USE OF A PRE-RECRUIT ABUNDANCE INDEX TO IMPROVE FORECASTS OF OCEAN SHRIMP (*PANDALUS JORDANI*) RECRUITMENT FROM ENVIRONMENTAL MODELS

ROBERT W. HANNAH
Oregon Department of Fish and Wildlife
Hatfield Marine Science Center
2040 SE Marine Science Drive
Newport, Oregon 97365, U.S.A.
Tel.: +1 541 867 0300 ext. 231; Fax: +1 541 867 0311
email: bob.w.hannah@state.or.us

ABSTRACT

I investigated the potential to improve forecasts of annual $\log_e$ recruitment to the ocean shrimp (*Pandalus jordani*) fishery using a pre-recruit index based on the percentage of age-zero shrimp from fishery samples in the year prior to recruitment. The index was incorporated into existing models in which $\log_e$ age-1 recruitment is forced by environmental variables related to the spring transition in coastal currents (negative correlation with April sea level height at Crescent City, California, $ASLH_{t-1}$) and the strength of April–July upwelling winds at 42°N. latitude (negative correlation, AJU_{t-1}) during the pelagic larval phase. For northern Oregon, the pre-recruit index improved model fit, increasing the coefficient of determination from 0.40 for a model based only on $ASLH_{t-1}$ to 0.62 for the combined model. For southern Oregon, the index did not improve the fit of a model based on $ASLH_{t-1}$ and AJU_{t-1}. However, the pre-recruit index alone had a higher correlation with age-1 recruits than the best environmental model (r^2 of 0.43 versus 0.27). Although precision of the final models was low, both correctly predicted a stronger than average 2009 recruitment.

INTRODUCTION

The trawl fishery for ocean shrimp (*Pandalus jordani*) is the second most valuable crustacean fishery operating in California Current waters, following only Dungeness crab (*Cancer magister*) in the average annual value of landings (The Research Group 2006). The ocean shrimp fishery is considered a "recruit fishery," in that annual catches are strongly influenced by the strength of the year class entering the fishery that year (Hannah and Jones 1991). Ocean shrimp are very short-lived, recruit to the fishery at age one and contribute to fishery landings for just 3 years (Dahlstrom 1973; Hannah and Jones 1991). Recruitment of ocean shrimp off Oregon has been linked to environmental variation in the California Current ecosystem, specifically to the timing of the spring transition in coastal currents (Huyer et al. 1979) that, on average, takes place shortly after ocean shrimp release their pelagic larvae (Dahlstrom 1973; Hannah 1993). The transition from predominantly northward to southward surface currents is forced by a similar shift in the predominant coastal winds in early spring, and is reflected in a sharp drop in coastal sea level height (Huyer et al. 1979). An early transition (generally in March or early April), results in a lower mean April sea level height (fig. 1, Crescent City, California, $ASLH_{t-1}$), which has been associated with strong age-1 recruitment of ocean shrimp in Oregon waters the following year (Hannah 1993). The mechanisms underlying this association are not well understood. However, an early spring transition, with associated coastal upwelling, can establish near-surface ocean conditions that are favorable to larval survival, including reduced sea surface temperatures (Rothlisberg and Miller 1983). A very late spring transition can result in continued northward transport of surface waters, possibly transporting larvae to areas where subsequent transport is unlikely to bring them back to areas off Oregon (Austin and Barth 2002).

Recently, recruitment success of ocean shrimp has also been shown to be negatively influenced by anomolously strong coastal upwelling during the pelagic larval phase (Hannah in press). Specifically, recruitment off southern Oregon was shown to be reduced in the years following the very high April–July upwelling values observed at 42°N. latitude in 1999 and in 2001–2003 (fig. 1). The mechanism underlying this relationship is also unknown, however, the excessive offshore transport of larvae is a reasonable hypothesis that has been proposed (Parrish et al. 1981; Hannah in press). This mechanism is also supported by data showing that large concentrations of ocean shrimp are typically found north of the zone of maximum upwelling, which is centered off California (fig. 2). In 1999 and in 2001–2003 the upwelling index at 42°N. latitude reached levels higher than had been observed previously in the complete available time series, starting in 1946. It's possible that these recent years with very strong spring upwelling represent normal extremes in local climate variability, however these observations are also consistent with a hypothesis that the zone of maximum upwelling may have shifted or simply expanded northwards, which in turn is consistent with predictions of many climate

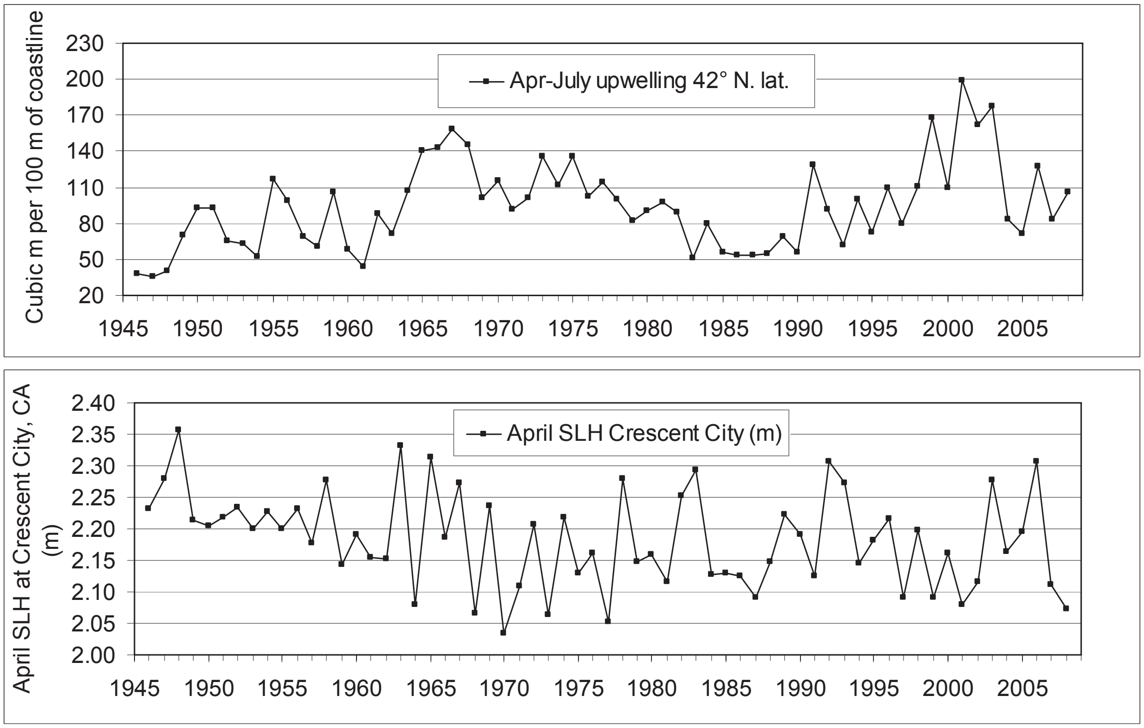

Figure 1. Time series of selected environmental variables, 1946–2008.

models under conditions of global warming (Yin 2005; Seidel et al. 2008; Hannah in press). Several researchers have suggested that global warming may have begun to intensify coastal upwelling off the U.S. west coast (Bakun 1990; Schwing and Mendelssohn 1997) and to alter its seasonal pattern (Snyder et al. 2003), with large potential effects on the California Current ecosystem (Barth et al. 2007).

The pelagic larval phase for ocean shrimp lasts from larval release in March and April through about August. Early stage shrimp larvae are found in near-surface waters (<150 m, Rothlisberg 1975) and occupy progressively deeper portions of the water column as they develop, however juveniles also migrate up into near-surface waters at night (Dahlstrom 1973; Rothlisberg 1975). By September and October, small age-0 ocean shrimp begin showing up in small numbers in commercial trawl catches. The fishery is closed each year from November through March to protect gravid females, so additional fishery-dependent information on the relative abundance of the incoming year class is unavailable until the fishery opens again in April. No fishery-independent surveys are conducted for ocean shrimp. The relative abundance of age-0 ocean shrimp in fall fishery samples has long been considered a questionable index of age-1 recruitment the following year (although see comments in Geibel and Heimann 1976). These young shrimp have not fully recruited to the near-bottom waters fished by trawls and have been considered too small to be completely retained by the mesh sizes typically used in ocean shrimp trawls (Rothlisberg 1975; Lo 1978; Jones et al. 1996). However, no research to try and relate the relative abundance of age-0 ocean shrimp in fall fishery samples to age-1 recruitment the following year has been conducted since the development of the recruit-environment models discussed above. The objective of this study was to develop a simple index of age-0 shrimp abundance from fall fishery samples and determine if it could be used to improve the forecasting ability of existing recruit-environment models for age-1 ocean shrimp.

It should be noted that the best fitting recruit-environment models for ocean shrimp have relatively low predictive power. This is not unexpected, as most recruit-environment relationships have been shown to break down over time (Myers 1998). The limitations of recruit-environment models are not surprising because the establishment of year class success is certainly a very complex process. It is unlikely to be fully captured in simple linear or non-linear recruit-environment models. For marine species with pelagic larvae, recruitment processes involve complex interactions between factors modulating larval mortality and transport in the open ocean, including interactions between life history, predation and larval behavior as well as variation in environmental conditions. The most recent research on recruit-environment relationships with ocean shrimp is a good example of this complexity. Prior to 1999,

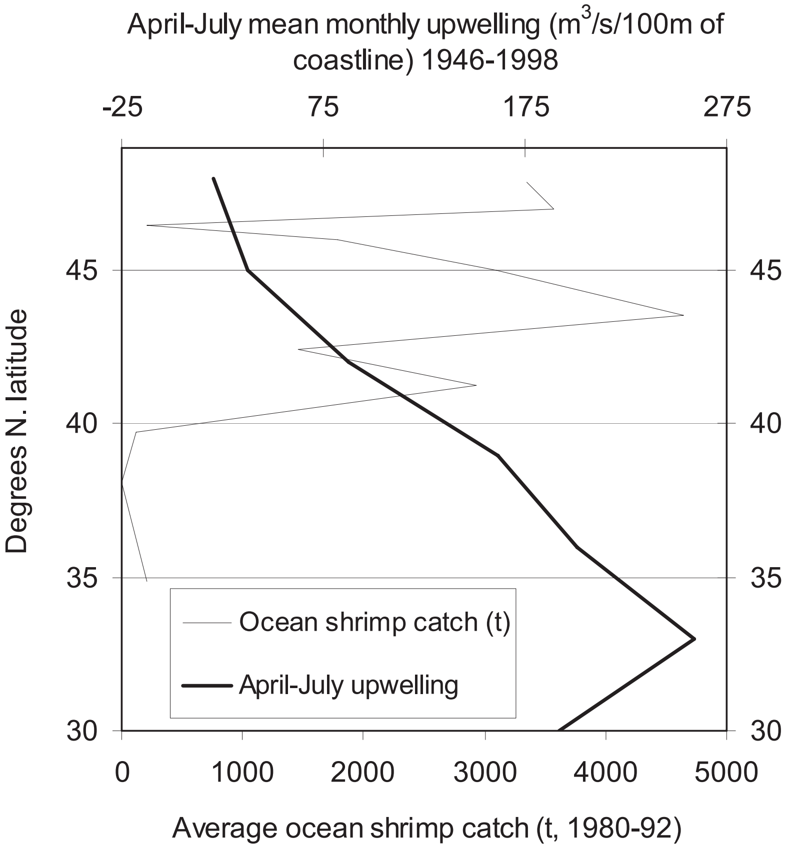

Figure 2. Comparison of latitudinal distribution of ocean shrimp catches (1980–92 average, t) and April–July upwelling (1946–98 average) for Oregon and California waters.

$ASLH_{t-1}$ predicted age-1 recruitment of ocean shrimp in Oregon waters fairly well. When spring upwelling increased to truly record levels in 1999 and 2001-2003 off southern Oregon, this simple relationship broke down for southern Oregon waters, probably because a different process was limiting local recruitment success in those years. A primary advantage of using pre-recruit indices to predict recruitment is that they may be able to indicate the final result of all of these complex processes that influence year class success.

METHODS

An index of the relative abundance of age-0 ocean shrimp was calculated as a simple average of the proportion of age-0 shrimp found in fishery samples for waters off northern and southern Oregon. First, the proportion of age-0 shrimp in September and October samples was averaged for each statistical area (fig. 3). Then these values were averaged for the three statistical areas off northern Oregon and the four statistical areas off southern Oregon, to provide a single index for each of the two larger areas each year. No adjustment was made for missing samples in some areas and years. The age-0 ocean shrimp index was highly skewed and was transformed using a Box-Cox transformation with an offset of 0.001 and 0.0005 for northern and southern Oregon waters, respectively. The Box-Cox transformation employs a log-likelihood function to find a power transformation that best normalizes the data (Sokal and Rolf 1981).

Age-1 recruitment of ocean shrimp was indexed using a simple virtual population estimate (VPE, a sum of catch-at-age, also called "utilized stock," Ricker, 1975) calculated from fishery-dependent data, after Hannah (in press). The index did not include catches of age-0 shrimp in fall samples so as to maintain statistical independence from the pre-recruit index detailed above. The age-1 recruitment index was calculated separately for northern and southern Oregon waters, which are separated by the large rocky reef system, Heceta Bank, where shrimping does not occur (fig. 3). Separate indices for northern and southern Oregon were used because recently, different environmental variables were linked to recruitment in the two areas (Hannah, in press). The successful use of fishery-dependent data to index recruitment of ocean shrimp has been demonstrated in several studies (Hannah 1993; Hannah 1999; Hannah in press) and is possible because of some rather unique characteristics of the stock and the fishery that targets it. The short life span of ocean shrimp and the

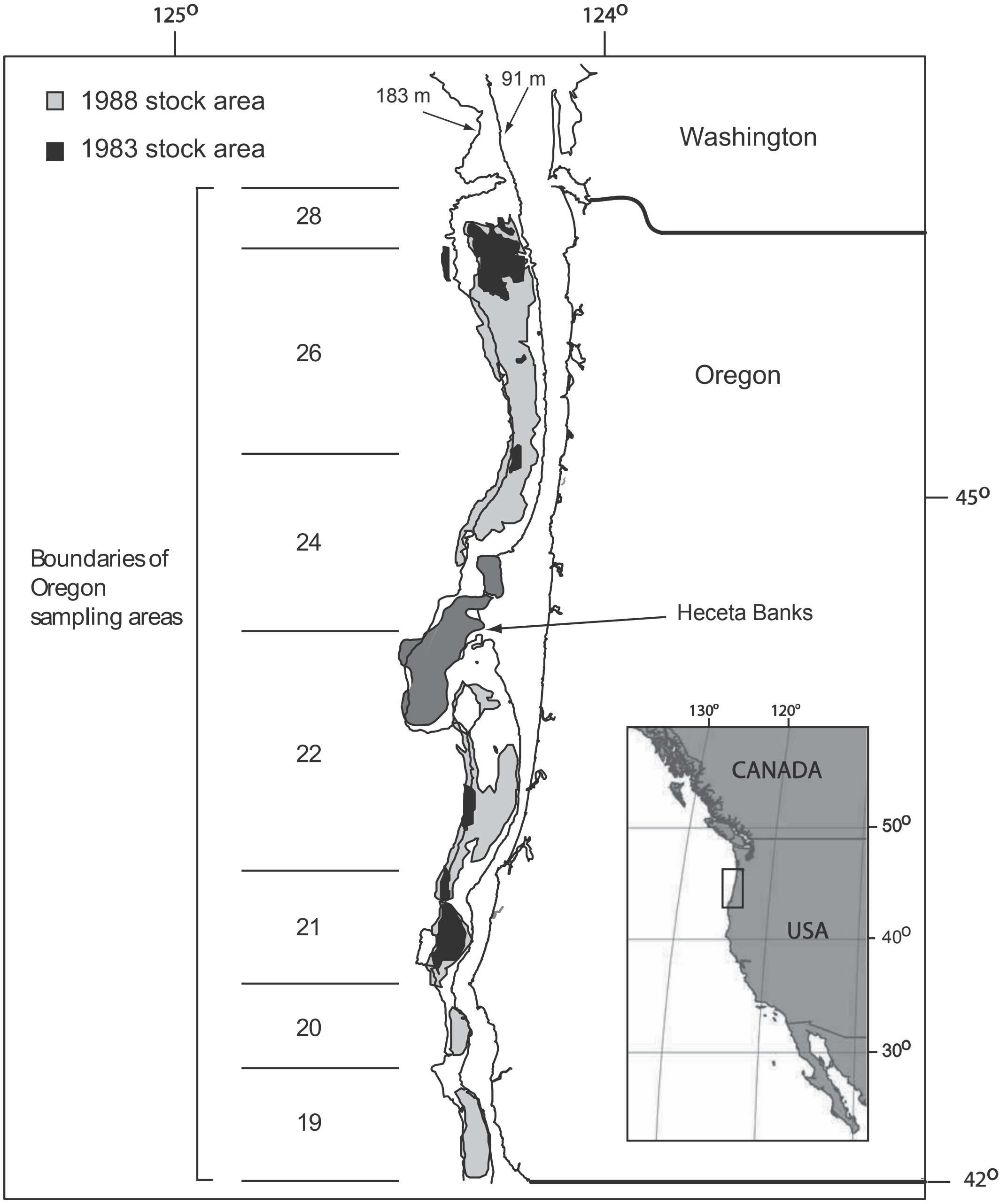

Figure 3. Map of the Oregon commercial fishing grounds for ocean shrimp at high (1988 recruitment, light grey) and low stock abundance (1983 recruitment, dark). Heceta Bank marks the division between northern and southern grounds.

strong dependence of trawl fishery catches on age-1 recruitment, creating a strong recruitment "signal" in the fishery, have already been mentioned. An active and ongoing fishery monitoring program in Oregon also provides high quality data including trawl logbook information that can be used, along with biological samples of the landed catch, to estimate catch-at-age by area (fig. 3). The ocean shrimp trawl fleet is also very mobile and searches widely for concentrations of shrimp (Hannah 1995). Major movements of ocean shrimp after settlement have not been shown and thus the distribution of age-1 shrimp captured in the fishery has been interpreted as roughly describing the distribution of newly-settled recruits (Hannah 1995). Limitations of the logbook data collected by the states of Washington and California after 1992 preclude the development of similar indices for waters off those states (Hannah 1999). Accordingly, this study was limited to the component of the stock found off of Oregon.

The utility of the pre-recruit index for improving forecasts of age-1 recruitment of ocean shrimp was evaluated in a straightforward manner. The coefficient of

TABLE 1
Ocean shrimp recruitment index (millions of age 1 recruits, VPE-based) and the mean proportion of age zero shrimp in fishery samples in September–October of the prior calendar year, for northern and southern Oregon waters (Figure 1), 1980–2006 (year of age-1 recruitment).

Year of age 1 recruitment	Northern Oregon recruit index (millions)	Mean proportion of age zero shrimp north (Sept.–Oct., t-1)	Southern Oregon recruit index (millions)	Mean proportion of age zero shrimp south (Sept.–Oct., t-1)
1980	728.6	0.0018	2,018.5	0.0276
1981	405.9	0.0000	1,158.9	0.0016
1982	360.4	0.0000	1,397.1	0.0133
1983	86.0	0.0000	91.3	0.0000
1984	422.4	0.0000	411.4	—
1985	1,207.0	0.0010	544.3	0.0078
1986	1,209.2	0.0200	1,162.6	0.0210
1987	3,459.2	0.0000	1,342.3	0.1102
1988	2,963.2	0.0045	2,563.2	0.0888
1989	1,997.4	0.0012	2,973.2	0.0438
1990	322.3	0.0000	262.2	0.0039
1991	815.0	0.0010	1,449.7	0.0801
1992	1,103.5	0.0010	4,072.7	0.0801
1993	123.1	0.0000	402.2	0.0033
1994	438.1	0.0000	1,106.7	0.0701
1995	296.6	0.0000	197.1	0.0016
1996	485.4	0.0010	1,106.7	0.0068
1997	376.5	0.0005	1,468.2	0.0275
1998	294.3	0.0000	197.1	0.0048
1999	2,005.9	0.0137	1,115.8	0.0158
2000	2,410.8	0.0057	644.1	0.0000
2001	1,502.3	0.0022	672.4	0.0000
2002	4,053.9	0.0027	488.7	0.0150
2003	2,529.0	0.0217	98.4	0.0185
2004	399.1	0.0038	79.1	0.0000
2005	2,249.1	0.0482	701.5	0.1308
2006	196.0	0.0015	209.9	0.0000
2007	—	0.0265	—	0.0255
2008	—	0.0000	—	0.0327
2009	—	0.0003	—	0.0603
1980–2006 average	1,201.5	0.0053	1,045.4	0.0297

determination was compared between the best-fitting recruit-environment models developed by Hannah (in press) for northern and southern Oregon waters with corresponding multiple regression models that incorporated the transformed pre-recruit index. As in Hannah (in press), the age-1 recruitment index was log-transformed prior to regression. The upwelling index was obtained from the Pacific Fisheries Environmental Laboratory (http://www.pfeg.noaa.gov/products-/PFEL/modeled/indices/upwelling). April SLH data were obtained from the National Oceanic and Atmospheric Administration (http://tidesandcurrents.noaa.gov). No recruitment index is yet available for the 2009 year class of ocean shrimp, however, catch rates and reports of very widespread and dense concentrations of ocean shrimp suggest a very strong year class in Oregon waters, especially off southern Oregon. Although further testing of the "best" models developed here will have to await more years of data, the prediction from each model for the 2009 year class was evaluated against a hypothesis of a strong recruitment event.

RESULTS

The mean proportion of age-0 shrimp in fishery samples was highly variable interannually and ranged from 0-0.0482 and from 0-0.1308 in samples collected from northern and southern Oregon, respectively, between 1980 and 2006 (year of age-1 recruitment unless noted, tab. 1). The generally higher proportions of age-0 shrimp off southern Oregon are consistent with faster growth at more southerly latitudes, resulting in more consistent retention in shrimp trawl gear (Hannah and Jones 1991). For northern Oregon, some samples were collected in every year, however, lack of fishing effort in all southern Oregon statistical areas in September and October of 1984 resulted in no samples being collected (tab. 1). Estimates of the mean proportion of age-0 shrimp were based on samples from multiple statistical areas in most years for both northern and southern Oregon. The age-0 index for southern Oregon was successfully normalized by transformation, however the index for northern Oregon was not. The age-1 recruitment index showed wide variation

TABLE 2

Regression models relating ocean shrimp recruitment indices to selected environmental variables (Hannah in press) and alternative models incorporating an index of pre-recruit abundance from September–October fishery samples in the year prior to recruitment (age zero index), by area, 1980–2006 (year of age 1 recruitment). April SLH_{t-1} and AJ $upwell_{t-1}$ are mean sea level height at Crescent City, California and mean April–July upwelling index at 42°N. latitude, respectively, for the year prior to recruitment.

Dependent variable	Parameters/variables	Coefficients	Standard error	R^2	P>F
Northern Oregon					
Log_e age-1 recruit index	Intercept	42.594	5.401		0.0001
	April SLH_{t-1}	-0.1021	0.025		0.0004
	Full model (1)			0.40	0.0004
Log_e age-1 recruit index	Intercept	37.806	4.610		0.0001
	April SLH_{t-1}	-0.075	0.022		0.0020
	Age zero index[1]	207.847	56.897		0.0013
	Full model (2)			0.62	0.0001
Southern Oregon					
Log_e age-1 recruit index	Intercept	35.091	6.366		0.0001
	April SLH_{t-1}	-0.063	0.029		0.0385
	AJ $upwell_{t-1}$	-0.011	0.005		0.0231
	Full model (3)			0.27	0.0228
Log_e age-1 recruit index	Intercept	30.774	5.963		0.0001
	April SLH_{t-1}	-0.035	0.028		0.2217
	AJ $upwell_{t-1}$	-0.006	0.005		0.1938
	Age zero index[2]	32.646	10.486		0.0051
	Full model (4)			0.49	0.0017
Log_e age-1 recruit index	Intercept	23.143	0.683		0.0001
	Age zero index[2]	40.303	9.526		0.0003
	Full model (5)			0.43	0.0003

[1] Fitted index = $((\text{proportion age zero}+0.001)^{-0.6}-1)/-7962.285941$

[2] Fitted index = $((\text{proportion age zero}+0.0005)^{0.2}-1)/8.343416$

in recruitment between years, as has been reported in previous studies (Hannah 1993; Hannah 1999; Hannah in press).

For ocean shrimp recruits off northern Oregon, incorporating the pre-recruit index into the best environmental model, which was based on just $ASLH_{t-1}$, increased the coefficient of determination from 0.40 to 0.62, a clear improvement (model 1 vs. model 2 in tab. 2). The sign of the coefficient for the pre-recruit index was positive, as expected. A plot of the residuals from the regression of loge recruits on $ASLH_{t-1}$ showed that the pre-recruit index, although correlated with subsequent age-1 recruitment, was very low in some years (untransformed proportion equal to 0), even when subsequent recruitment was above average (fig. 4A). Predictions from the model incorporating both independent variables (model 2 in tab. 2) matched the time series of the transformed recruitment index fairly well and correctly indicated an above-average recruitment event in 2009 (fig. 5A).

For southern Oregon waters, adding the pre-recruit index to the best environmental model did not result in an improved model (compare model 3 to model 4 in tab. 2), as neither environmental term contributed significantly to the combined model. The best fitting model for all combinations of these three independent variables was a simple regression of loge recruits on the transformed pre-recruit index (model 5 in tab. 2). This model was an improvement over the best environmental model statistically, raising the coefficient of determination from 0.27 to 0.43, while reducing the number of independent variables by one (tab. 2 and fig. 4B). However, this model does not fit the data well, in that predictions do not match the wide range observed in recruitment (fig. 5B). Particularly notable is the failure of the model to accurately predict major southern Oregon year class failures in 1983 and 1998, years of strong extra-tropical ENSO events, and also in 2003–2004 (fig. 5B). The model did, however, correctly indicate an above-average age-1 recruitment for 2009.

DISCUSSION

The brief analysis presented here suggests that a pre-recruit abundance index derived from fishery samples may have some utility in forecasting age-1 recruitment of ocean shrimp. Although improved coefficients of determination were achieved utilizing the pre-recruit index for both northern and southern Oregon waters, neither of the "best" models (models 2 and 5 in tab. 2) showed an excellent fit to the transformed recruitment index, suggesting a continued low ability to predict age-1 recruitment with accuracy. A reasonable expectation for the best-fitting models for both northern and southern Oregon is that they may be useful for indicating whether an incoming year class is likely to be above- or below-average, although additional years of

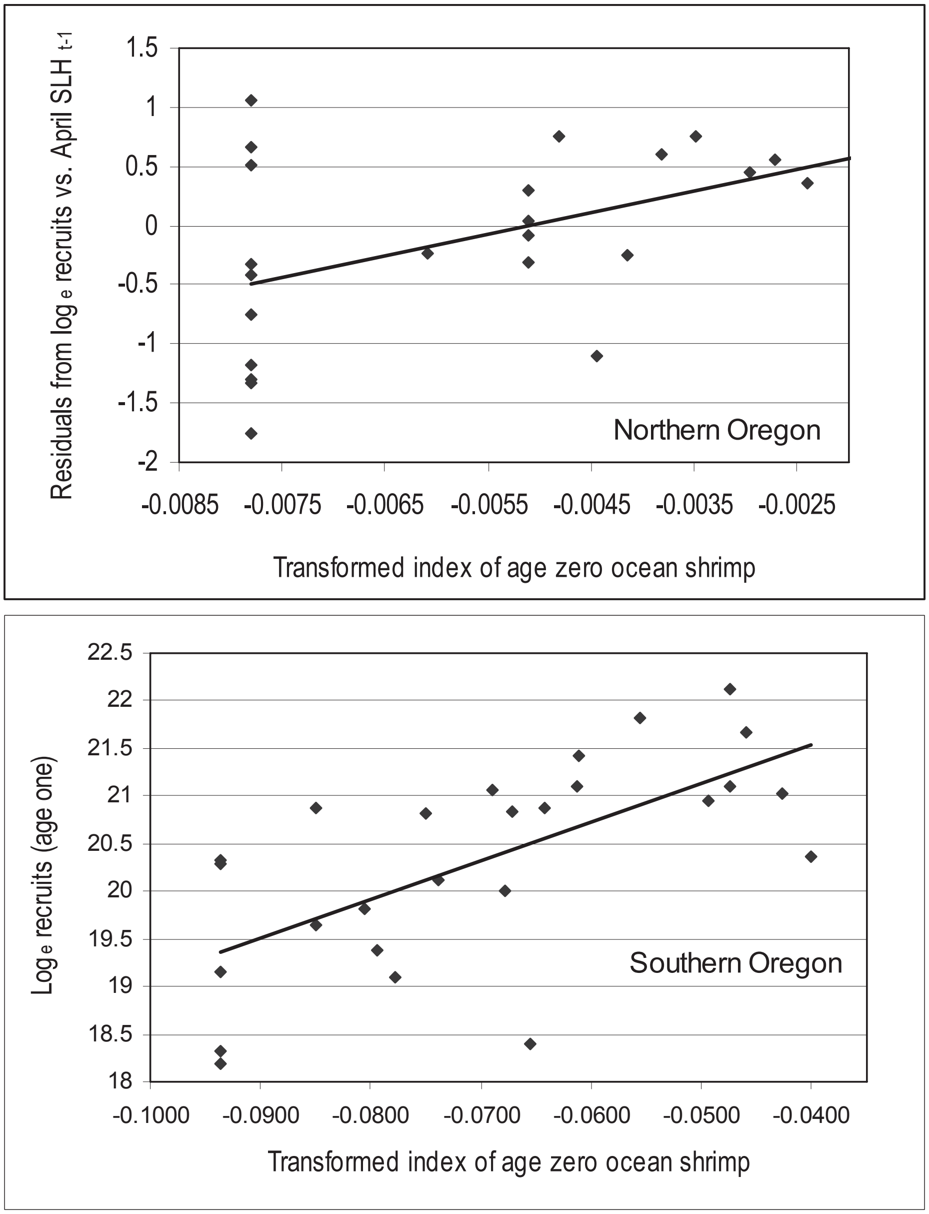

Figure 4. Linear regression of residuals from a regression of $\log_e$ age-1 ocean shrimp recruits (northern Oregon) on April SLH_{t-1} and $\log_e$ ocean shrimp recruits (southern Oregon) on the ocean shrimp pre-recruit index.

data will be needed even to validate this modest predictive ability.

The modest success reported here for forecasting ocean shrimp recruitment based on the relative abundance of pre-recruits in fishery samples suggests that better forecasts could be developed with more extensive sampling for pre-recruits. Sampling levels of fishery landings could be increased to obtain somewhat better spatial coverage from September and October samples. However, shrimp trawling is usually directed at areas producing the best catches of age-1 shrimp, which may not correspond with areas in which age-0 shrimp are abundant. In some years, a wide geographic coverage simply cannot be obtained from fishery samples. However, fishery-independent sampling could be conducted to provide a more representative index of pre-recruits. To date, the economic value of accurate forecasts of ocean shrimp recruitment has not been considered sufficient to warrant spatially extensive fishery-independent sampling for pre-recruits.

Even though highly accurate forecasting of recruitment of ocean shrimp has not been achieved, the models presented here, both environmental models and those based on pre-recruits, do have some scientific utility. In this study, the statistical significance of the pre-recruit index provides additional support for the hypothesis that

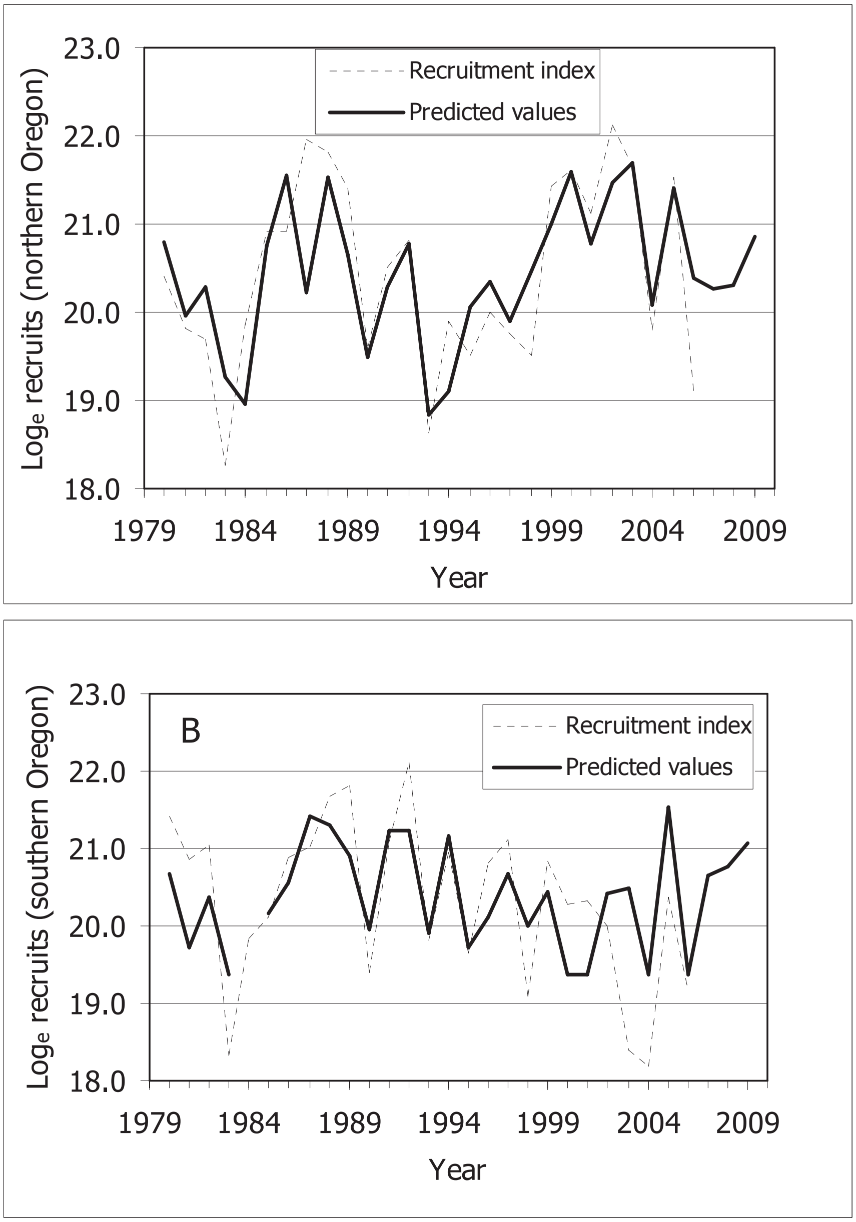

Figure 5. Comparison of the age-1 recruitment index for ocean shrimp with predicted values from the best models incorporating the pre-recruit index (models 2 and 5 in Table 2).

recruitment success of ocean shrimp is determined during the pelagic larval phase, as has been demonstrated for Dungeness crab (*Cancer magister*), another commercially important crustacean species found in California Current waters. It should be noted however, that the failure of the pre-recruit index to accurately predict major year class failures associated with strong extra-tropical ENSO events in 1983 and 1998 may indicate that under extreme environmental conditions, year class strength or geographical distribution of recruits may continue to be modified after settlement. The environmental models that formed the basis for this analysis show the dependence of successful recruitment of ocean shrimp on a timely spring transition in coastal currents and therefore on large-scale atmospheric forcing, another commonality with Dungeness crab (Hannah 1993; Shanks and Roegner 2007).

The primary benefit from exploring predictive recruitment models is the potential to identify, and perhaps eventually verify, hypotheses about how the ocean environment, species life history and anthropogenic effects like fishing interact to determine regional and local recruitment success. For example, the ocean shrimp recruit-environment models that have been developed suggest a link between southern Oregon recruitment failures and excessive offshore transport of larvae under extreme spring upwelling conditions (Hannah in press). If spring upwelling intensity off southern Oregon returns to record high levels in future years and is again associated with recruitment failure it will support this hypothesis, especially if ocean shrimp recruitment is not suppressed broadly by a weak or late spring transition. Similarly, in this study, the comparison of ocean shrimp pre-recruit indices with subsequent recruitment to the fishery showed that although pre-recruit indices have predictive value, they perform poorly at predicting severe year class failures associated with strong ENSO events, especially off southern Oregon (fig. 5). A possible explanation is that northward transport of ocean shrimp takes place during ENSO-influenced winters as a result of anomolously strong northward-flowing bottom currents. There is some evidence that this may have been the case in the extremely strong ENSO event of 1982/83 (Huyer and Smith 1985, Hannah 1993).

ACKNOWLEDGEMENTS

This research was funded, in part, by NOAA award NA09NMF4070362 under the Interjurisductional Fisheries Act.

LITERATURE CITED

Austin, J. A. and J. A. Barth. 2002. Drifter behavior on the Oregon-Washington shelf during downwelling-favorable winds. J. Phys. Oceanogr. 32:3132–3144.

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247:198–201.

Barth, J. A., B. A. Menge, J. Lubchenco, F. Chan, F., J. M. Bane, A. R. Kirincich, M. A. McManus, K. J. Nielsen, S. D. Pierce and L. Washburn. 2007. Delayed upwelling alters nearshore coastal ocean ecosystems in the northern California current. Proc. Nat. Acad. Sci. 104(10):3719–3724.

Dahlstrom, W. A. 1973. Status of the California ocean shrimp resource and its management. Mar. Fish. Rev. 35:55–59.

Geibel, J. J. and R. F. G. Heimann. 1976. Assessment of ocean shrimp management in California resulting from widely fluctuating recruitment. Calif. Fish and Game. 62(4):255–273.

Hannah, R. W. 1993. The influence of environmental variation and spawning stock levels on recruitment of ocean shrimp (*Pandalus jordani*). Can. J. Fish. Aquat. Sci. 50(3):612–622.

Hannah, R. W. 1995. Variation in geographic stock area, catchability and natural mortality of ocean shrimp (*Pandalus jordani*): some new evidence for a trophic interaction with Pacific hake (*Merluccius productus*). Can. J. Fish. Aquat. Sci. 52:1018–1029.

Hannah, R. W. 1999. A new method for indexing spawning stock and recruitment in ocean shrimp, *Pandalus jordani*, and preliminary evidence for a stock-recruitment relationship. Fish. Bull. 97:482–494.

Hannah, R. W. (in press). Variation in the distribution of ocean shrimp (*Pandalus jordani*) recruits: links with coastal upwelling and climate change. Fish. Ocean.

Hannah, R. W. and S. A. Jones. 1991. Fishery induced changes in the population structure of pink shrimp (*Pandalus jordani*). Fish. Bull. U.S. 89:41–51.

Huyer, A., J. C. Sobey and R. L. Smith. 1979. The spring transition in currents over the Oregon continental shelf. J. Geophys. Res. 84, No. C11. 6995–7011.

Huyer, A. and R. L. Smith. 1985. The signature of El Niño off Oregon, 1982–83. J. Geophys. Res. 90(C4): 7133–7142.

Jones, S. A., R. W. Hannah and J. T. Golden. 1996. A survey of trawl gear employed in the fishery for ocean shrimp *Pandalus jordani*. Oregon Dept. Fish Wildl., Information Rept. Ser., Fish. No. 96-6. 23 p.

Lo, N. C. H. 1978. California ocean shrimp mesh experiment. Calif. Fish Game 64:280–301.

Myers, R. A. 1998. When do environment-recruitment correlations work? Rev. Fish Biol. Fish. 8:285–305.

Parrish, R. H., C. S. Nelson and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California current. Biol. Oceanogr. 1(2):175–203.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Fish. Res. Board Can., Bull. No. 191. 382 p.

Rothlisberg, P. C. 1975. Larval ecology of *Pandalus jordani* Rathbun. Ph.D. Dissertation, Oregon State University, Corvallis, Oregon. 117 p.

Rothlisberg, P. C. and C. B. Miller. 1983. Factors affecting the distribution, abundance, and survival of *Pandalus jordani* (Decapoda, Pandalidae) larvae off the Oregon coast. Fish. Bull. 81(3):455–472.

Schwing, F. B. and R. Mendelssohn. 1997. Increased coastal upwelling in the California Current System. J. Geophys. Res. 102(C2):3421–3438.

Seidel, D. J., Q. Fu, W. J. Randel and T. J. Reichler. 2008. Widening of the tropical belt in a changing climate. Nature Geosci. 1:21–24.

Shanks, A. L. and G. C. Roegner. 2007. Recruitment limitation in Dungeness crab populations is driven by variation in atmospheric forcing. Ecology 88:1726–1737.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh and J. L. Bell. 2003. Future climate change and upwelling in the California current. Geophys. Res. Lett. 30, 15,1823, doi:10.1029/2003GL017647.

Sokal, R. R. and F. J. Rolf. 1981. Biometry. Freeman, New York.

The Research Group. 2006. Review of the west coast commercial fishing industry in 2004. Prepared for Pacific States Marine Fisheries Commission. September 2006.

Yin, J. F. 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophys. Res. Lett. 32,L18701, doi:10.1029/2005GL023684.