THE RELATIONSHIP OF WINTER TEMPERATURE AND SPRING LANDINGS OF PINK SHRIMP, *PENAEUS DUORARUM*, IN NORTH CAROLINA[1]

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ABSTRACT

Spring landings of pink shrimp in North Carolina were highly correlated with water temperature during the previous winter. The strongest relation was found between landings and the average water temperature of the two coldest consecutive weeks of each year ($r^2 = 0.82$). Following the cold winters of 1977, 1978, 1980, and 1981, when temperatures averaged below 5°C, landings were <160,000 kg. Following the warm winters of 1965, 1974, and 1975, when temperatures averaged above 8°C, landings were >450,000 kg. Changes in water temperature through the year were described by a sine-cosine curve in which minimum temperatures generally occurred during the 5th week and maximum temperatures occurred during the 31st week of the year. Weekly mean air temperatures were linearly related to water temperatures ($r^2 = 0.97$) over the entire range of data, but they were not useful as proxy data for predicting pink shrimp landings ($r^2 = 0.50$) because the air-water relation was more variable at low temperature. Local rainfall did not have a significant effect on shrimp landings.

Temperature is a critical environmental factor influencing metabolism, growth, reproduction, distribution, and survival of animals (Kinne 1963). Local abundance may be affected by migration or death in response to extreme deviations from temperatures to which the animal is adapted. The effect of such temperature extremes is expected to be more severe for a population at the limit of its geographic range, particularly when temperature is known to be a factor limiting north-south distribution (Williams 1969a).

For species whose life cycle is completed in 1 yr, or in fisheries where reliance on annual recruitment is heavy (Loucks and Sutcliffe 1978), temperature records may be useful as a predictor of landings. A cause-and-effect relationship between harvest and temperature may be more obvious for species with one year class than for long-lived species whose landings are complicated by multiple year-class contributions (Norcross and Austin 1981). Penaeid shrimp, which have an annual life cycle, have no significant contribution from other year classes to compensate for a reduction in biomass caused by unfavorable temperatures.

Shrimp mortality in the southeast United States due to cold has been reported by Gunter and Hildebrand (1951), Lindner and Anderson (1956), and Lunz (1958). Of the three species of *Penaeus* that occur in North Carolina waters, only pink shrimp, *Penaeus duorarum* Burkenroad, overwinter in shallow estuaries (Williams 1955a) and, therefore, would be more likely to suffer from abnormally cold winter temperatures than either brown shrimp, *P. aztecus*, or white shrimp, *P. setiferus*. Pink shrimp have an annual life cycle in which the adults spawn offshore during early summer and postlarvae and juveniles utilize the estuaries, where several environmental factors can affect distribution and survival. These factors include temperature, salinity, substrate, debris cover, and seagrass species and density (Costello and Allen 1970; Grady 1971; Gunter 1950, 1961; Williams 1955a, 1958, 1969b). Peak recruitment of postlarvae into North Carolina estuaries occurs from July to September (Williams 1969b). Juveniles that overwinter in the estuary migrate towards the sea as adults, primarily in May and June, and become the object of a trawl and channel net fishery located in the mouth of the Neuse River, southwestern Pamlico Sound, Core Sound, Bogue Sound, and in the ocean between Beaufort Inlet and Bogue Inlet (Williams 1955b).

The primary purpose of this study was to investigate the relationship between winter tem-

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peratures and spring landings of pink shrimp in North Carolina to determine if temperature could be used as a predictor of landings. Several recent harsh winters (Diaz and Quayle 1980; Ingham 1979) provided an opportunity to compare landings over a range of temperatures. This relationship may serve to focus attention on the importance of temperature extremes in understanding ecosystem productivity. We also analyzed available water and air temperatures to model the annual temperature in the lower Newport River estuary, to compare the weekly mean temperatures of each year with the annual model, and to test the use of air temperature as proxy data for periods when no water temperatures were available. Finally, we examined the effect of local winter rainfall on pink shrimp landings.

METHODS

Temperature records were analyzed from the Newport River estuary, which is centrally located within the North Carolina pink shrimp nursery and fishing grounds, the "Carteret-Onslow Area" of Williams (1955b) (Fig. 1). This estuary had been the site of several studies conducted by our laboratory during which temperatures were routinely monitored at one or more locations, but the entire time-series of temperature records had not been analyzed.

Seawater temperatures were obtained from recordings made at Pivers Island near Beaufort, N.C., at the mouth of the Newport River estuary beginning in 1962. From 1962 until 1968, records were kept on the island's north channel, and from 1968 to the present, records were kept on the east channel. These locations are <400 m apart. From 1968 to mid-1974, continuous records either were not kept or were inadvertently lost. Thus, complete continuity from 1962 to 1981 was not possible.

Seawater temperature was recorded continuously on 7-d circular charts. Recordings since 1974 were calibrated (±0.1°C) with a precision mercury thermometer. The accuracy and precision of pre-1974 records could not be determined. Weekly means from 1962 to mid-1974 were calculated by averaging hourly readings during each 7-d cycle. Weekly means from mid-1974 to 1981 were calculated by using a compensating polar planimeter. The planimeter method permitted rapid integration of the entire weekly temperature record into a single temperature by converting the mean radius of the area encompassed by the temperature cycle to the equivalent weekly mean temperature.

Daily air temperatures and monthly precipitation totals were recorded at the National Weather Service observation station in Morehead City, N.C., 6.2 km west of Pivers Island, and were pub-

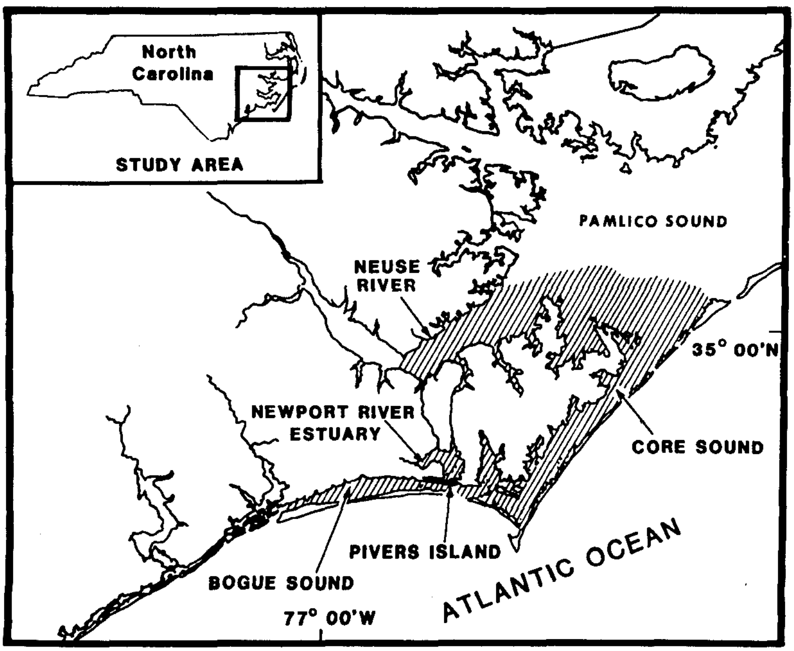

FIGURE 1.—Pink shrimp nursery area (indicated by hatched lines). Pivers Island was point-source of water temperature data.

lished by NOAA Environmental Data and Information Service, National Climatic Center, Asheville, N.C. Weekly mean air temperatures were calculated by averaging daily maximum and minimum records. Rainfall records for December, January, and February were totalled for each winter.

The commercial landings of pink shrimp (kilograms of abdomens) were obtained from records published by the U.S. Department of Commerce (North Carolina Shrimp Landings, Current Fisheries Statistics series) (Table 1). Landings from late winter through July of each year comprised the portion of the fishery considered by our hypothesis to be influenced by severe overwintering conditions, primarily extensive periods of low temperatures and, possibly, reduced salinities. Landings after July were excluded because, in late summer, size and weight decreased, reflecting recruitment of postwinter juveniles into the estuary.

RESULTS AND DISCUSSION

Annual Temperature Cycle in the Newport River Estuary

Weekly mean water temperatures in the Newport River estuary displayed a basically sinusoidal annual pattern (Fig. 2). Actually there appeared to be a slight distortion in the seasonal sine relationship whereby vernal warming proceeded at a slower rate than autumnal cooling. Available data from 1962 to 1981 were used to mathematically define the annual temperature cycle according to the following least-squares, multiple regression equation:

$$T_W = a + b_1 \text{ SIN } \left(\frac{2\pi W}{52}\right) + b_2 \text{ COS } \left(\frac{2\pi W}{52}\right),$$

where T_W was the mean weekly temperature for week W, a was an intercept reflecting the overall average yearly temperature, and b_1 and b_2 were regression coefficients controlling the timing and amplitude of annual minimum and maximum temperatures.

The derived equation (Fig. 2) was an adequate representation of the annual cycle of temperature in the Newport River estuary ($R^2 = 0.93$) and helped illustrate several aspects of the plotted data. Minimum temperatures tended to occur during the 5th week of the year (early February); maximum temperatures occurred during the 31st week (mid-August). Winter temperatures were characterized by greater week-to-week variability than summer temperatures. In general, the fitted curve consistently overestimated winter temperatures. This trend arose from an apparent asymmetry of the minimum and maximum temperatures about the yearly mean. That

TABLE 1.—Landings of pink shrimp in North Carolina compared with various combinations of winter water temperature data collected at Pivers Island, N.C., and air temperature and rainfall data collected at Morehead City, N.C. Air temperature biweekly periods corresponded with the coldest two consecutive weeks used for water temperature.

Year	Landings Feb.-July (kg, heads off)	Average water temperature (°C)				Average coldest biweekly air temp. (°C)	Total rainfall (cm, Dec.-Feb.)
		Dec.-Mar.	Jan.-Feb.	Coldest week	Coldest two consecutive weeks		
1962	365,390	8.5	8.1	6.2	7.0	8.5	20.3
1963	70,237	7.5	7.0	5.9	6.0	5.5	34.4
1964	274,298	8.1	8.3	6.1	6.2	3.2	39.7
1965	452,246	9.9	9.7	7.1	8.4	—	18.0
1966	150,080	9.0	8.2	4.3	5.2	2.9	27.2
1967	387,773	9.0	8.9	6.9	7.6	8.9	33.7
1968	266,781	—	—	—	—	—	27.7
1969	321,693	—	—	—	—	—	21.2
1970	91,968	—	—	—	—	—	32.8
1971	353,767	—	—	—	—	—	31.7
1972	205,667	—	—	—	—	—	41.1
1973	330,455	9.7	8.7	4.7	5.6	3.6	35.5
1974	518,670	12.1	12.6	7.9	9.1	8.8	49.3
1975	497,163	11.6	11.6	10.2	10.6	8.4	34.7
1976	367,671	10.6	9.6	6.0	7.6	4.4	26.7
1977	13,272	6.4	4.9	2.8	3.1	1.0	28.2
1978	15,567	6.9	6.2	3.5	3.8	4.6	37.8
1979	293,432	8.8	7.6	5.6	5.6	3.8	47.6
1980	157,781	8.4	8.2	3.8	4.8	4.8	29.9
1981	134,626	7.8	7.0	3.7	4.9	2.8	36.7
r^2		0.790	0.804	0.720	0.822	0.50	0.003

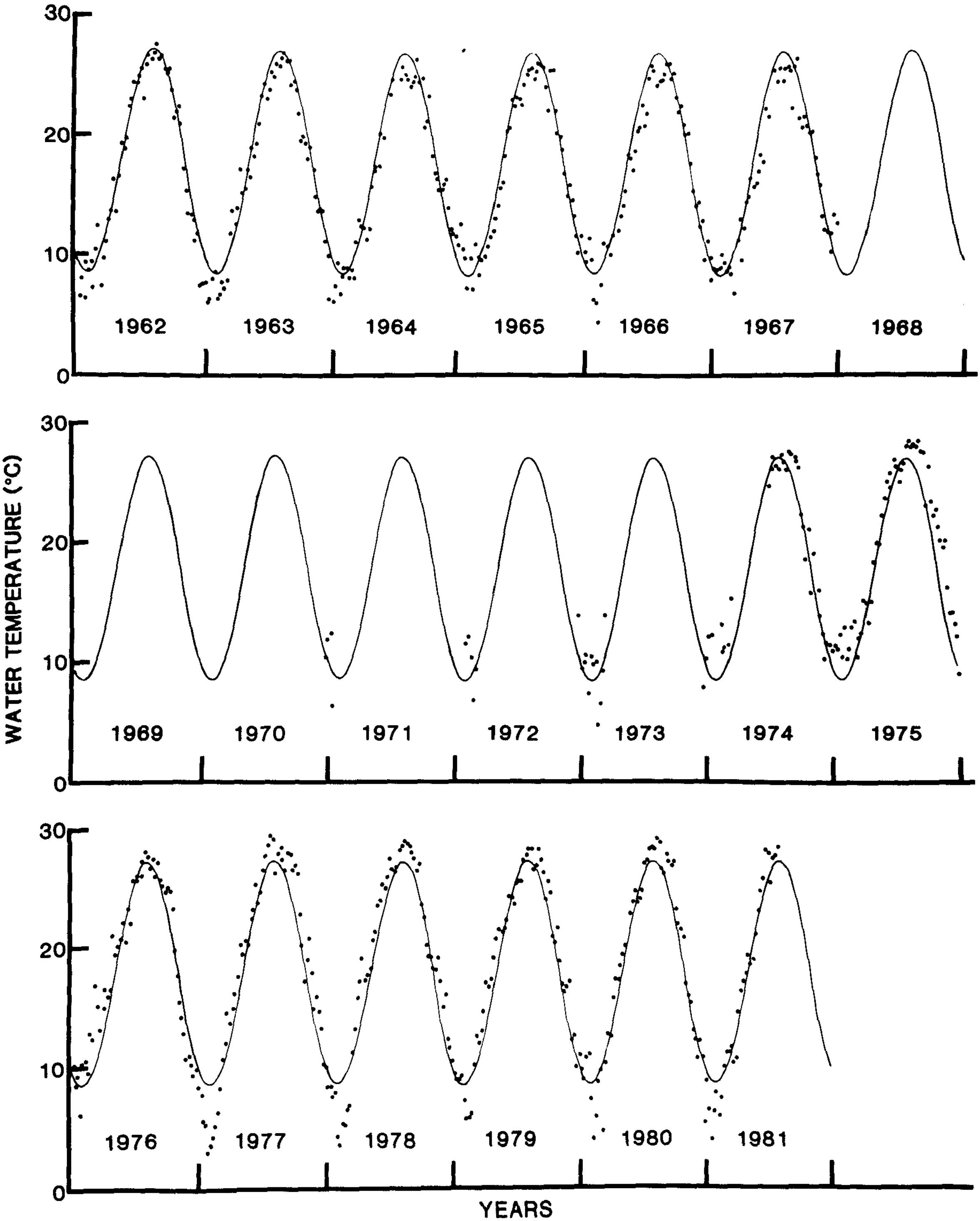

FIGURE 2.—Newport River estuary (Pivers Island) weekly mean water temperatures. Fitted line represents the least squares determined equation: $T_W = a + b_1 \sin\left(\frac{2\pi W}{52}\right) + b_2 \cos\left(\frac{2\pi W}{52}\right)$, where T_W is the mean weekly temperature for week W, $a = 17.88$, $b_1 = -5.20$, and $b_2 = -7.94$ ($R^2 = 0.93$).

is, winter lows were displaced farther from the mean than were summer highs.

As a group the years 1962-67 were cooler in the summer and warmer in the winter than 1974-81. Lower temperatures during cold months reflected a series of very cold winters in the mid-1970s (Diaz and Quayle 1980). An analysis of covariance showed that the average yearly temperature of the 1962-67 year group was significantly different ($P<0.05$) from the 1974-81 group. Either a systematic calibration bias was introduced by different observers, thermographs, and recording locations, or temperatures were actually more extreme in the latter year group. Calibration bias does not satisfactorily explain how both high and low temperature extremes could occur, but a climate phenomenon can be cited. According to R. G. Quayle, NOAA National Climatic Center, Asheville, N.C., the 1962-67 winters were less variable in daily temperature means than the 1973-81 winters. For example, the January and February monthly mean air temperatures at Wilmington, N.C., and Cape Hatteras, N.C., were not different between the two year-groups, but the standard deviations of the monthly means were significantly different at both stations between year-groups (Table 2). Thus, our recorded depressions in weekly winter temperatures in the 1973-81 group probably reflect more extreme actual fluctuations.

TABLE 2.—Comparison of means and standard deviations of January and February air temperatures at two North Carolina coastal stations for year-groups 1962-67 and 1973-81.

	Air temperature (°C)			
	Wilmington		Cape Hatteras	
Year-group	$\bar{X}$	SD	$\bar{X}$	SD
1962-67				
Jan.	7.67	1.51	7.56	1.17
Feb.	8.44	1.73	7.06	1.16
1973-81				
Jan.	7.94	3.74	7.61	3.26
Feb.	8.00	3.10	6.83	3.20

Air-Water Temperature Relation

Close thermal coupling between air and water has been found in shallow estuaries. Roelofs and Bumpus (1953) reported that water temperature in Pamlico Sound showed a seasonal cycle closely related to air temperature. Lindner and Anderson (1956), documenting a winter kill of white shrimp in south Atlantic and Gulf of Mexico waters of the United States, also referred to a close relationship between air temperature and surface water temperature. Smith and Kierspe (1981) presented a model of air-water heat exchanges in a shallow estuary and suggested that their model could reduce the need for in situ instrumentation while providing for close approximation of daily average temperatures.

For the purpose of using air temperatures as proxy data for missing water temperatures (1968-72, Table 1), we decided to examine the relation between local air and water temperatures (Fig. 3). Although air temperature fluctuations were accompanied by a predictable shift in water temperatures over the entire range ($r^2 =$ 0.97), at water temperatures below 12°C the relationship was not as useful ($r^2 = 0.68$). We believe that water temperatures rather than air temperatures are required for acceptable predictions of fishery yields in estuaries.

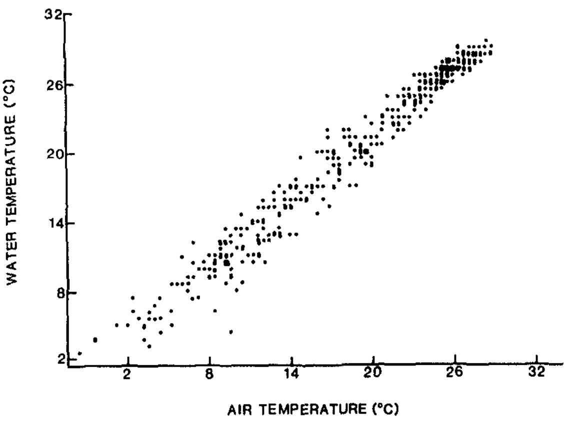

FIGURE 3.—Correlation of Morehead City, N.C., average weekly air temperatures with Newport River estuary (Pivers Island) average weekly water temperatures over 339 consecutive weeks from 1974 to 1981. (Intercept = 2.21, slope = 0.96, r^2 = 0.97.) For points below a water temperature of 12°C, r^2 = 0.68; and this relationship is not considered useful for predictive purposes during winter.

Relationship Between Temperature, Rainfall, and Pink Shrimp Landings

The February through July pink shrimp landings were considered a dependent variable to be plotted against various combinations of winter temperature data (Table 1). Landings were regressed on average winter water temperature from December through March ($r^2 = 0.79$), average temperature in January and February ($r^2 =$ 0.80), average temperature of the coldest week

($r^2 = 0.72$), and average temperature of the two coldest consecutive weeks ($r^2 = 0.82$). All relationships were significant ($P<0.01$). If the average temperature of the two coldest consecutive weeks was <6°C, then shrimp landings were below average (Fig. 4).

Although average winter temperatures (December-March) and average monthly temperatures (January plus February) each accounted for significant portions of the variance in annual landings, the strongest relationship was found between landings and the average of the two coldest consecutive weeks. This may arise because, as Williams (1969b) stated, averages do not adequately represent extremes since they dampen the duration and intensity of the cold. Using a process of expressing temperature in heating degree days, Williams (1969b) postulated that the catch of all species of penaeid shrimps of a given year in North Carolina may depend on net heating degree days during the coldest preceding 6 mo (November-April). He found the poorest catches in cold years (1958, 1961, and 1963) for all three species combined and further suggested that warm years may be as beneficial as cold years are deleterious.

The role of temperature on activity and osmoregulation of pink shrimp has been documented (Williams 1955a, 1960). The lower temperature for activity under experimental conditions was about 14°-16°C; complete cessation of activity was noted below about 10°C. Below 8.8°C, osmoregulatory ability was impaired. Pink shrimp may survive periods of winter cold by burying deeply into the substrate, and Fuss and Ogren (1966) reported that below 14°C, shrimp remain buried, abandoning the usual pattern of nocturnal emergence. Laboratory experiments showed pink shrimp to be more tolerant to combinations of low salinity and low temperature than brown shrimp, and this may explain the occurrence of pink shrimp in North Carolina estuaries during the winter (Williams 1960). In contrast, fall and midwinter brown shrimp immigrants do not survive cold weather as well. The usual recruitment period for brown shrimp postlarvae is February and March; for white shrimp it is June through September (Williams 1965).

Because osmoregulation is impaired at low temperatures, we considered that low salinity could increase mortality caused by low temperatures. Although salinity records were not available, we compared local rainfall measurements with pink shrimp landings from 1962 to 1981.

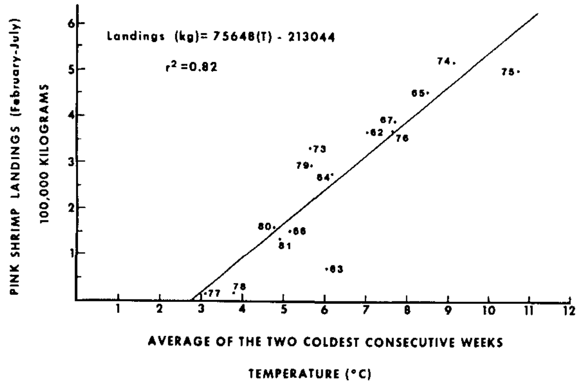

FIGURE 4.—Relation of pink shrimp landings in North Carolina to the average water temperature of the two coldest consecutive weeks in the Newport River estuary. Numbers by dots represent year of landings. (Actual landings of 198,000 kg were predicted to be 165,200 kg, based on the coldest average biweekly period temperature in 1982 of 5.0°C.)

We found no correlation between rainfall and landings ($r^2 = 0.003$) (Table 1). Further, rainfall added no significant contribution to the explanation of variance in landings data when it was included with temperature as a predictive variable (multiple $R^2 = 0.826$). Both the driest (18.0 cm in 1965) and wettest (49.3 cm in 1974) winters occurred in years when landings were very large, approximately 500 metric tons. Williams (1969a) also found no significant relationship between rainfall and total catch of all shrimp species. However, Hunt et al.[3] reported that salinities ≥10‰ and temperatures ≥20°C during April and May are necessary for good brown shrimp harvests in North Carolina. Similarly, Gunter and Hildebrand (1954) found a strong correlation of total rainfall and white shrimp catch in Texas.

Deviations from the shrimp landings-temperature relationship may, in part, be due to the process of estimating landings. Errors may include improper species identification by fish dealers, lack of accuracy in estimated weight landed, and incomplete landing coverage. The direct trading of shrimp to private individuals by numerous part-time fishermen, plus the recreational landings, neither of which is reported, undoubtedly causes an underestimate of total

[3]Hunt, J. H., R. J. Carroll, V. Chinchilli, and D. Frankenberg. 1980. Relationship between environmental factors and brown shrimp production in Pamlico Sound, North Carolina. N.C. Dep. Nat. Resour. Community Dev. Div. Mar. Fish. Spec. Sci. Rep. 33, 29 p.

landings (Caillouet and Koi 1980). On the other hand, because of increased demand and higher prices for shrimp, fishing effort is probably more intensive in recent years. We did not consider effort in our analysis because reliable data were not available. Williams (1969b) concluded that pounds landed almost paralleled his calculated catch-effort index and therefore that actual harvest data satisfactorily represented annual productivity independent of effort. Another source of variability to be considered, the annual variation in the recruitment of postlarvae, was dismissed because Williams (1969b) and Williams and Deubler (1968) found no relation between densities of penaeid shrimp postlarvae and subsequent landings. Similarly Lindner and Anderson (1956) found that a severe cold kill of adult white shrimp in 1940 had no effect on the next year's landings.

A number of complications in relating catch and climate were listed by Austin and Ingham (1979). In our study, which began with a conceptual model of an organism and its relation to a physical parameter, some of the following suggested complications were mitigated: 1) A causal relationship of temperature to production was biologically appropriate, because the life history and temperature tolerance of pink shrimp are known; 2) the use of proxy data (air temperature instead of water temperature) was avoided; 3) major variations in the shrimp landings are probably due to cold kill of overwintering shrimp caused by cold-water temperatures ($r^2 =$ 0.82); 4) while the quality of the biological data (landings) cannot be judged, the length of the time series (15 yr) is probably adequate; 5) an interest does exist among fishery biologists and managers in using environmental data and relationships for predictive, explanatory, or modeling purposes; 6) although environmental data were point source, landings were from a geographical area (<100 km radius) sufficiently restricted so as not to have masked biota-environmental relations.

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