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VARIABILITY IN ESTIMATING ABUNDANCE OF POSTLARVAL BROWN SHRIMP, *FARFANTEPENAEUS AZTECUS* (IVES), MIGRATING INTO GALVESTON BAY, TEXAS.

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ABSTRACT: Three sets of monitoring data were used to examine the variability associated with abundance estimation of postlarval brown shrimp, *Farfantepenaeus aztecus* (Ives) in Bolivar Roads, Texas—the main connection between the Gulf of Mexico and Galveston Bay. Abundance of postlarvae (PL) caught with Renfro beam trawl varied greatly in different years on the same dates. A "spring peak" of brown shrimp PL migrating into Galveston Bay was found for 2 April with a quadratic regression fit to 6-day moving averages of daily mean abundance from 22 yrs of monitoring data: $\ln(PL+1) = 0.8736 + 0.09037Day - 0.0004934Day^2$ (adj-R^2 = 0.83, n = 159), where Day is Julian day. Abundance varied by four orders of magnitude (0 to 24,616 PL/tow) in just 4 d during a four-week intensive monitoring of PL during the 1987 spring peak. Abundance also varied by three orders of magnitude between the North and South Jetty sites during the same collection time. During a third study, PL abundance varied by two orders of magnitude along 360 m of the beach in < 4 hr. These investigations demonstrate that detecting significant differences in PL shrimp abundance in a pass requires substantial sampling that may not be logistically possible. However, best estimates could be obtained by including as many dates as possible, followed by including more sites, and finally by collecting during both day and night. Conclusions drawn from abundance studies of PL shrimp, fish, and crab immigrants through estuarine passes that are based on only a few samples should be reviewed.

INTRODUCTION

The brown shrimp, *Farfantepenaeus aztecus* (Ives), is a key commercial species in the shrimp fishery of the northwestern Gulf of Mexico (GOM). Most adults inhabit water depths of 20-65 m (Darnell et al. 1983, Neal et al. 1983) and spawning and larval development occur in these waters. Postlarvae (PL) migrate into the bay where they grow for about three months in salt marshes (Zimmerman and Minello 1984). Then, as advanced juveniles or sub-adults, they migrate back through the bays to the GOM, during which time they recruit to the bait and bay shrimp fisheries. All shrimp fisheries are valuable, are managed based on age-0 individuals (J. Nance and F. Patella, pers. comm., NMFS, Galveston, TX), and are characterized by large variability in annual catches (Klima et al. 1986). It is beneficial to commercial shrimp fishers and resource managers to have a forecast of the upcoming harvest, and the abundance of immigrating PL is a potential indicator of shrimp harvest (Baxter 1963, Berry and Baxter 1969, Baxter and Sullivan 1986).

Various attempts to establish an early forecast using PL abundance have been unsuccessful (Williams and Deubler 1968, Berry and Baxter 1969, Sutter and Christmas 1982, DeLancey et al. 1994). These forecasting models have relied upon three important assumptions: (1) mortality rates for young brown shrimp in the estuary are either constant or vary in a regular manner seasonally from year to year; (2) the majority of recruitment of PL shrimp to estuarine nurseries occurs during the same months each year; and (3) accurate estimates of PL immigration to bays and estuaries have been obtained. Mortality rates of juvenile shrimp can be highly variable on a weekly or annual basis, but few measurements of this mortality are available (Minello et al. 1989). Accurate estimates of the influx of PL might not be possible; even the precision of such estimates has been studied only to a limited degree (Berry and Baxter 1969, Caillouet et al. 1968, 1970, Lochmann 1990). Only about 60% of the age-0 shrimp recruit to the fishery during the early summer, the rest recruit mostly during the next four months. The PL for the summer recruitment enter the estuaries in late winter and early spring, and Berry and Baxter (1969) hypothesized that the magnitude of the spring peak immigration might control fishery recruitment for that year. However, during winter and spring Arctic frontal passages, when the water is chilled and blown out of the estuaries by north winds (i.e. during a "blue norther"), the immigration of PL is delayed (Wenner et al. 1998, Blanton et al. 1999, Benfield and Downer 2001). These events weaken temporally-dependent models, increase the variability in the rate of PL immigration, and increase the variability in estimated density obtained by sampling.

Brown shrimp larvae grow and develop as plankton in shelf waters of the GOM, and many factors lead to a patchy distribution as the PL migrate towards shore and immigrate through passes into bays. As meroplankton, their distribution is governed by seasonal circulation patterns, shelf gyres, wind-driven coastal and tidal currents (Temple and Fischer 1965, 1967, Temple and Martin 1979), and by wind and temperature controlled upwelling and downwelling (Wenner et

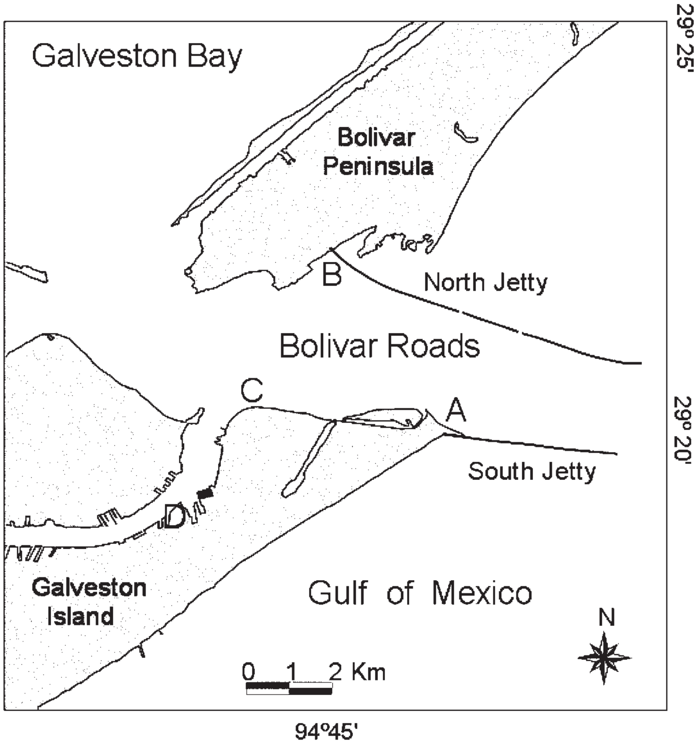

Figure 1.
Postlarval shrimp sampling sites along Bolivar Roads, the main pass connecting Galveston Bay, Texas, with the Gulf of Mexico. Sites: A= South Jetty site, B= North Jetty site, C= Fort Point (USACE water temperature gage), D= Pier 21 (NOS tide gage).

al. 1998, Queiroga et al. 2006). The PL stage is the last of 12 planktonic stages (Cook 1966) that develop in the GOM on a schedule dictated by food availability and environmental conditions, and larvae and PL are transported across the shelf towards shore by coastal currents (Rogers et al. 1993, Rothlisberg et al. 1983, 1995, Criales et al. 2006), and through passes to estuarine nurseries by tidal currents (Lochmann 1990, Herke et al. 1996, Houser and Allen 1996, Criales et al. 2000). Both types of currents can be altered seasonally by winds, particularly in the spring by Arctic frontal passages along the Gulf coast (Smith 1975, 1978). The immigration of PL would be expected to change as these currents change.

The main objective of this paper is to elucidate the potential for drawing erroneous conclusions about the abundance of immigrating PL brown shrimp by looking at time and space differences in PL abundance. Three sets of collections of immigrating PL were examined for variability in a "spring peak" and in short temporal and spatial variability in abundance estimates. Though the accuracy of an abundance estimate cannot be measured because the true number of immigrating PL can never be known, the data presented here demonstrate that monitoring programs also are limited in the precision of their abundance measurements.

MATERIALS AND METHODS

Sampling Procedures

The studies were conducted at Bolivar Roads (29° 20' N, 93° 44' W), a jettied tidal pass forming the main entrance into Galveston Bay, Texas, from the GOM (Figure 1). The South Jetty site (Figure 1, point A) and the North Jetty site (Figure 1, point B) were located along the south and north shorelines of the pass, respectively. These beach sites were sandy and mostly gently sloping (~ 1:25) with some small bottom ripples that changed weekly due to tidal currents and wave action.

All PL collections were made using a modified Renfro beam trawl constructed with a 1.8 m galvanized iron pipe (12.7 mm) that spread a 1.5 m semi-conical trawl of 1 x 2 mm mesh woven nylon netting (Renfro 1963). During a tow, the net was opened by a floating head rope while the foot rope was kept on the bottom by multiple weights and the pipe beam. A standard tow involved walking the net around a 23 m radius semi-circular path from shore to shore along a central pivot point. Maximum water depth sampled was 1.2 m, and towing speed was about 1 m sec^{-1} . The catch was preserved in 5-10% buffered formalin. Each standard tow swept about 102 m^2 of bottom and filtered about 36 m^3 of water based on water depth, mouth opening, and distance towed. Because the vertical distribution of PL was unknown and the volume of water filtered was only approximated, the number of PL per tow (PL/tow) is used to present catch/abundance data.

Spatial and temporal effects on variability in PL abundance were studied during intensive sampling in spring 1987. Postlarvae were collected during daylight (0800-1700) and nighttime (2000-0400), Monday through Friday from 9 March – 3 April 1987 at both South Jetty and North Jetty collection sites. Collections each week were scheduled to include at least two ebb and two flood tides during daylight and darkness based on predicted tide tables (NOS 1986). For each collection three beam trawl tows were made at each site, tow paths being spread along the shoreline with 25 m between ending point of one tow and starting point of the next. During the third week, separate crews sampled both sites simultaneously, and one hour after the first collection, a second collection was made at the South Jetty site to discover if significant differences should be expected over a 1 hr period—the usual travel time between sites.

The effect of tow length (m) was examined at the South Jetty site on 17 September 1987. Ten sets of tows were made between 0840 and 1200 h. For each set, three semicircular concentric tows using radii of 11, 23, and 46 m (37, 75, and 150 ft) were made simultaneously. Only the 46 m radius tows had to be overlapped slightly because the length of shoreline shallows was limited. Because tows reached from the shore into open shallow water, variation in tow length also incorporated differences in abundance due to water depth.

Hydrographic and weather data were recorded during each collection. Hourly wind speed (Kmph) and direction and air temperature (°C) data were obtained from the National Weather Service for spring 1987. Also, hourly water temperature (°C) data were obtained from the U.S. Army

Corps of Engineer's gauge at Fort Point (Figure 1, point C), and tide levels (cm) were obtained from the National Ocean Service gauge at the Galveston Pier 21 that is located beside the Galveston Channel (Figure 1, point D) for spring 1987.

All PL in each catch were picked, identified, and counted for the normal monitoring samples. Catches were sub-sampled (≥ 12.5% of total catch, for a target of 200 PL) when catches were large in the intensive sampling study. White shrimp, *Litopenaeus setiferus* (Linnaeus) PL were separated by key characteristics including presence or absence of dorsal carinal spines (Williams 1959, Cook 1966, Ringo and Zamora 1968) and by size. In the year-round monitoring samples (1960-1975, 1983-1987, 1989), PL were identified as white, pink (*Farfantepenaeus duorarum* (Burkenroad)), or brown shrimp. In the intensive sampling and the three radii studies PL were identified as white or brown shrimp. Any potential pink shrimp PL were pooled with brown shrimp. It is likely that over 95% of the pink and brown (grooved) PL in this research were brown shrimp based on key characteristics, season of occurrence, and the species composition of the shrimp fisheries in Galveston Bay (Baxter et al. 1988). Studies to separate grooved PL and juveniles up to 7 mm carapace length are ongoing because characteristics in published keys appear to be only about 60% accurate for separating pink and brown shrimp specimens collected in the northwestern GOM estuaries (J. Ditty, pers. comm., NMFS, Galveston, TX).

ANALYSIS

Regression and correlation analyses between PL abundance and environmental conditions were estimated using MS Excel 2000, Sokal and Rohlf (1969), and SAS (1987) for personal computers. Postlarval abundance was transformed using Ln(PL+1) to reduce the variance-to-mean correlation (Berry and Baxter 1969, Caillouet et al. 1970); however, an F_{max} test revealed the variances were still heteroscedastic. Thus, Wilcoxon matched-pairs signed-ranks tests (Siegel 1956) and graphical inspections were used to compare PL abundance from tow to tow, hour to hour, day to night, day to day, site to site, and among radii.

The abundance data from earliest monitoring of PL immigration covered 1960-1966 (Baxter and Renfro 1966, Berry and Baxter 1969) and has been combined here with additional data collected during 1967-1975, 1983-1987, and 1989. Early collections usually did not include replicates at a site, so a daily datum for a year was from either a single sample or from the geometric mean of single samples from the South and North Jetty sites. In the 1980's triplicate samples were taken twice per week at the South Jetty site. Daily means for all years combined were calculated using daily data or means for as many years as were sampled for that Julian day. Multiple moving averages (MA) were calculated, including from 2 to 6 d. Each MA included one or more days leading up to and including the day of record; the more days included, the smoother the spring peak. A quadratic regression analysis was used to determine the spring peak in PL abundance because it yields a parabolic shape with a peak and appeared to have the best potential fit to the data when viewed in a scatter plot. Day, the independent variable, was the Julian day of the year and ranged from 1 (1 January) to 161 (10 June).

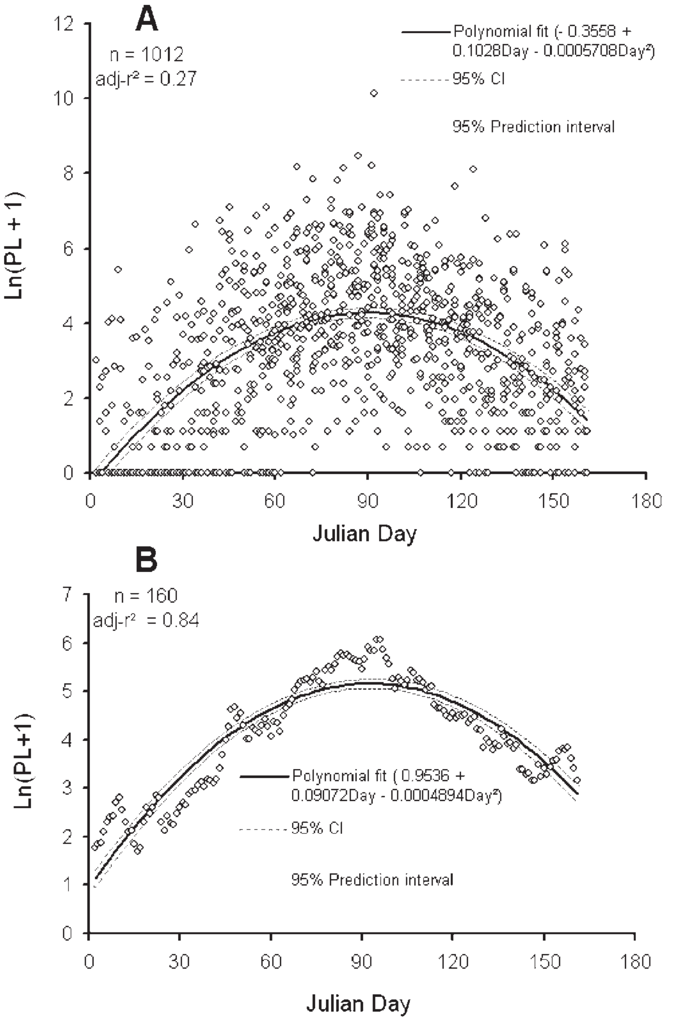

Figure 2.
Postlarval brown shrimp sampled by NMFS monitoring of Bolivar Roads, Texas.

(A) Daily mean catches for each year for January through mid-June of 1960-1975, 1983-1987, and 1989.

(B) The quadratic regression line for 6-day moving average of the daily mean abundance of years combined. 95% confidence limits (dotted lines) and 95% prediction intervals (dashed lines) are indicated in each section. Julian Day 1 – January 1; Julian Day 150 = May 30.

Relationships between PL abundance and water temperature (°C), salinity (‰), and north-south wind vectors (see below) were examined graphically and by correlation analyses. North-south wind vectors were calculated using wind speeds and directions. Northwest, north, and northeast directions produced negative vectors, east and west produced zero vectors, and southeast, south and southwest directions produced positive speed vectors (Kmph) for correlation analyses.

RESULTS

Postlarval Brown Shrimp Spring Peak

An inspection of 22 yr of January through early June abundance data from collections in Bolivar Roads revealed that PL brown shrimp immigrated into Galveston Bay throughout the year. Immigration was found even during the coldest months, but was usually greatest during March and April (Figure 2). High abundances (> 1000 PL/tow) were found February through May depending on the year (Figure 2A). Using Ln(PL+1)-transformed daily mean catches during each year a quadratic regression produced an adjusted-r^2 of only 0.27 (n = 1020). The quadratic regression using 6-d moving averages (MA6) of daily means for years combined formed an acceptable spring peak that accounted for about 84% of the variability (Figure 2B) and established the peak on 2 April from the equation: MA6 Ln(PL+1) =0.8736 + 0.09037Day - 0.0004934Day^2 (adjusted-r^2 = 0.84, n = 159, $p < 0.001$). The mean and 95% confidence limits for Ln(PL+1)-transformed abundance data for the 62 samples (all years) collected during 30 March – 5 April, the week of the peak, were 144 PL/tow and 88-235 PL/tow, respectively, compared to the regression peak of 149 PL/tow and 95% confidence limits of 57-392 PL/tow.

1987 Intensive Spring Sampling Study

Abundance of brown shrimp PL ranged from 0 to 24,616 PL/tow, with a mean of 409 PL/tow (se = 119, n = 262 samples; Table 1) during spring 1987. No white shrimp PL occurred in the samples; they were never found before May during 22 yr of monitoring in Bolivar Roads. This maximum catch (24,616) was higher than any recorded catch during the 22 yr of standard monitoring. The means for triplicate tows ranged from 0.7 to 15,673 PL/tow and averaged 440 (se = 207, n = 77). Means for a calendar day (n = 12; 3 day and 3 night at the two sites) ranged from 18 to 4,488 PL/tow with the grand daily mean being 426 (se = 218, n = 20). The means for the North and South Jetty sites were 82 (se = 14, n = 57) and 962 PL/tow (se = 523, n = 55) for daylight, 288 (se = 42, n = 60) and 449 PL/tow (se = 110, n = 60) for night, and 188 (se = 24, n = 117) and 694 PL/tow (se = 257, n = 115) overall, respectively. For all daytime and nighttime tows the means were 514 (se = 259, n = 112) and 369 PL/tow (se = 59, n = 120), respectively. High variability in abundance found among the triplicates, day/night, dates, and sites was not constant and may not have been obvious without intense sampling (Figure 3).

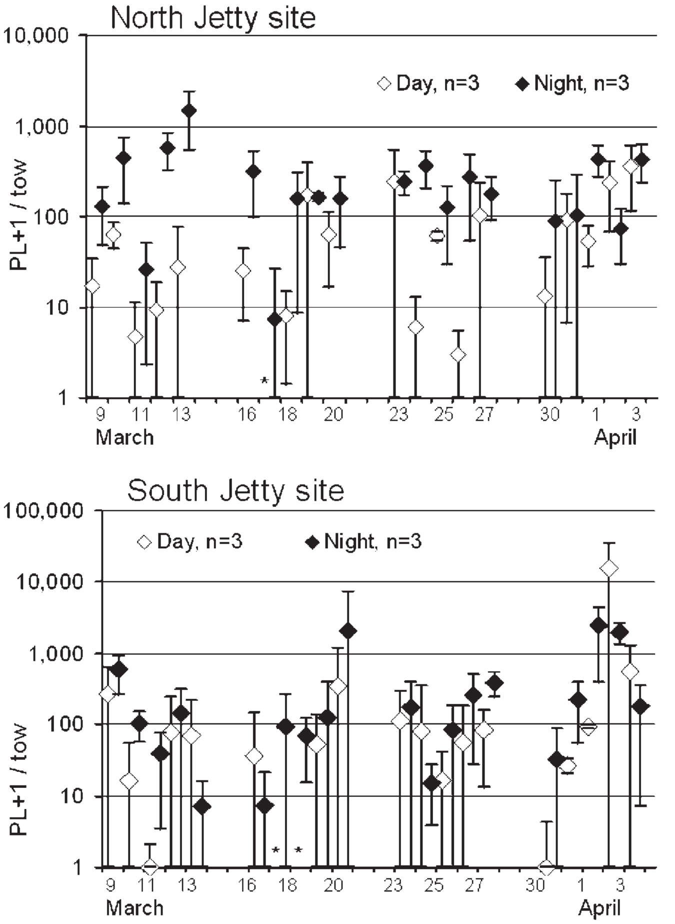

Figure 3.

Means and 95% confidence intervals for abundance of postlarval brown shrimp during March 1987 in Bolivar Roads, Texas for two sites. Sampling occurred Monday through Friday for 4 weeks. Means are for triplicate tows using Renfro beam trawls.
** = no data.*

Times and Sites

Observing changes in PL over various periods is useful for understanding PL influxes through passes and for establishing sampling regimes. The largest coefficient of variation (CV) for triplicate Ln(PL+1)-transformed abundance was 86.6%, and the smallest was 0.6%; both were for daytime collections at the South Jetty. Abundance in nighttime triplicates generally varied less than those in daytime triplicates (Table 2). Among all triplicate samples, 55% had CV's ≤ 10% and 77% had CV's ≤ 20%.

Postlarval abundance varied from hour to hour, and had a mean absolute difference of 104 PL/tow (se = 64) for the ten paired sets of triplicate samples. This difference was less than the mean of the 20 triplicate means, 154 PL/tow (se = 40), used for the comparison. Changes occurring during half a day (~12 h) were confounded by the light factor—day becoming night and vice versa. Night abundance at each site was greater than the corresponding day 78% of the time (Table 1 and Figure 3). The mean absolute difference over 12 h was 650 PL/tow (se = 286, n = 66). This difference was considerably larger than the mean, 446 PL/tow (se = 212), of the 74 triplicate means used for the comparisons. Changes in abundance from day to day (~24 h) were tested by comparing means from one daytime sampling to the next and from one nighttime sampling to the next for each site separately. The mean absolute difference was 767 PL/tow (se = 363, n = 59). This difference was also considerably larger than the mean, 451 PL/

TABLE 1. *Brown shrimp postlarval abundance in Bolivar Roads, Texas during spring 1987, as caught in Renfro beam trawl shoreline based tows. Each tow swept 102m² of bottom and filtered about 36m³ of water; nd = no data; +1 Hr = samples taken one hour later at same sites.*

	DAY						**NIGHT**						
	North Jetty Site			South Jetty Site			North Jetty Site			South Jetty Site			Daily
Date (1987)	Tow 1	Tow 2	Tow 3	Tow 1	Tow 2	Tow 3	Tow 1	Tow 2	Tow 3	Tow 1	Tow 2	Tow 3	mean
9-Mar	24	11	16	127	253	420	99	163	127	721	458	583	250.2
10-Mar	36	56	63	17	10	6	469	311	554	103	84	122	152.6
11-Mar	7	5	2	1	0	1	16	27	35	31	56	31	17.7
12-Mar	12	11	5	95	6	135	554	686	489	86	126	216	201.8
13-Mar	21	13	49	23	138	49	1,672	1,040	1,703	9	9	3	394.1
16-Mar	28	31	17	22	3	86	322	396	222	13	7	2	95.8
17-Mar	nd	nd	nd	nd	nd	nd	16	4	2	35	167	78	50.3
18-Mar	5	9	10	197	nd	nd	201	89	182	58	94	55	90.0
19-Mar	73	250	191	16	82	57	173	160	160	248	76	48	127.8
20-Mar	52	53	85	729	68	254	153	205	115	4,503	922	746	657.1
23-Mar	219	135	376	173	37	126	255	267	213	141	270	115	193.9
+ 1 Hr				59	20	45				154	215	175	111.3
24-Mar	8	3	7	3	35	202	434	310	344	18	10	18	116.0
+ 1 Hr				20	93	50				128	118	119	88.0
25-Mar	59	59	64	7	17	26	156	135	82	58	66	129	71.5
+ 1 Hr				23	19	34				891	912	473	392.0
26-Mar	4	2	3	70	3	99	346	175	287	162	265	348	147.0
+ 1 Hr				2	1	10				124	304	220	110.2
27-Mar	80	91	57	109	53	90	145	175	218	345	363	453	181.6
+ 1 Hr				87	36	64				528	365	155	205.8
30-Mar	3	20	16	2	2	0	71	38	161	37	52	8	34.2
31-Mar	60	85	127	24	29	27	24	123	164	286	227	152	110.7
1-Apr	42	62	55	95	90	92	512	404	390	3,194	1,558	2,534	752.3
2-Apr	287	265	159	12,644	24,616	9,760	61	94	66	1,776	1,856	2,272	4,488.0
3-Apr	457	355	260	237	589	830	384	387	522	259	130	150	380.0

tow (se = 212), of the 75 triplicate means used for the comparisons. The increase in absolute differences with increasing time between collections indicates that the abundance of PL moving through the pass is extremely dynamic and that short term, even hourly, changes could be substantial.

Differences in abundance between north and south jetty sites were examined by comparing means of triplicate catches for days and nights separately. The mean absolute difference was 730 PL/tow (se = 418, n = 37), and is considerably larger than the grand mean, 455 PL/tow (se = 215), of the 74 triplicates used in the comparisons. This difference was very close to that found for changes that occurred over about 24 h, and larger than that found over 12 h.

Sources of variation in PL abundance were ranked according to magnitude of CV. CV's were calculated for abundance based on replicates (triplicates), hour to hour, day-night, sites, and dates. The CV was highest for sites, followed by dates, day-night, replicates, and hours, respectively (Table 3). However, when abundance was Ln(PL+1)-transformed, the hierarchy of CV's changed to dates and day-night being greatest, followed closely by sites, and then hours and finally replicates.

Tides and Environment

Weather and tides varied considerably, as is typical for spring along the northern GOM (Figure 4A). Water temperature (Figure 4B) ranged from 8-28°C and salinity from 15-28‰ at the sampling sites. Pearson product moment correlations between Ln(PL+1)-transformed abundance and water temperature ($r = 0.22$, $p = 0.057$, $n = 77$), salinity ($r = 0.08$, $p = 0.464$, $n = 77$), and wind speed vectors ($r = -0.07$, $p = 0.527$, $n = 77$) were weak and not significant. Postlarval abundance was depressed during two significant "blue northers", one on 10-11 March and a larger one on 29

TABLE 2. *Frequency distributions of coefficients of variation of postlarval brown shrimp caught in triplicate samples. Collections were made along Bolivar Roads, Texas from 9 March – 3 April 1987. Catches had been transformed using: Ln(PL+1). PL = postlarvae.*

	NORTH JETTY		**SOUTH JETTY**			
CV (%)	**Day**	**Night**	**Day**	**Night**	**Sum**	**Cum. %**
0 - 10	9	16	6	17	48	55
11 - 20	7	2	5	5	19	77
21 - 30	2	1	4	2	9	87
31 - 40	1		1	1	3	90
41 - 50		1	1		2	93
51 - 60			3		3	96
61 - 70			1		1	97
71 - 80						97
81 - 90			2		2	100
90 - 100						100
n =	19	20	23	25	87	

March, and rebounded as each "norther" abated (Figure 5).

Flood-tides, which bring the PL into the pass from the Gulf waters, did not appear to be particularly important when weekly PL catches were examined with respect to tides, day-night, and location (Figure 6). In only 5 of 8 North Jetty cases and only 2 of 6 South Jetty cases were PL abundances greater on flood tides than on ebb tides. Eddy currents located between the ship channel and the shoreline probably added to the disconnect between abundance and tidal flows.

The Effect of Tow Radius

Postlarval abundances for the ten replicates of each radius differed by nearly two orders of magnitude along this short, 500 m, stretch of beach (Table 4). Among the standard 23 m radius tows, grooved shrimp, white shrimp, and total shrimp catch ranges were 48 to 3,224, 9 to 1,478, and 57 to 4,702 PL/tow, respectively. These large differences for both species were from just 360 m along the beach (Tows 1 and 8).

Short tow (11 m) abundances did not correlate well with those in the standard tows (r = -0.18, p = 0.61, n = 10), and when doubled to match the tow length of the standard, they were always less than standard tow abundances. Total PL abundances from the standard and long tows (46 m) correlated well (r = 0.88, p = 0.002, n = 9), but when standardized for tow length, the standard tow catches were greater than those of the long tows 78% of the time. Such results indicate the PL were irregularly distributed out from shore as well as along shore, with more PL appearing to be in the intermediate depth that was sampled most by the standard radius.

DISCUSSION

Federal and state fishery biologists and managers in the GOM have been particularly interested in maintaining the valuable brown, white, and pink shrimp fisheries. While other fisheries have been or are being over-fished and harvests declining, the shrimp harvests are holding fairly steady or declining only slightly through 2006 (NMFS 2007). An important correlation linking the adult shrimp harvest from the GOM with estuarine marsh nursery habitat (Turner 1977) coupled with the increase in man's developments along the bay shores suggests dismantled or degraded salt marsh nursery habitat may lead to reductions in shrimp harvests. For example, Browder et al. (1989) pointed to the insidious correlation between marsh break-up and shrimp populations, in that shrimp production increases as break-up increases to a point beyond which both crash. Marsh restoration efforts are not keeping pace with marsh destruction, and another few decades of marsh destruction could well lead to significant decreases in shrimp populations and harvests in the GOM.

The objectives of monitoring PL brown shrimp immigration are to better understand this shrimp's annual cycle, and then to use the intensity and/or timing of spring estuarine immigration of PL to forecast the summer harvests. High densities of immigrating brown shrimp PL have been not-

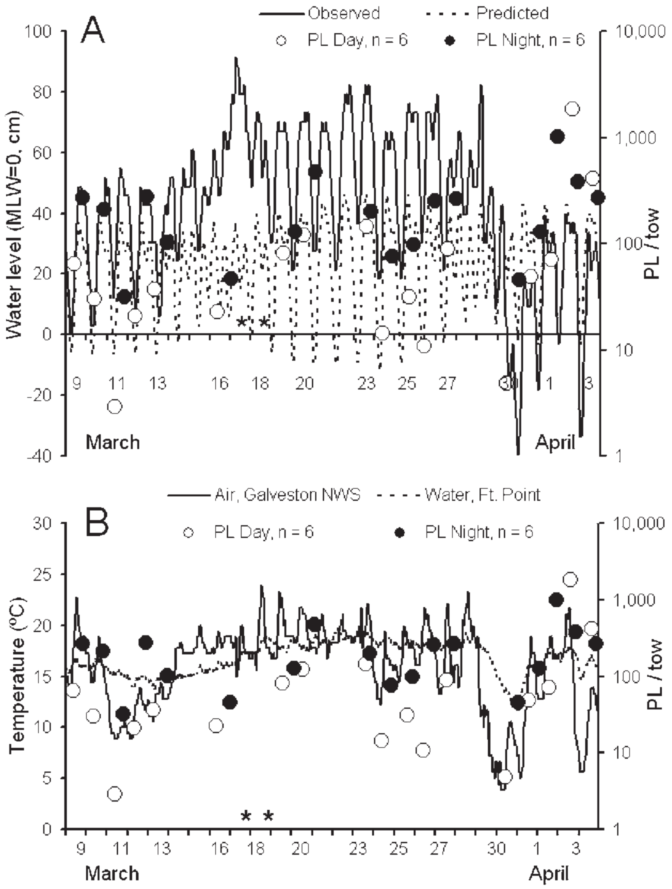

Figure 4.
Comparison of postlarval abundance from an intensive sampling study in Bolivar Roads, just east of Galveston, Texas in 1987 with environmental variables.

A. Hourly observed and predicted water heights (NOS).

*B. Hourly air temperatures (NWS) and water temperatures (USACE). * = no data.*

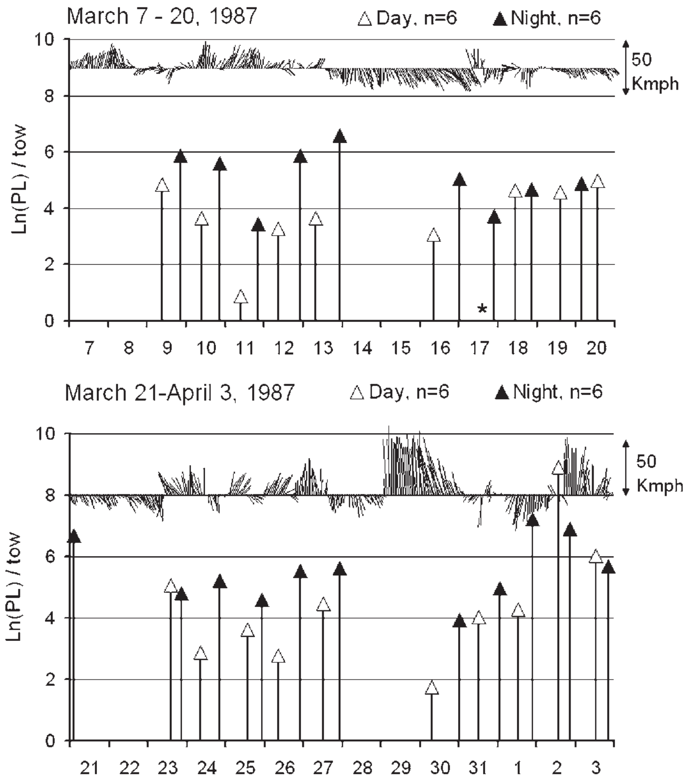

Figure 5.
*Hourly wind speed (Kmph) vectors are compared with postlarval brown shrimp abundance (vertical arrows) from Bolivar Roads, Texas, Spring 1987. A vertical wind vector above the horizontal axis indicates a wind from the north, and vector length may be compared with the 50 Kmph double headed arrow on the right. * = no data.*

ed during March and April in Texas (Copeland and Truitt 1966, Berry and Baxter 1969, Kutkuhn et al. 1969), Louisiana (Caillouet et al. 1971, Rogers and Herke 1985, Rogers et al. 1993), North Carolina (Williams 1964, Williams and Deubler 1968), and South Carolina (DeLancey et al. 1994). The timing of peak abundance has differed substantially from year to year, and some years the peak was absent—exchanged for intermittent highs and lows. These variations offered potential annual differences for forecasting models.

Without data from multi-year monitoring, characterization of the "spring peak" lacks substantive form. Individually, many of the previously cited studies suggested a "spring peak" but were unable to define it. Fortunately, annual sampling by Baxter allowed calculation of a regression equation to define the peak abundance which may be valid for the Texas coast. A similar regression based on long term data may also define peaks and migrations for *F. aztecus* PL along the north central GOM and Carolina coasts. However, one should not expect to reliably find large numbers of PL in a pass on a date based on the regression because many environmental and biological factors operate on PL distributions to reduce or inflate numbers on any particular day of a particular year. At present, the importance of the spring peak seems to be that it conceptualizes the importance of the estuarine habitat during that time of year for perpetuating brown shrimp. To use its changes in magnitude and/or timing of occurrence as forecasting variables will depend on our ability to adequately assess and evaluate the changes, and that will require addressing short-term variability in PL density measurements.

Small scale variability in density estimates appears high and has a large range that is significant over time and space. Thus, this variability can cause the annual influx event to be misrepresented in small-scale sampling efforts. For Bolivar Roads this study reported a maximum of 24,616 PL/tow or 684 PL/m^3 whereas Baxter and Renfro (1966) reported a maximum of 131 PL/m^3 and Duronslet et al. (1972) reported a mean high of barely over 1 PL/m^3. Arnold et al. (1960) observed in the same area that PL "... were swimming at the surface and so concentrated that several thousand could be caught with a single scoop of a dip net. On each occasion, large numbers of fish (mostly pinfish and anchovies) could be seen decimating the relatively helpless shrimp." These varying reports suggest high density collections may be quite ephemeral and no more important than some intermediate density for distributing PL in the bay. Other maxima of note in Texas are: 76 PL/m^3 along the front beach of Galveston Island during the spring (Benfield and Downer 2001), 60 PL/m^3 at Rollover Pass, Texas, from plankton tows (Berry and Baxter 1969), and 299 PL/m^3 in plankton net collections in Cedar Bayou that connects the GOM to Mesquite Bay (King 1971).

The greatest abundance reported here, and the largest in 22 yr of sampling, was 684 PL/m^3 and occurred on the theoretical spring peak and just three days after a strong "blue norther" had blown through and reduced PL density to < 1 PL/m^3. Similar increases in PL after northers have been reported in Louisiana (Rogers et al. 1993). The norther not only pushed the water out of the bay and held it out for about a day, but also chilled the shallow water to below 10 °C which probably caused PL to bury themselves in the bottom (Aldrich et al. 1968). Postlarvae may also have

TABLE 3. *Sources of variation in postlarval (PL) brown shrimp catches that used Renfro beam-trawls to sample at shoreline sites in Bolivar Roads, Texas. Coefficient of variation (CV) indicates the importance of the factor in contributing to the total variance.*

Factor	n	$\bar{x}$	Variance	CV	CV of Ln(PL+1)-transformed catches
Triplicates	87	440	881,636	214	14
Hourly	10	154	23,915	100	21
Day/Night	66	472	2,869,345	359	32
Site	39	439	3,241,015	410	30
Date	18	465	3,381,709	375	32

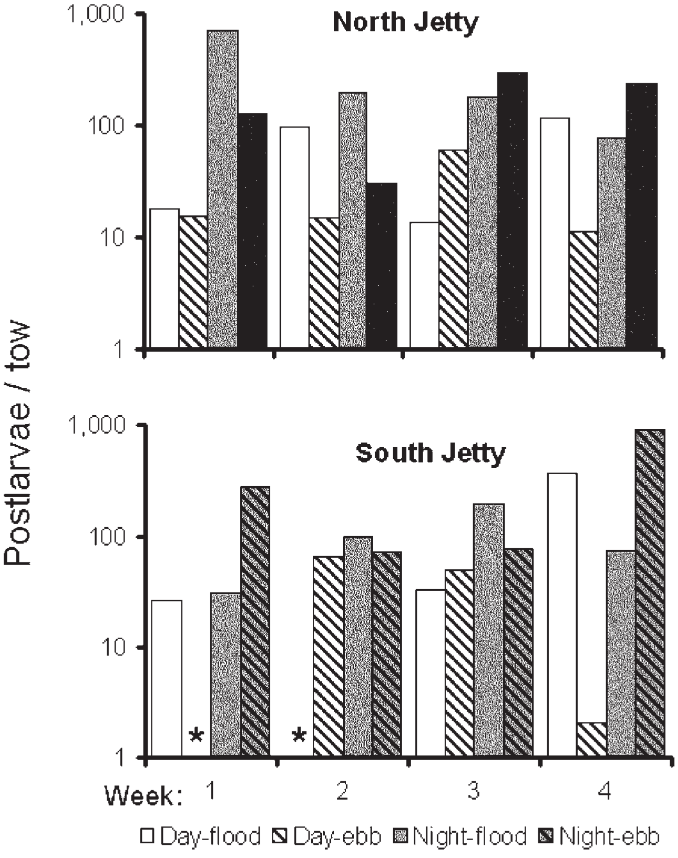

Figure 6.
*Weekly mean abundance of postlarval brown shrimp showing differences due to tidal flows, sites, and day or night conditions at two sites in Bolivar Roads, Texas, Spring 1987. * = no data.*

been concentrated in the near-offshore area by the offshore winds of the norther. Smith (1975, 1978) showed that as cold winds blow offshore they carry surface water offshore and consequently bring subsurface water towards the coast. The cold surface water may also have made PL drop into the warmer mid- and bottom water, concentrating them there, and bringing them towards shore. With the return of warmer onshore winds from the southeast and the rising water flooding back into the emptied bay, the PL are then carried into the bay. The observed super-abundance may have resulted from the addition of PL that emerged from the bottom to join those concentrated near shore by wind and cold and those approaching the coast in the normal manner. Knott et al. (1994) found wind forcing to be important for white shrimp PL and blue crab ingress to South Carolina passes.

It also appears that it might take more than one tidal flood to transport the accumulated PL through Bolivar Roads, a large pass with eddies along its sides. This could add more PL to the emerging group, if they had been trapped in the shallows during the norther as they immigrated. The fact that my data are from shoreline sampling may explain some of the lack of correlation between abundances and environmental and tidal conditions. By the time PL reach the sides of the pass where they were sampled tidal conditions may have changed, and their immigration slowed by slower currents and more eddies. Thus, the abundances observed may represent an accumulation rather than an instantaneous occurrence which would be reflective of environmental conditions when they initially arrived.

Although the existence of the variability in abundance during the spring offers potential for forecasting the shrimp fishery, the numerous sources causing differences in abundance estimates appear not to have been accommodated in past monitoring regimes. For example, the currently non-correlative existence between environmental factors and PL abundance is not a surprise as brown shrimp PL are widely tolerant of temperature and salinity (Zein-Eldin and Aldrich 1965), but it will complicate selection of relationships for forecasting models, and will diminish the usefulness of PL abundance for forecasting unless a connection can be found. Brown shrimp PL immigration continues through the summer with another smaller peak occurring in the fall, all of which offer additional potential for population modeling. A strong sampling regime will be required to address and separate the combination of biological and environmental factors that are responsible for changes in fishery harvest later in the year. Criales et al. (2006) found a similar need while studying pink shrimp PL immigration to Florida Bay.

High variability in abundance of PL was observed in studies designed to examine effects of time, date, day/night, tide, and tow distance. Some of this variability had been noted previously by Berry and Baxter (1969), Caillouet et al. (1968), Lochmann (1990), and Benfield and Downer (2001). Such extensive variability as was found over short time periods and distances illustrates that collecting only a few samples a couple of times per week or month, and at one or two sites, is likely to be inadequate to describe the dynamic PL immigration in a pass during an expanded time period. Limited data so gathered is potentially misleading, and would not likely be useful in forecasting the fishery harvest as was noted by Benfield and Downer (2001) for shrimp, or for predicting changes in fish populations (Osenberg et al. 1994). To increase the power of a monitoring program for immigrating PL, it seems best to increase sampling to account for the factor contributing the largest variance. Our CV calculations suggest that increasing the number of dates and sites sampled would add most to a sampling regime, with both day and night sampling and replicates having less importance.

This research pertained mainly to *F. aztecus* PL, but these high variability problems in Bolivar Roads likely apply to other estuarine passes as well, and to other species of shrimp, fish, and crab larval and PL populations that immigrate through passes. The strength of PL shrimp immigration may be a good indicator of future shrimp fishery harvest, but obtaining an accurate measurement of immi-

TABLE 4. *Postlarval shrimp catches during the triple radius test at the South Jetty site in Bolivar Roads, Texas, 17 September 1987. Brown = brown shrimp; White = white shrimp; sd = standard deviation; CV = coefficient of variation.*

Radius		**11 m**			**23 m**			**46 m**	
SET	**Brown**	**White**	**Total**	**Brown**	**White**	**Total**	**Brown**	**White**	**Total**
1	24	1	25	48	9	57	182	30	212
2	29	3	32	138	28	166	142	39	181
3	76	8	84	286	51	337	244	56	300
4	95	15	110	293	65	358	289	80	369
5	30	5	35	235	61	296	269	50	319
6	46	18	64	175	72	247	318	103	421
7	90	62	152	604	208	812	1,019	294	1,313
8	27	41	68	3,224	1,478	4,702	1,616	576	2,192
9	7	7	14	2,498	821	3,319	nd	nd	nd
10	89	125	214	400	95	495	742	357	1,099
$\bar{x}$:	**51**	**29**	**80**	**790**	**289**	**1,079**	**536**	**176**	**712**
sd:			**63**			**1,592**			**684**
CV (%):			**79**			**148**			**96**

gration may not be possible. Thus, we may need to also consider environmental parameters that affect juvenile growth and survival to provide an accurate fishery forecast.

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