redistribution over the inner portion of the shelf at this time by a transient, wind-forced alongshore or offshore component of the Texas Current can physically alter their chances to gain the life-sustaining embayments or to be swept away, back onto the shelf. This study provides an initial estimate of the sensitivity of critical processes to atmospheric forcing. Dynamic evolution of submesoscale physical features and their spatial and temporal phasing with respect to biological processes have the potential to be dominant factors in penaeid recruitment variability.

DEDICATION

To Tommy Hill, my very patient fiancé, and
to Garry and Dee Anna Manitzas, my dedicated parents,
for all their loving and support.

ACKNOWLEDGMENTS

I wish to sincerely thank my advisor, Dr. Andrew Vastano, for all his help, kindness, patience, etc. Without his invaluable guidance, we would not be where we are today. He is truly a saint for putting up with all my shenanigans and stubbornness. Cheers.

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Finally, I would like to thank my friends and family for all their love and support. I especially thank my loving fiancé, Tommy (for all his patience during those many long nights proofreading this paper), my two roommates, Marcy and Sarah (for putting up with a ghost for roommate), my two special friends, Jeannie and Becca (for being my cheering section), and my wonderful family (for always supporting my dreams and goals).

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INTRODUCTION

One of the most accessible marine resources of the Gulf of Mexico is fished on the northwestern continental shelf and landed along the Texas-Louisiana coastline. With a shrimp yield that amounted to $250 million (Quast, et al., 1989), it has been called "the most valuable marine fishery resource of the Gulf of Mexico" (Baxter and Renfro, 1966). However, from year to year, the total catch varies by ±30% of the preceding year (Quast, et al., 1989). Although a complete understanding of this disparity is presently unknown, it appears possible from recent research results that environmental variability (Vastano, et al., 1995) could exert an influential role through transient, episodic events.

Estimates of the brown shrimp (*Penaeus aztecus*) stock are assessed by sampling at an early life cycle stage. For example, observations from December 1981 to April 1982 exhibited maxima in "estuarine-caught postlarvae" at the end of March and in early April (Rogers, et al., 1990). This is in keeping with similar postlarval catches (Figure 1) reported by Baxter and Renfro (1966) in the early 1960's. Baxter and Renfro noted the variability evident in postlarvae numbers from year-to-year at the same catch site and Rogers, et al. (1990) speculated that the presence of postlarvae in estuaries was correlated with the passage of atmospheric cold fronts and "the post-frontal return of southerly winds and northward flowing currents." Vastano, et al. (1995) observed the development of a

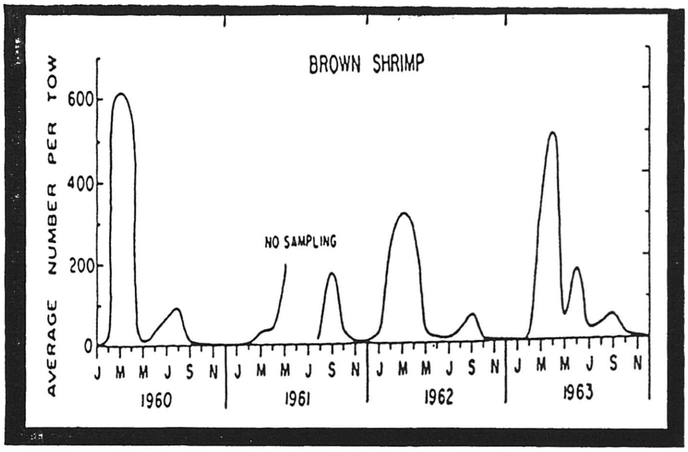

Figure 1 Seasonal abundance of postlarval brown shrimp at Galveston Entrance (Baxter and Renfro, 1966).

nearshore transient flow regime, a southwestward realization of the Texas Current, that can result during this type of frontal passage. Taken together, the results of these researchers foster an unique view of a relationship between the brown shrimp and the surrounding environment. The associated concept of a joint biophysical process provides a multiplicity of systematic pathways that can influence the shrimp population by redistribution of postlarvae along the Texas-Louisiana coastline. The physical transport mechanisms present in the springtime include transient turbulent eddies and advective currents that move postlarvae unable to stem such flow regimes. The spatial and temporal phasing of these physical features along with the brown shrimp life cycle are the basis for pathway alternatives. These factors contribute to the presence or absence in the "estuarine caught postlarvae" and as a result, have the potential to influence an estimate of the observed year-to-year variability in landed adult shrimp catches.

Biological Background

Penaeus aztecus pass through six major stages during their life cycle (Figure 2): demersal eggs, free-swimming planktonic larvae, estuarine-dependent postlarvae, benthic juveniles, sub-adults, and adults (Epifanio, 1988). The eggs are spawned by the adult brown shrimp offshore on shelf mid-grounds during spring to early winter. The demersal

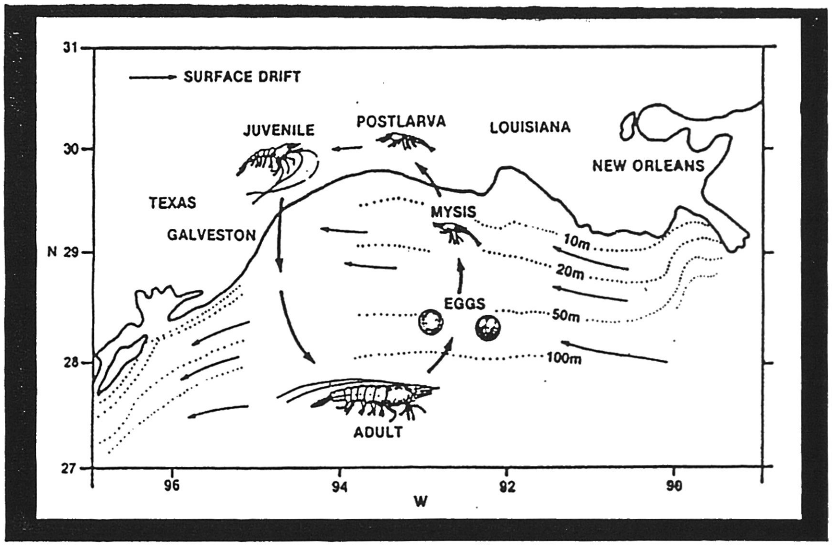

Figure 2 Schematic diagram of the brown shrimp (*Penaeus aztecus*) life cycle.

eggs hatch and develop into larvae that become estuarine-dependent postlarvae during a two to four month developmental stage. At the end of this stage, the shrimp are bottom-oriented and complete their life cycle by passing through both juvenile and sub-adults phases in estuaries. Within six months, they migrate seaward through the passes and move offshore to complete the cycle as adults and spawn (Rothschild and Brunenmeister, 1984). Thus, a general life cycle and a progressive sequence of stages has been identified and approximate intervals of time and seasonal associations have been made. Even so, comprehensive information about brown shrimp larval numbers and distributions on the continental shelf is not readily available. For instance, there has been speculation about hatching in late fall, "overwintering" on the shelf bottom, and then movement off the bottom in the spring when shelf temperatures begin to rise (King, 1971). There is also another line of evidence that suggests spawning takes place all year, and further, that this activity peaks in early spring and fall (Lochmann, 1990).

Environmental cues can trigger life cycle behavior. These cues, such as light, water temperature and salinity, and tidal stage (hydrostatic pressure), and the resulting behavior (Copeland and Truitt, 1966; Lochmann, 1990; Godwin, 1991) can combine with coastal physical processes to gain advantages for shrimp survival through their vertical and the ocean's horizontal movements. The influence of light level in diel vertical migration of larval and postlarval penaeids toward the surface was observed by Temple and Fisher (1965). Hughes (1969) reported laboratory experiments that established postlarvae can detect and react to salinity changes as small as 1ppt. Lochmann (1990) found that there was a greater abundance in penaeid postlarvae in the water column during night flood tides than any other times and attributed this to "a combination of nocturnal activity pattern and some mechanism related to flood tide." His regression analyses discerned strong correlations between postlarval presence and water temperature, salinity and motion in an estuary entrance.

During the postlarval stage, the brown shrimp must enter bays and estuaries in order to reach an appropriate substrate and sea grass nursery environments to become a juvenile and mature to the adult stage. The influx into this environment takes place in spring and fall. The spring event, primarily between the months of March and April, often peaks in approximately a four-day interval and is the most significant in terms of numbers. The movement from mid-shelf to aggregation off an estuary entrance is a shoreward part of brown shrimp migration that brings postlarvae into the shallow depths and surface layers of coastal waters. Considered as the critical moment during a shrimp's life, it is also the time when they are easiest to find and catch. Springtime passage into the estuaries is regarded and observed as the recruitment stage for brown shrimp. Recruitment is a measure of a population or fishery's stock at some stage in its life cycle. It is usually evaluated when a species is congregated, accessible, *and* easiest to catch, i.e., the postlarval stage of the brown shrimp.

Physical Background

In situ and remote observations of circulation on inner portions of the Texas Shelf have revealed the prevalence of episodic and transient submesoscale (<50 km characteristic length) physical features. Their presence can be conceptually related to combinations of either seasonal or short term (weekly, daily, hourly) regimes (Shaar, 1994), the constraints imposed by the coast and bottom topography, and the influence of external forcing by winds, rivers, estuaries, and features adjacent to the shelf (Vastano, et al., 1995). Mean motion patterns that vary on seasonal time scales have been statistically derived from a progression of shelf hydrographic data by Cochrane and Kelly (1986). For ten months of the year, the patterns indicate a cyclonic gyre on the shelf that can be correlated with monthly wind statistics (Shaar, 1994).

The mean description of the gyre (Cochrane and Kelly, 1986) includes a variable, southwestward (downcoast) flow along the Texas coastline in the vicinity of Aransas Pass.

The return flow is a slower, more diffuse, northeastward and eastward motion along the shelf break to the latitude of the Mississippi Delta, and then along the Louisiana coast westward toward Galveston. This pattern is reversed during the months of July and August when prevailing northerly winds give way to weaker southerly winds. The hydrographic data reflect this atmospheric shift in a partially-formed anticyclone flowing northward (upcoast) along the Texas coast from approximately Pass Cavallo to Sabine Pass and then easterly to Louisiana.

Recent research (Barron and Vastano, 1994; Shaar, 1994) has demonstrated that rapid changes in local winds in short intervals of time can disrupt established Texas shelf circulation, reducing a highly-organized flow regime into one of chaos in two days. For example, one of the prevalent features on the shelf is a fast, nearshore jet stream known as the Texas Current (Vastano, et al., 1995). This current is characterized by its episodic nature and flow either downcoast or upcoast. The current typically flows in a southwest direction at an average speed of 31 cm s^{-1}; however, "variations in [wind] forcing can produce responses which range from rapid southwestward jets in excess of 100 cm $s^{-1}$to widespread northeastward flow" (Vastano, et al., 1995).

Though wind is the primary forcing function on the shallow shelf, the coastal flow regimes are also affected by three other elements: ocean features and flow along the shelf break, estuarine plumes and river outflow. "Estuaries and rivers can discharge significant quantities of brackish water onto the surface of the Gulf,...[and] often form plumes which interact with the Texas Current, deflecting the current offshore and forming submesoscale eddies which can interfere with Current flow“ (Figure 3) (Vastano, et al., 1995).

The Texas Current exhibits strong spatial and temporal variability. Figure 4 presents high resolution image and drifter observations of the velocity gradient across the Current coincident with evidence for its alongshore continuity. Although only 40 km separate the two vectors there is a substantial difference in velocity and direction. The vector representing the nearshore, downcoast jet is moving at a 24 hr average velocity of 62

Figure 3 Satellite infrared image of wind-driven plumes issuing from Texas-Louisiana estuaries

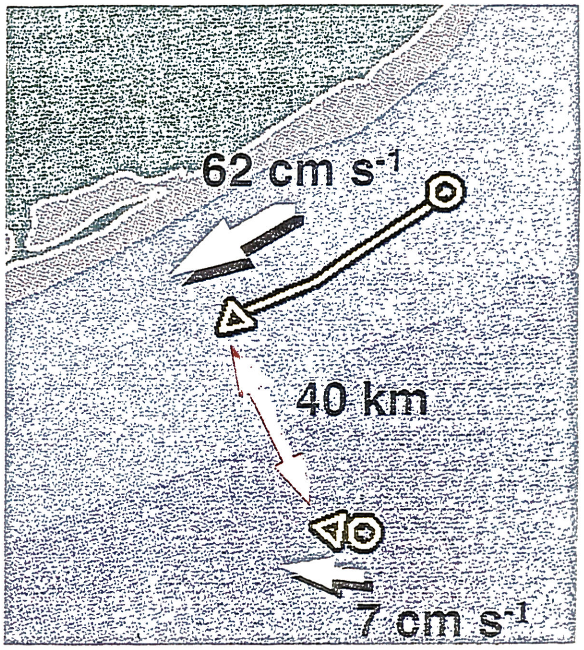

Figure 4 1989 drifter trajectories and satellite flow vectors for a 24 hour interval 5-6 April. Velocities are 24 hour averages and indicate the extreme spatial variability in surface flow.

cm s^{-1} whereas the offshore vector indicates a much slower eddy motion at a speed of 7 cm s^{-1}. This is significant for recruitment because of the implication that initial locations of larvae prior to an event may heavily weight their eventual destination.

The temporal variability represented by Figure 5 demonstrates the tremendous influence a submesoscale event, such as a change in wind direction, has on the shelf circulation. In approximately three days, the highly organized, southwesterly flow regime (1200 October 3 to 0000 October 4) deteriorates, first, into 2 countercurrents -- the original southwestward current and a new northeastward current (1200 October 4 to 0000 October 5) and finally, into a flow regime where turbulence reigns in the form of five eddies (1200 October 5 to 0000 October 6). The speed at which a "normal" flow regime can become a chaotic bundle of eddies is highly important if this event occurs during the 4-5 day critical stage in which the postlarvae must enter the bays and estuaries.

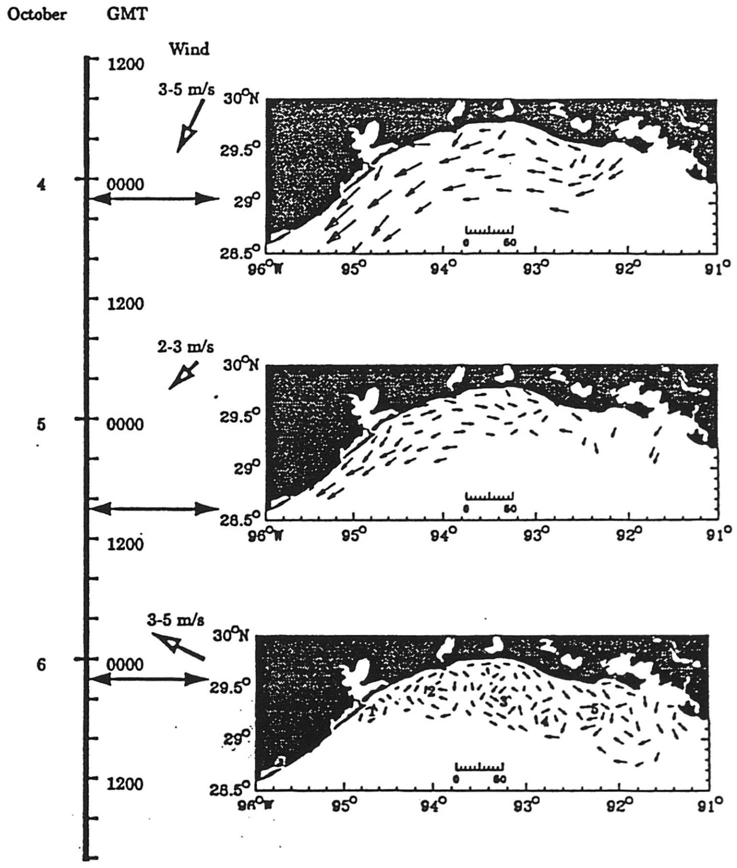

Figure 5 Surface flow estimates from 24 hour AVHRR infrared image pairs during the interval between 1200 GMT on 3 October 1992 and 0000 GMT on 7 October 1993 (Vastano et al., 1995).

OBJECTIVES

Year-to-year brown shrimp postlarval recruitment is usually assessed by sampling for numbers of individuals/12 hr at monitored entrances and estuaries. Springtime recruitment at Galveston Entrance has shown an as yet, unexplained interannual variability. However, these numbers do not necessarily have to be constant for the fishery to have a stable population. A penaeid population in equilibrium could be maintained because the processes which compose and affect the life cycle are relatively constant and their joint effects generate multiple pathways to success. The recruitment variations can be caused by either biological or environmental processes or some combination that can best be thought of as a functioning biophysical process. There are physical features and processes that can arise and intervene in recruitment. Given this, their spatial and temporal scope is pertinent to understanding the biophysical process. The research approach herein is to examine slight variations in the character of seaward atmospheric frontal passages for corresponding changes in alongshore transport of larvae. Hence the objective is an initial examination of nearshore responses to this commonplace springtime event as a possible environmental influence on recruitment and a factor in its variability.

METHODS

Physical characteristics and geographic locations of episodic, nearshore circulation features determine their potential to play dominant roles in the *Penaeus a.* life cycle. Circumstances can arise in which an estuary's recruitment can be determined by the influence of local or event distant, relatively short-lived phenomena (Vastano, et al., 1994). Examination of two local effects will be carried out for Galveston Bay:

1. an analysis of satellite and *in situ* observations made during the 30-31 March 1987 plume formation,
2. utilization of a computer model to simulate the results of a wind-driven dynamic process, and

3. combination of the results from the case study and the computer simulation in a realistic recruitment scenario.

Recently, two important methods for understanding the sensitivity of surface waters to changes in forcing functions have been developed. First, a method for extracting surface motion (Vastano and Reid, 1985) from satellite infrared images of sea surface temperature patterns has been generalized to produce accurate high resolution flow patterns for surface waters (Barron, 1994). Second, an associated computer model was created by Barron (1994), calibrated, and verified for accurate short-term studies of wind-forcing of the Texas-Louisiana Shelf. This model will be utilized for determining the sensitivity of circulation to variations in the wind-forcing function. An interpretation of the model's results will be made with regard to possible influences on postlarval distributions. Following the experimental conclusions, a speculation will be advanced as to the possible implications for future fishery research.

Case Study 30-31 March 1987 - Seaward Plume at Galveston

This study was a synthesis of coincident *in situ* [*] and remotely-sensed observations at Galveston Entrance (Figure 6) during the 1987 spring recruitment of brown shrimp. At the end of March 1987 a sequence of infrared satellite images were taken of the Gulf of Mexico, that clearly indicated the surface expressions of plumes extending over the shelf from Galveston Entrance, Sabine and Calcasieu Passes.

Figure 7 is a summary of the wind direction, sea surface temperature and water level of Galveston Bay with the superimposed semidiurnal tides . This figure represents the frontal passage that swept across Galveston Bay during March 29 through April 3. Paired with Figure 8, the brown shrimp recruitment at Bolivar Roads during this time frame, a correlation is evident between the events in Figure 7 and the recruitment. The interval just before recruitment (March 25-March 27) shows very few shrimp, as it is for

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[*] The *in situ* observations for this case study were taken, gathered and provided by Dr. Geoffrey Matthews of the National Marine Fisheries Service, Galveston Laboratories.

March 30 and 31. However, March 30 and 31 were the appropriate spring tide days and should have seen a dramatic increase in recruitment levels such as those seen on April 1 and 2. Recruitment did not begin on March 31 because the water level was still in a downward trend and the wind had just ceased blowing (Figure 7).

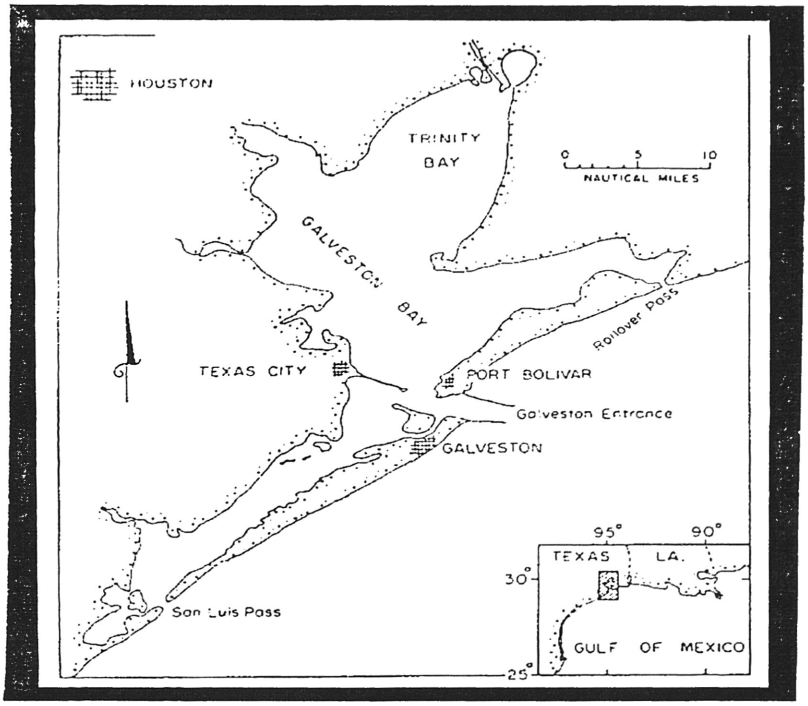


Figure 6 Chart of Galveston Bay and vicinity with place names.

During the image interval, a cold front with very strong winds from the north blew over the Texas-Louisiana shelf. This forcing caused the bay levels to lower and wind-generated seaward plumes formed at the bay entrances. These nearshore plumes and the associated surface flow pattern (Figure 9) stayed the primary migration of postlarvae into the estuary during a four-day interval. As a result, the postlarvae, aggregated at the surface off Bolivar Peninsula, were susceptible to advective transport from Galveston. Among the possible pathways was a pre-existing alongshore, northeastward component off Bolivar Peninsula which could have advected the larvae toward Sabine Pass. At the seaward periphery of the plume, offshore and cross-shelf flow was present, also, with the potential to advect the larvae away from the estuaries and most likely to their demise.

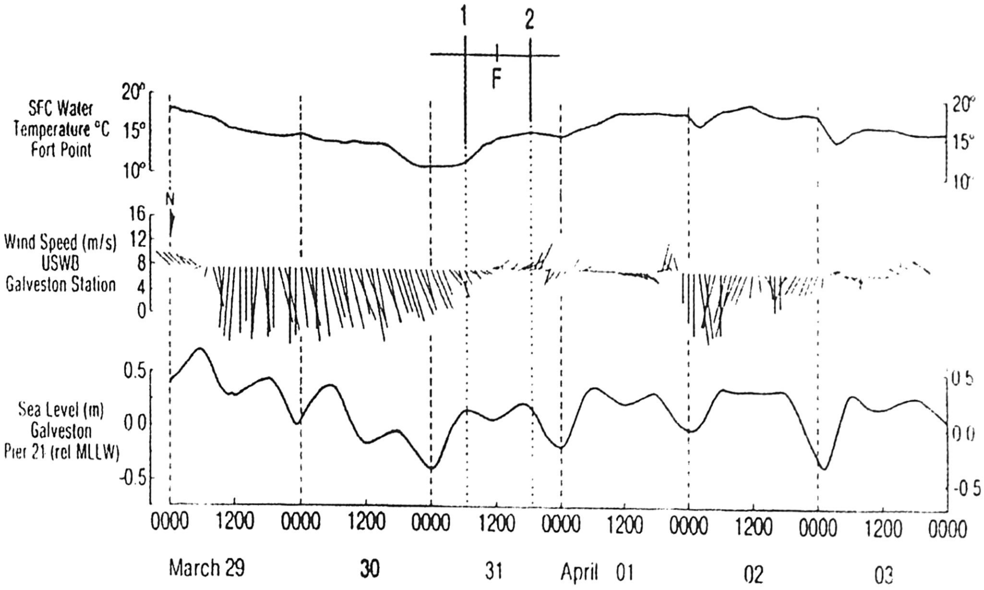


Figure 7 Surface temperature, wind velocity, and sea level observations for Galveston Bay, 29 March - 03 April 1987

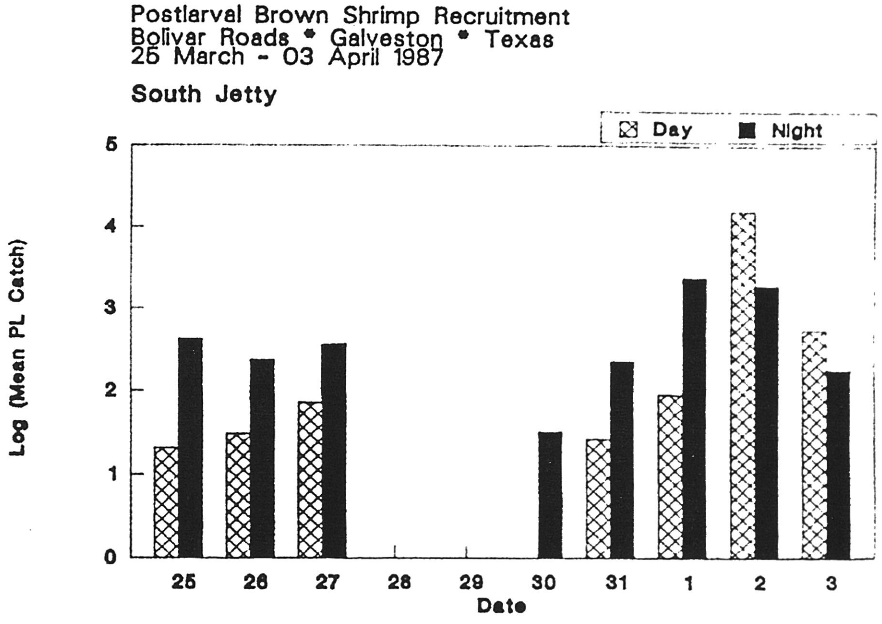
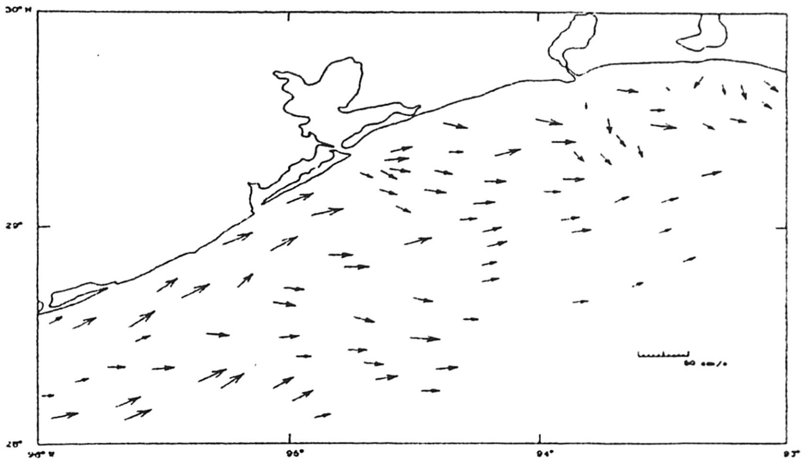


Figure 8 Postlarval Brown Shrimp recruitment as mean PL count per 12 hours versus 25 March - 03 April 1987



31 March

Figure 9 Satellite flow vector distribution

The Physical Model

The computational model employed to simulate wind-driven circulation off Galveston required a suite of simplifying assumptions applied to physical equations for continuum fluid motion. The final, fundamental relationships are differential expressions that embody the physical principles of conservation of mass, energy, and momentum in a rotating, earth-fixed reference system. Prediction of the fluid's dynamic evolution requires casting these relations in a suitable finite difference form before their necessary integration with respect to time.

Barron's model (1994) of circulation off Galveston has a time dependent, depth dependent, baro-tropic, quasi-geostrophic form, expressed in terms of vorticity on a two-dimensional, orthogonal, boundary-fitted coordinate system. In order to better understand how the model functions a brief explanation of the above descriptions will be given.

time dependent

The sum of forces acting on any water parcel is non-zero in this wind-driven study. This means that the water's momentum, and therefore, its velocity, will change due to some acceleration. Even if the winds stop blowing, friction between the water and the bottom will decelerate every parcel, and the dynamic system will slow down.

depth dependent

The model allows for the depth of water to change over the continental shelf. This accounts for changes in momentum due to bottom topography variations. For instance, in the vicinity of Sabine and Heald Banks off Galveston, the depth changes quickly and the shallow depths have a tendency to steer the flow. Drifter experiments in 1989 demonstrated that the waters tend to move -- essentially steered -- through the gap between these Banks. In addition, energy transfer from the atmosphere to the water is much more effective in shallow water per unit of time, so a parcel can have its momentum or velocity changed quickly relative to one that is in a deeper depth.

two-dimensional

This means that the model will only consider momentum changes in horizontal directions. If the model accounted for the effect of winds in shallow water in relation to upwelling or downwelling, then this type of motion would have to enter in the computer solution. This adds another whole dimension to the computations, the vertical dimension. Barron disregards vertical motion in the model and does it on the basis of the amount of time it takes to change momentum in the vertical direction against the force of gravity. It is not quite right to do this, especially in shallow water, and so this places a limit on the interpretation of the model results.

barotropic

The barotropic assumption entails consideration of vertical differences in horizontal motions, that is, should the model consider that water in a parcel travels in different directions at different speeds with depth? If this is to be considered, then the computational effort would again be further complicated. Since short intervals of time (several days) are of interest, then the two-dimensionality of the calculations, the physics of distributing momentum in the vertical direction, becomes an important consideration. The model assumes that motion in the vertical direction can be broken into several parts, a linear decomposition of the problem. The first part is movement of the parcel such that, from top to bottom, all the mass is going in the same direction at the same speed. Therefore, there is no vertical variation in the horizontal velocity. Then, the second part is a single reversal of the horizontal velocity somewhere in the water column. This linear decomposition, therefore, considers various "modes" in the vertical variation and in the horizontal motion. The mode name for the first part is "barotropic" whereas the second part is called the "first baroclinic mode." Barron discounted all baroclinic modes of motion.

quasi-geostrophic

Geostrophy (earth-turning) is the fundamental balance struck in the ocean that accounts for placing the model in the earth's rotating frame of reference. Balanced against the pressure gradient established by water above or below mean sea level, geostrophic currents have no start or end, that is, there is no time-dependency in this approximation to ocean movement. The model is referenced to such a rotating coordinate system, including the Coriolis term in the dynamic equations. This relates a portion of the motion to geostrophy. However, the model accounts for other unbalanced forces, and so, the currents are changing. The term, quasi-geostrophic, indicates that the rotation of the earth and the pressure gradient are only part of the dynamics.

vorticity

Barron decided to calculate the spin of the water parcel rather than its straightline velocity components. This type of model is common because it lends itself to certain efficient computer algorithms needed to speedily and accurately solve the equations. A mathematical transformation converts the physics into statements about the parcels' rotational or angular momentum rather than its straightline momentum.

orthogonal

In simple terms, orthogonality means that the coordinates people use and the associated numerical grid, form a system in which the cardinal directions are always at ninety degrees to one another. This system simplifies the fundamental resolution of the dynamic equations. Unit steps in either direction form an area that is one square unit when the system is the familiar rectangular coordinate (x,y) system. When a warped orthogonal system is used, the area contained within a unit step in both directions varies from place to place in the coordinate system. The calculations account for this variation in grid area from time step to time step.

boundary-fitted

The manipulation of orthogonal coordinate lines to fit one or more special lines of another coordinate system is called coordinate transformation, and it literally warps lines in one system into the lines of another by a mathematical prescription. Finding the prescription is equivalent to finding how the area of a unit step in each coordinate direction changes. We do this for our circulation model for (at least) two reasons. First, the approximation of a curvy coastline with, say, a familiar (x,y) coordinate system creates little $\Delta x,\Delta y$ steps and sequences of these steps have to approximate the curve of the coastline. So in order to specify the coastline in rectangular coordinates one must have the model's computer algorithm remember the coordinates of every incremental step. If, however, the transformation is known that warps one line of either x or y into the shape of the coastline, then this boundary is specified by one number, of the new coordinates (a,b), like $b = 1$. It is easier for the computer to count coordinates along the boundary, in this manner. Our second reason has a basis in the physics of the problem. If we are working on a physical scale that allows us to assert that the curving boundary of, say, Padre Island is smooth [which we are], then approximating the shoreline with $\Delta x,\Delta y$ steps actually creates small embayments that will perturb the flow regime at just the size perturbation that we want to avoid. The same problem would occur on the outer boundary of our coordinate system at the edge of the continental shelf, so our transformation warped a rectangular coordinate system to a curvy one while fitting the Texas-Louisiana coast and the sweep of the shelf edge at the same time (Figure 10).

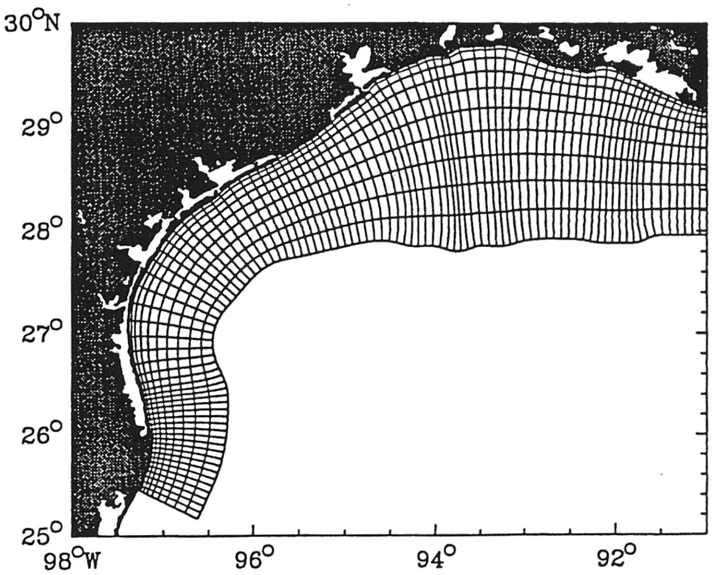


Figure 10 An orthogonal boundary-fitted coordinate system for a portion of the northwestern Gulf of Mexico (Vastano et al., 1995).

synoptic

Synoptic refers to understanding the distribution of some model variable at a given moment. It is a term that means instantaneous in the sense of "the synoptic surface wind velocity pattern over the shelf waters at some given date and time" even though the pattern is produced by an average over some time interval.

damped

Energy is removed from the shelf circulation system by two mechanisms - the friction between the wind blowing over the water and the water and the friction between the water and the ocean floor. Therefore, the model utilizes a frictional term that does not act unless the water moves. It accounts for the removal of energy or momentum from a water parcel.

Non-linear models, among other things, are ones whose results are very sensitive to the specification of how a system starts, that is, its initial state or the initial conditions that are provided to the model. In these circumstances, predictions that begin with even slight inaccuracies relative to specifying *what is out there in the water* can evolve into a useless solution. By carefully crafting the mathematical expressions of a complicated system's physical dynamics, one can generate models capable of reasonable results for a selected spatial and temporal ranges. However, coastal ocean dynamics are sufficiently complex that the models are clearly susceptible to chaotic effects. When predictions for the Galveston environs are necessary for a span of several days, the overriding consideration is the á priori production of sufficiently accurate initial conditions so the inevitable departure from reality does not obscure the required flow information as the computed solution evolves.

The model is externally forced by the action of synoptic surface wind distributions, slowed by friction against the shelf bottom, and initialized with synoptic satellite-derived flow conditions. It attempts to predict high-resolution surface flow evolution over short time intervals while accounting for oceanic turbulence that can dominate nearshore patterns of motion in the coastal region of the Texas continental shelf. Results have demonstrated the model's capacity to quickly forecast surface flow in a computer workstation environment with an accuracy that will, for the first time, support real-time direction of oil spill remediation efforts as well as the studies of advective transport effects on biological distributions (e.g., shrimp). Hence, the Barron model will be accepted as an adequate simulation of the environment, and will therefore be used in the first examination of the sensitivity of circulation to variations in a frontal passage off Galveston.

MODEL SENSITIVITY TO WIND FORCING

The computer model of the northwestern portion of the shelf successfully simulates response to the strong seaward passages of atmospheric fronts at spatial and temporal scales over tens of kilometers and several days. Observations have identified seaward plumes as physical features with these characteristic scales and established that they are important causal elements in a biophysical process describing brown shrimp recruitment. It is also apparent that springtime recruitment at any given location may be dependent on episodic coastal current events that have the capacity to distribute larvae along the coastline just as they gather to enter the estuaries. The extent to which transient coastal currents can vary in flow strength and direction under the influence of surface winds is then fundamental to this capacity for redistribution.

The Barron model utilized observed drifter trajectories from two field experiments in early Fall 1992 and mid-winter 1993. The Fall simulation was used to adjust the parameters that represent damping to get a best fit to drifter trajectories. The second field experiment was to testify the model accuracy against independent trajectory observations. The model accuracy in predicting velocities was established as ± 4-9 cm/sec over 5 days, an accuracy that is very good for a model that includes small scale turbulence.

Barron's calibrated and verified model for short-term prediction has a capability to examine variations in flow response as a function of variations in wind forcing. There is an undetermined number of wind variations that should be considered in the delineation of the effect on the recruitment. Tests of changes in wind speed and direction about a known frontal passage and its associated circulation response can provide some indication of the degree of influence. An initial estimate of circulation variability is assessed herein by the simple approach of varying the direction of frontal passage over the shelf off Galveston.

The initial condition and wind system obtained for the late January 1993 model verification were used as a basis for this test. Model results in the form of simulated water parcel trajectories were compared to the trajection of actual drifting buoys (drifters) released on the shelf in late January.

The alteration in wind forcing is achieved by a general rotation of all wind vectors for the interval of the integration. This effectively introduces a wholesale shift in the time-dependent wind patterns relative to the sea while the initial flow conditions (Figure 11) are left changed. The first computer runs were made over four and a half days to generate trajectories that begin with the location of an actual drifter and show the variation in simulated trajectory end points that accompany the verification run and the 10° rotations to the west and east. The black line in Figure 12 shows the simulation of a drifter trajectory that began at the heavy open circle on the southeastern side of Sabine Bank. Filled dots marked 0,1,2,3,**S** indicate the parcel position at 0000 hours on 25-29 January. A 10° shift in the wind pattern to the west (**W**) resulted in a slight displacement shoreward and generated a trajectory approximately 12 km longer than the simulated drifter track. The converse 10° shift to the east (**E**) shows a foreshortening of a trajectory by 13 km relative to the simulated drifter and a slight shift of the trajectory seaward. These two tests suggest that even more pronounced changes in response could occur in nearshore shallower waters. This sensitivity study occurred in a nearshore area, immediately seaward of waters that are pertinent for recruitment. The next section will concern a speculative scenario that represents an extension of the above sensitivity study.

MODEL EXTRAPOLATION

The computer model has been used to simulate three possible circulation responses to variations in wind forcing. First, prediction of the circulation using strong winds from the north. Second, winds that have been shifted 10° to the west, and third, winds shifted 10° to the east.

Winds generally become more effective agents for change in shallower water. The following tests examine the range of nearshore surface flow transients that occur with the 10° wind direction shifts. The coastal domain selected for study extends from Calcasieu Pass to Galveston Entrance and the water parcel seeding was chosen to examine flow variations in a bight defined by the coastline and the offshore banks. Sabine and Heald Banks halve the depth of water to seaward and are separated from the coast by a trough that marks the depth transition from coastal shallow to deeper water in the bight and then to shallow waters over the Banks. These topographic features are capable of steering flow in the region (Barron and Vastano, 1994; Vastano et al, 1995). Three cases were run for four and a half days with the seven seed locations shown in Figure 13. From east toward the

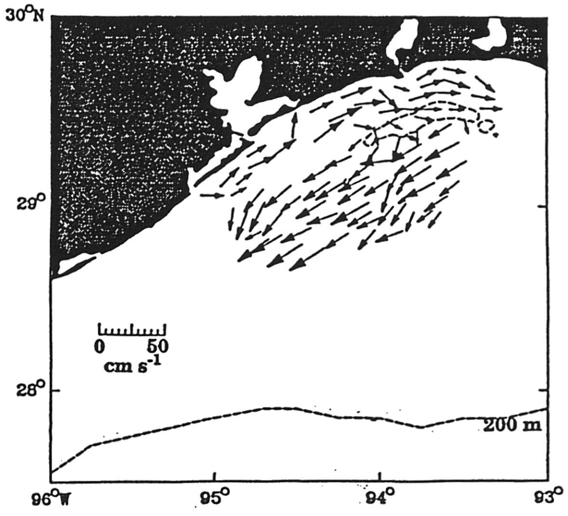


Figure 11 Sea surface velocity distribution extracted from sequential AVHRR images, 26-27 January 1994 (Barron, 1995).

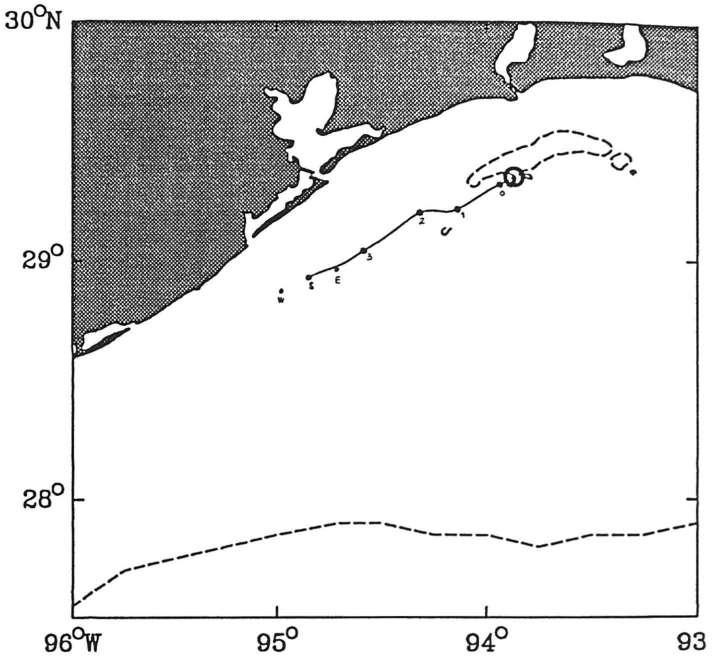


Figure 12 Comparison of drifter trajectory model simulations during 26-30 January 1993 for the actual wind field (S), 10° west rotation (W), and 10° east rotation (E).

southwest, these are referred to as Calcasieu Pass, Eli Ridge, Sabine Pass, Star Lake, North and South High Island and Galveston Entrance; CP, ER, SP, LS, NH, HS, and GE.

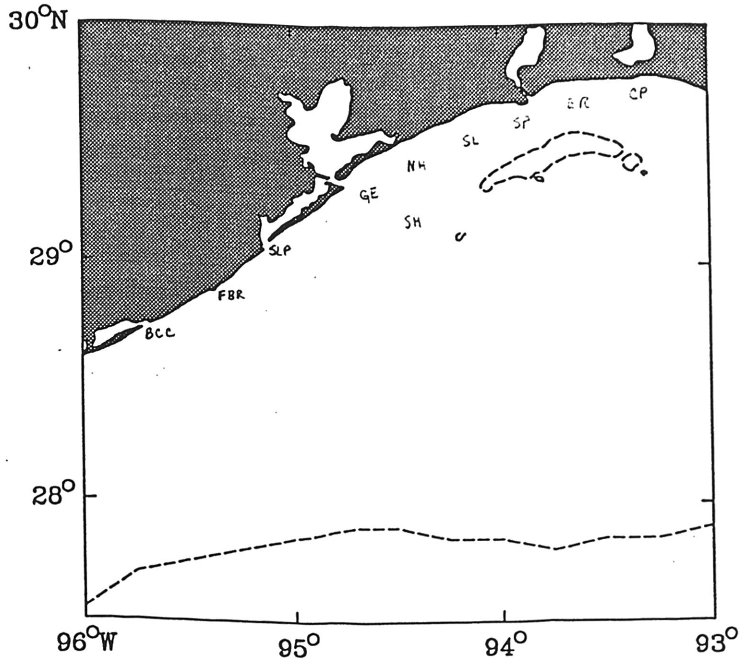


Figure 13 Chart of the Northwestern Gulf of Mexico with abbreviations for simulated drifters and place names.

The first computer run (Figure 14) was taken without changing the wind forcing, that is, the same relationship between the evolving winds and flow as in the January 1993 verification of the model. The nearshore regime indicates high speed flow along the coastline south of GE. The five parcels southwest of Sabine Pass participated in this longshore flow. Each of the four inshore parcel's initial northeastward movement (Figure 11) was overcome as the front passed over the shelf and they began to move southwestward. The parcels in the vicinity of Sabine Pass and Galveston Entrance each indicate the downcoast advection of postlarvae away from an estuary entrance. However, the parcel (ER) seeded off Eli Ridge moved into deeper waters of the bight and proceeded slowly toward the initial SP location. The model simulation showed the generation of a transient coastal jet, associated nearshore movement that would support an advection hypothesis, and the possibility of postlarvae reaching the vicinity of another downstream entrance.

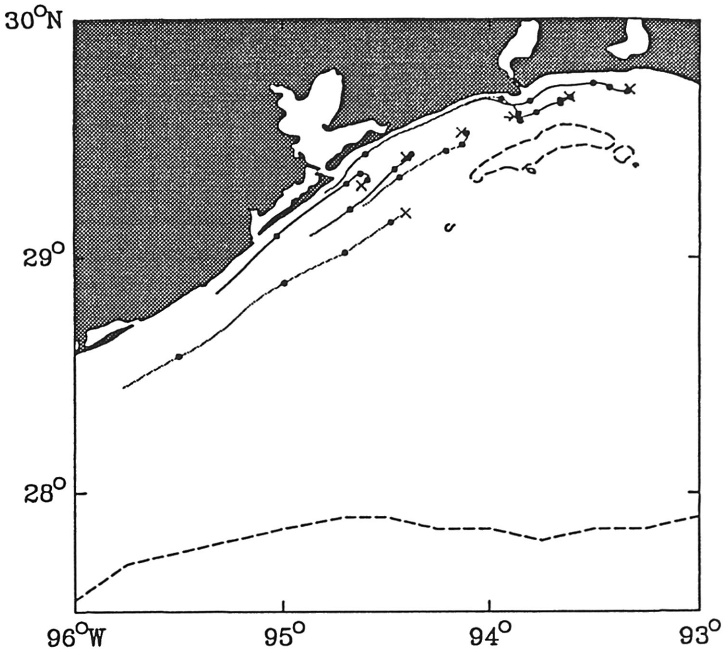


Figure 14 Simulated drifter trajectories for 26-30 January 1993 actual wind field.

When a 10° shift of the winds to the west is invoked, the flow response (Figure 15) produces nearshore trajectories that are extended further to the southwest at higher speeds and the development of a broader version of the coastal current off Freeport. The Sabine Pass parcel moved past Galveston Entrance and almost reached San Luis Pass (SLP) at the southern end of Galveston Island. The trajectory of the Galveston Entrance parcel tracked past Freeport and the mouth of the Brazos River (FBR) to the vicinity of Caney Creek

(CC). One difference in the standard and 10° west trajectories is the increased probability of larvae making entrances further to the southwest.

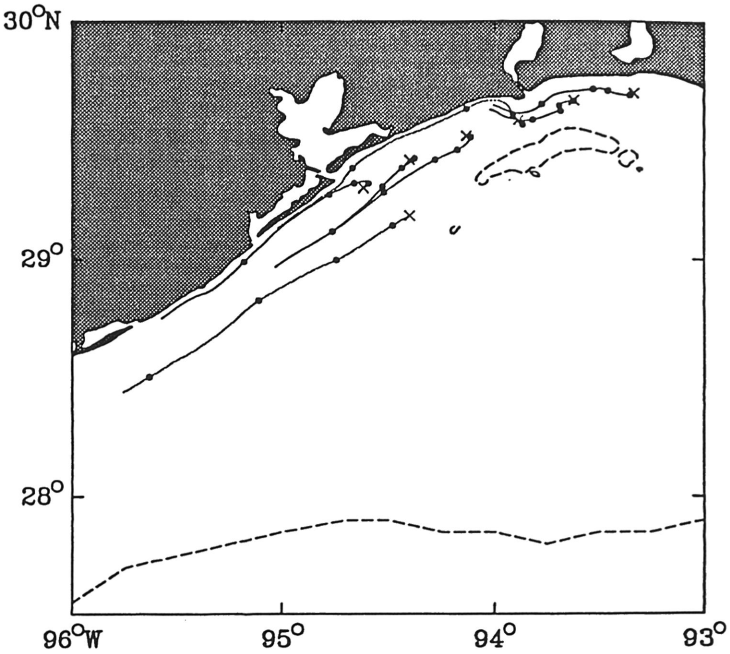


Figure 15 Simulated drifter trajectories for 26-30 January 1993 with the actual wind field rotated ten degrees to the west.

The 10° east trajectories in Figure 16 reveal much different circumstances. While there is a possibility of larvae represented by the Calcasieu Pass (CP) parcel moving to Sabine Pass as in the standard and the 10° west trajectories, the remainder of the trajectory pattern indicates motion to the southwest along tracks that remain much further offshore. This outcome suggests that the possibility of reaching some entrance to the southwest has been somewhat reduced. However, the southwestward motion in the transient coastal current is not as great and this would tend to reduce the advective transport away form Galveston Entrance and Galveston Bay.

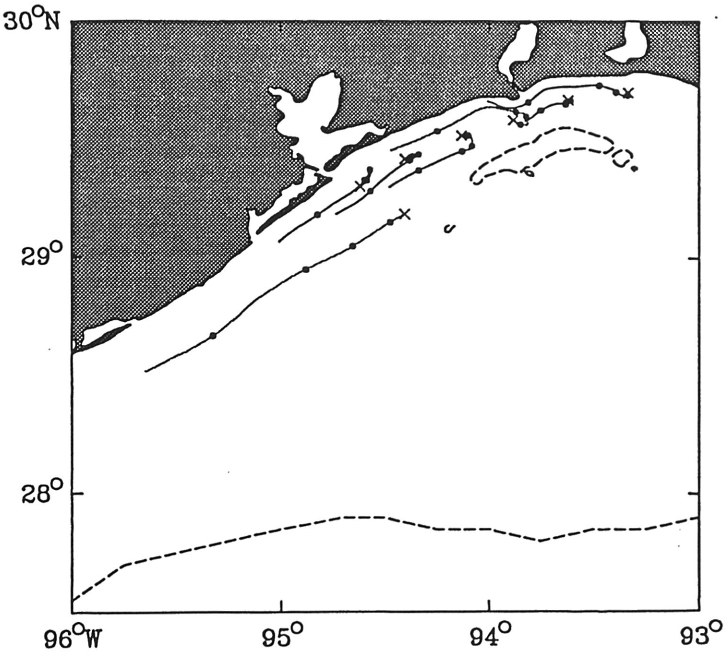


Figure 16 Simulated drifter trajectories for 26-30 January 1993 with the actual wind field rotated ten degrees to the east.

Figures 17 and 18 are enlargements that present the trajectories for the actual (black), 10° west rotation (blue), and 10° east rotation (red), winds that are traced from two locations, SP and ER. These locations are only 30 km apart, but the region clearly marks a transition is dynamic response to the wind systems for the same initial conditions (see Figure 11). In fact, all the water parcels started southeast of Sabine Pass form a similar family of rapid and near uniform trajectories while those responses to the northeast, ER and CP, move southwestward around the Pass at slower speeds and overall, cover far less ground. The remaining distinction is the fact that west rotation of the winds brought all parcel trajectories further inshore than those of the actual wind system, and conversely, east rotation moved trajectories offshore with clear implications for postlarval access to the coast and estuary entrances.

The computer experiments discussed herein have established that the motion of nearshore waters off Sabine Pass and Galveston Entrance is sensitive to the nature of wind forcing. The field case study showed similar sensitivity for Galveston Bay, Lake Sabine, and Lake Calcasieu wind response. Rogers, et al. (1990) indicated that the return of

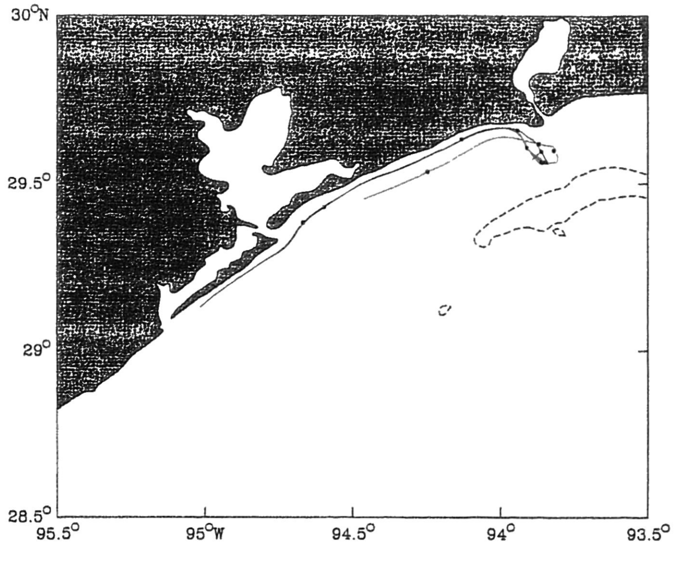


Figure 17 SP trajectory summary for wind direction variations: actual winds (black), 10° west rotation (blue), 10° east rotation (red)

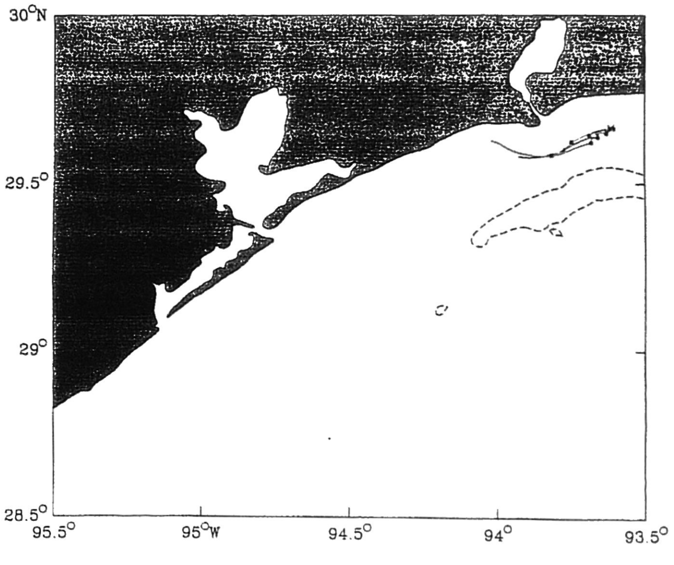


Figure 18 ER trajectory summary for wind direction variations: actual winds (black), 10° west rotation (blue), 10° east rotation (red)

northeastward flow adjacent to the entrance would herald influx of postlarvae into an estuary. This flow condition exists for the vector pattern for April 3, 1987 shown in Figure 19. The additional and very important feature is the development of a nearshore clockwise eddy from the Galveston plume. A speculative scenario for sequential frontal passages follows.

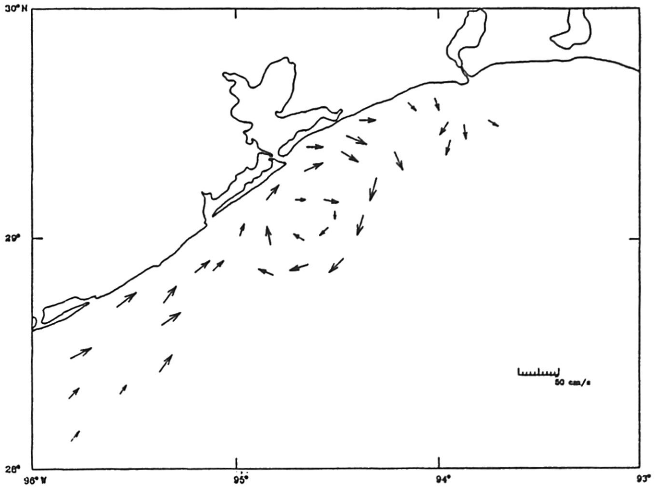


Figure 19 Satellite flow vector distribution for 04 April 1987

The generation of an eddy off Galveston Entrance carries with it the possibility of entraining and holding postlarvae relatively close to the Bay. Such an occurrence has been documented for wind-generated eddies and pollock larvae off Wide Bay at Shelikof Strait, Alaska (Vastano, et al., 1990). Once established, the eddy becomes an additional factor bearing on alternatives associated with the recruitment biophysical process. A second episode initiated at this stage can take a number of paths. For instance, advective transport forced by another frontal passage such as that accompanying the 10° west wind rotation (blue trajectories, Figure 17) suggests the eddy and larvae might be advected as a whole by a Texas Current or serve as a source of postlarvae by turbulent transfer from a position adjacent to the Current southwestward along the coast. In this case, the first wind system would set up the concentration and the second would produce its transport. It is important to recognize and emphasize that timing and location are critical in this scenario. The significance to a biophysical process is the importance in phasing between biological behavior, environmental forcing, and surface water response.

CONCLUSIONS

The model computations varied the direction of frontal passage to the west and east from an actual northward approach over the coastal region from Lake Calcasieu, Louisiana to Freeport, Texas. Over four and a half days, in waters greater than 25 m depth, and relative to Argos drifter trajectories, ten degree variations in wind direction forced incremental alongshore trajectory end point differences of approximately ± 12.5 kms (+, westward wind shift; -, eastward) relative to observed motion. Conversely, in nearshore waters less than 15 m deep, substantial variations developed in response and alongshore displacements. The recruitment scenario based on field observation and computer results suggest that sequential seaward frontal passages could increase the potential for larval advective transport.

Overall, the research shows that small changes in the direction of the frontal passage can significantly alter the number of postlarvae available to be recruited at any given entrance. This study's results indicate that the sensitivity of the shelf's waters is a major factor in determining alternatives within the biophysical process that represents brown shrimp recruitment.

RECOMMENDATIONS

Future research should continue examining perturbations in the wind forcing function. Some examples include modifying wind speed, or combining variations in wind speed with those of wind direction. Advances should also continue in the realm of Texas Shelf circulation modeling. Refining the present models could produce a more accurate estimation of shelf circulation, and therefore one element of recruitment variability. In turn, these improved estimates will support more refined fishery management decisions and cultivate an active involvement in the preservation of a viable brown shrimp population.

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