## APPENDIX 6

# SAW 47 Working Paper 11 (TOR 6) – Modeling Environmental Factors

September 5, 2007

## Modeling environmental factors and summer flounder recruitment success

by
Mark Terceiro
NOAA Fisheries NEFSC
166 Water St.
Woods Hole, MA 02543

A Report to the Northeast Regional (NER) Stock Assessment Workshop (SAW)
Southern Demersal Working Group (SDWG)

## INTRODUCTION

There is interest among scientists, managers, and fishermen in exploring the relationship between environmental processes and summer flounder recruitment. Such processes might include the influence of physical parameters such as water temperature and salinity, and biological ones such as the density of prey (e.g., zooplankton and small fish) or the density of predators (e.g., spiny dogfish, bluefish, or striped bass). The most recent stock assessments for summer flounder (Terceiro 2006a, b; SDWG 2007) indicate that over the last 25 years recruitment has varied annually by a factor of about seven (Table 1, Figure 1). The weak year class that recruited to the stock in 2005, which was spawned by the largest spawning stock biomass (SSB) of summer flounder since the 1970s, brought increased focus to the influence of environmental factors on the success of summer flounder recruitment.

Evidence from several studies suggests that low water temperatures could negatively impact summer flounder recruitment. Summer flounder spawning occurs during an annual offshore migration from coastal areas to the continental shelf from August through December, and is generally considered to peak around November 1 (O'Brien et al. 1993). Summer flounder eggs have been collected as early as September in the northern Mid-Atlantic Bight and as late as January off Cape Hatteras, NC, with peak egg concentrations in October and November (Smith 1973, Able et al. 1990). Summer flounder eggs in the wild are tolerant to a wide range of temperatures between about 9 and 22$^{o}$C, with most occurring in temperatures of about 13-17$^{o}$C (Smith 1973). Summer flounder larvae have been collected over an even wider range of temperatures (0-23$^{o}$C; Smith 1973). Laboratory studies suggest that summer flounder eggs and larvae are tolerant to relatively high temperatures (Johns and Howell 1980, Johns at al. 1981), but that both eggs and larvae are susceptible to shock exposure to low temperatures of about 0°C (Hoss et al. 1974).

Summer flounder larvae undergo metamorphosis during the late autumn and early winter months as they enter the estuarine zone along the mid-Atlantic coast (Able et al. 1990). Szedlmayer et al. (1992) investigated the first year growth and effects of water temperature on survival for summer flounder juveniles migrating into New Jersey estuaries in the winter of 1988-1989, and found that the survival of metamorphosing larvae decreased drastically when water temperatures dropped below 2°C. Keefe and Able (1992) found that the survival of metamorphosing larvae was lower at laboratory water temperatures of 4°C than at 10°C, and concluded that estuarine summer flounder larvae suffer increased mortality based on both the duration and severity of cold water temperatures. Malloy and Targett (1991) conducted laboratory experiments on juvenile summer flounder and found 100% survival above 3°C, suggesting that the juveniles were able to survive most winter water temperatures encountered in the Mid-Atlantic Bight. However, Malloy and Targett (1994) found 42% mortality of juveniles at 2°C and concluded that mortality in the wild from acute exposure to low water temperatures probably occurred during one 2 to 4 week period each winter, and that summer flounder recruitment success in the north/central Mid-Atlantic Bight may be lower in years with late winter cold periods due to increased exposure to lethal temperatures.

Over the last decade, persistent significant relationships have been found between environmental factors and recruitment success for a variety of fish species around the world. Daskalov (1999) used General Additive Modeling (GAM; Hastie and Tibshirani 1990) to document significant correlations between the recruitment success of Black Sea anchovy, whiting, sprat, and horse mackerel and environmental factors including sea surface temperature, wind speed, wind stress, mixing, atmospheric pressure, and river run-off. Williams and Quinn (2000) used correlation analyses to identify significant environmental factors affecting Pacific herring recruitment success. Beentjes and Renwick (2001) used correlation analysis to identify a significant relationship between New Zealand red cod recruitment success and sea surface temperature. Chen and Ware (1999), Chen at al. (2000), Chen (2001), and Dreyfus-Leon and Chen (2007) used neural network, fuzzy logic, and genetic algorithm models to explore the relationships between environmental factors and recruitment success of Pacific herring stocks. Megrey et al. (2005) examined the utility of linear and non-linear regression, Generalized Additive Models (GAMs), and Artificial Neural Network (ANN) models in identifying relationships between recruitment and the environment for both simulated and real Norwegian herring stock-recruit data. Brodziak and O'Brien (2005) used randomization methods and the GAM approach to evaluate the response of New England groundfish recruit-spawner ratios to environmental variables such as the North Atlantic Oscillation (NAO) index, water temperature, windstress, and shelf water volume anomalies. This work explores the relationships between water temperature anomalies, NAO indices and metrics of summer flounder recruitment success by applying some of the approaches of Brodziak and O'Brien (2005) and Megrey et al. (2005) to summer flounder spawner-recruit data and relevant environmental data.

## DATA AND MODELING APPROACH

### *Data*

Spawning stock biomass (SSB) and recruitment estimates (VPA0) for summer flounder were taken from a version of the 2007 assessment update Virtual Population Analysis (VPA)

F07_ALL sensitivity run (includes all available survey indices; SDWG 2007), which has historically exhibited a milder retrospective pattern and more precise estimates of stock size (a "degrees of freedom" phenomenon) than the F07_1 final run used to determine the official status of the stock. Because no accepted parametric stock-recruit relationship was available (Terceiro 2006b), the RSAs were computed as the difference between the observed annual RS ratio values and the mean RS ratio value for the 1983-2006 year classes (Table 1, Figure 1).

NEFSC research survey surface and bottom water temperature anomalies for the Mid-Atlantic Bight North (MABN; Nantucket Shoals to Hudson Canyon) and South regions (MABS; Hudson Canyon to Cape Hatteras) were obtained from the NEFSC database (http://www.nefsc.noaa.gov/epd/ocean/MainPage/ioos) following the methods developed by Mountain (2004). Seasonal temperatures anomalies were computed for the two regions for winter/spring (season 1; January-June) and fall (July-December) for both surface and bottom water temperatures (Figure 2). Fall season anomalies are forward lagged to the next calendar year for correspondence with summer flounder age-0 year class designation (because summer flounder are born during September-March, and appear in fishery and research survey catches from 9-16 months after birth, a fish spawned in fall 1990 by the 1990 SSB may not appear in fishery and catches until late fall/early winter 1991 – but it is classified as a age 0 fish even though it may be up to 15 months old, since the abundance of the year class is estimated as of January 1, 1991).

North Atlantic Oscillation (NAO) climate index monthly values were obtained from the University of East Anglia database (http://www.cru.uea.ac.uk/cru/climon/monthly) and winter (December-March) and fall (September- November) indices were computed as per Jones et al. (1997)(Figure 3). NAO indices were also forward lagged one and two years because the NAO can produce both contemporary local and time-lagged broad-scale physical changes in the climate that could influence recruitment success (Brodziak and O'Brien 2005).

### *Modeling Approach*

The works cited in the Introduction set the foundation for the hypothesis that relatively cold water temperature, or some mechanism associated with cold and/or severe weather, is correlated with poor recruitment success for summer flounder. Aspects of the current work follow the general approach of Brodziak and O'Brien (2005), who examined relationships between environmental indices and summer flounder Recruit-Spawner Anomalies (RSAs), considered a measure of summer flounder recruitment success that is independent of the size of the Spawning Stock Biomass (SSB). Brodziak and O'Brien (2005) found that the NAO2 index (NAO winter index forward lagged by two years) was a significant predictor of summer flounder RS ratios, with positive NAO anomalies (wet and mild winters) correlating with positive RSAs (high recruit survival rate). This work also follows aspects of the work of Megrey et al. (2005), by considering the absolute estimates of recruitment (VPA0) as another measure of recruitment success, which may or may not be subject to strong influence of the magnitude of SSB.

Correlation analyses among the environmental factors and RSAs and absolute estimates of recruitment (VPA0) were performed first to identify potentially significant relationships. The GAM approach to modeling (Hastie and Tibshirani 1990), suggested by Daskalov (1999), Megrey et al. (2005), and Brodziak and O'Brien (2005) as an effective tool for modeling biological responses to environmental factors, was then used to model relationships for environmental (predictive) factors initially identified by the correlation analysis as significant at the $p = 0.10$ level. The GAM approach is a nonparametric regression technique that relaxes error distribution assumptions in modeling the relationships between independent predictive variables and dependent response variables. The initial null predictive model in the GAM framework used smoothing splines with 3 degress of freedom for each predictive factor. Following the procedures suggested by Brodziak and O'Brien (2005), a stepwise model-selection process was applied to eliminate predictive factors from the model if they had a *p*-value <= 0.20, with the step repeated until only predictive factors with *p* <= 0.20 were included in the model. Finally, the time series of the environmental factors with best fitting GAM models were used in an exercise to investigate their performance as potential VPA recruitment calibration indices.

## RESULTS AND DISCUSSION

The most prominent features of the summer flounder absolute recruitment series (VPA0) are the strong year class that recruited in 1983, and the two weak year classes that recruited in 1988 and 2005 (Table 1, Figure 1). The most prominent features of the summer flounder recruit-spawner anomaly (RSA) series are the generally positive anomalies before 1996, and the uniformly negative anomalies since. The strong negative RSAs in 1988 and 2005 correspond to the weak absolute magnitude of recruitments (VPA0) in those years. The pattern of relatively low (negative) RSA since 1995 is one that would be expected for a fish stock exhibiting a Beverton-Holt (1957) asymptotic stock-recruitment relationship as that stock grows toward $SSB_{MSY}$ (Terceiro 2006b).

Visual inspection of the temperature anomaly and climate index series indicates a few instances of prominent environmental factors that correspond with the metrics of recruitment success. For example, a) the relatively high MAS_ST2 and MAS_BT2 (Mid-Atlantic South region Fall surface and bottom) temperature anomalies in 1983 correlate with the strong 1983 year class (VPA0) and positive 1983 RSA, b) the negative MAS_BT2 anomaly correlates with the weak 2005 year class and negative 2005 RSA, and c) the slightly negative MAS_ST1 anomaly in 1988 is the strongest correlate with the weak 1998 year class/negative 1988 RSA (Figure 2). For the NAO climate indices, the unlagged positive NAO_WIN climate indices in the early 1990s correlate with the positive RSAs during that period; the positive 1983 NAO_FAL index correlates with the strong 1983 year class and positive 1983 RSA (Figure 3). The lagged NAO indices likewise have a positive correspondence with positive RSAs in the early 1990s (Figures 3-4), but do not appear to correlate strongly with any of the prominent recruitment success features (i.e., 1983, 1998, or 2005 year classes or RSAs).

Several of the regional, seasonal temperature anomalies exhibit significant statistical correlation over the time series. The strongest positive correlations were between annual values of the Mid-Atlantic North region winter-spring surface (MAN_ST1) and bottom (MAN_BT1) anomalies ($r = 0.50$) and the MAN_BT1 and MAS_BT2 ($r = 0.57$) anomalies, both significant at the $p = 0.01$ level. None of the correlations between NAO indices were significant at the $p = 0.10$ level. The strongest relationships between temperature anomalies and NAO indices were negative correlations between the MAN_BT1 anomaly and NAO_WIN index ($r = -0.42$; $p = 0.03$) and the MAS_ST1 anomaly and the NAO_FAL index ($r =-0.41$; $p = 0.04$).

The strongest statistical correlations between the metrics of recruitment success and environmental factors (Table 2) were between the RSA and the NAO_WIN index ($r = 0.59$; $p < 0.01$), the RSA and the MAN_BT1 anomaly ($r = -0.43$; $p = 0.04$), the VPA0 and the MAS_BT2 anomaly ($r = 0.38$; $p = 0.08$), the VPA0 and the NAO_FAL_1 index ($r = 0.35$; $p = 0.09$), and the VPA0 and the NAO_FAL index ($r = 0.34$; $p = 0.09$). Correlations of this magnitude are of about the same statistical significance as the highest correlations between the F07_ALL absolute recruitment estimates (VPA0) and research survey VPA calibration indices (e.g., MDDNR $r = 0.53$, $p < 0.01$; CTDEP $r = 0.45$, $p = 0.03$; RIDFW $r = 0.35$, $p = 0.09$; VIMS $r = 0.34$, $p = 0.09$; NEFSC $r = 0.33$, $p = 0.10$; SDWG 2007).

Based on the combined results of the correlation analyses, the initial GAMs related either absolute recruitment (VPA0) or recruitment survival rate (RSA) to the MAN_BT1 and MAS_BT2 temperature anomalies and the NAO_FAL, NAO_FAL_1, and NAO_WIN climate indices. The final GAM relating RSA to the predictive factors included only the NAO_WIN index (i.e., $p <= 0.20$). The estimated effect of the NAO_WIN index (predictive factor; x-axis) on summer flounder recruit-spawner anomaly (RSA; y-axis) is presented in Table 3 and Figure 4 (GAM 1). Comparison of the observed NAO_WIN index and estimated RSA indicates a positive and fairly strong predicative relationship, in line with the results of the correlation analysis (Figure 4, bottom panel).

The final GAM relating VPA0 to the predictive environmental factors included the MAS_BT2 temperature anomaly and the NAO_WIN and NAO_FAL_1 climate indices (i.e., $p <= 0.20$). Note that the NAO_WIN index emerged as a significant predictive factor for VPA0 in the GAM model, even though the correlation of this factor with VPA0 was not initially identified as significant ($r = 0.08$, $p = 0.72$). Also, the NAO_FAL index failed to be retained in the GAM (i.e., $p > 0.20$), even though NAO_FAL was significantly correlated with VPA0 ($r = 0.34$, $p = 0.09$). The estimated combined effects of these predictive factors (x-axis) on the absolute magnitude of summer flounder recruitment (VPA0; y-axis) are presented in Table 3 and in the first panel of Figure 5 (GAM2). The combined predictive fit characterizes the strong 1983 year class and the weak 1988 and 2005 year classes relatively well. However, the subsequent panels of Figure 5 demonstrate that the relationship between VPA0 and the individual environmental factors is relatively weak as evidenced by the wide confidence intervals of the predicted VPA0.

The time series of the predictive factors from the GAM2 model (NAO_WIN, NAO_FAL_1 and MAS_BT2) were included as indices of age 0 recruitment (VPA0) in three derivative configurations of the summer flounder ADAPT VPA F07_ALL run to investigate their performance as potential calibration indices (i.e., as proxy indices of recruitment). Summary diagnostics for runs F07_ALL (all available survey indices included), F07_ALL_GAM2 (same as F07_ALL, but including environmental factors MAS_BT2, NAO_WIN, and NAO_FAL_1 as recruitment calibration indices), F07_GAM2_ONLY (including only the environmental factors MAS_BT2, NAO_WIN, and NAO_FAL_1 as recruitment calibration indices), and F07_MD0_MAS_BT2 (including only the MD DNR age 0 survey index [the best correlated trawl survey index with estimates from run F07_ALL] and the environmental factor MAS_BT2 [the best correlated environmental factor with estimates from run F07_ALL] as recruitment calibration indices) are presented in Table 4.

The inclusion of the environmental factors as recruitment calibration indices degraded the overall fit of the VPA, as diagnosed by increases in the magnitude of the MSR for the alternative runs (MSR = Mean Squared Residual = total sum of squared residuals divided by degrees of freedom). Estimates of the strong 1983 and weak 1988 year classes, estimated in the converged (stabilized) part of the VPA, were unchanged by the inclusion of the environmental factors. Estimates of the weak 2005 year class increased by up to 30% in the alternative runs; estimates of the average 2006 year class increased by up to 13% in the alternative runs.

In summary, the results of this work suggest there are relationships between commonly measured environmental factors such as regional water temperature anomalies and larger scale climate indices and metrics of summer flounder recruitment success. However, these relationships are no stronger than those currently modeled using research survey indices of abundance. Inclusion of these environmental factors in alternative configurations of the current summer flounder assessment VPA does not significantly change the pattern of the recruitment time series or increase the precision of current recruitment estimates. The inclusion of the environmental factors in other summer flounder population dynamics models would not be expected to improve the reliability of forecasts or biological reference points.

Finally, it should be noted that a value of the NAO_WIN index for the 2006-2007 winter season (Dec. 2006-Mar 2007: NAO_WIN = 1.83) is available to use in the GAM1 model to predict the RSA for 2007 = 0.78; given the estimate of the SSB that will produce the 2007 year class (44.451 kmt), this predicted RSA equates to predicted recruitment in 2007 of 34.7 million fish – about 2% below the F07_ALL VPA time series average of 35.4 million fish. Since the fall NAO and temperature anomaly data are lagged forward, environmental factor data are also available to fit the GAM2 model to predict the 2007 VPA0 (NAO_FAL_1 = -0.43; MAS_BT2 = 1.205). The GAM2 model predicted 2007 value for VPA0 in 2007 is 50.4 million fish – about 42% above the F07_ALL VPA time series average of 35.4 million fish.

## REFERENCES

Able KW, Matheson RE, Morse WW, Fahay MP, Shepherd GP. 1990. Patterns of summer flounder (*Paralichthys dentatus*) early life history in the Mid-Atlantic Bight and New Jersey estuaries. Fish Bull. U.S. 88(1): 1-12.

Beverton RJH, Holt SJ. 1957. On the dynamics of exploited fish populations. Chapman and Hall. London. facsimile reprint 1993.

Brodziak J, O'Brien L. 2005. Do environmental factors affect recruits per spawner anomalies of New England groundfish? ICES Mar Sci. 62: 1394-1407.

Beentjes MP, Renwick JA. 2001. The relationship between red cod, (*Pseudophycis bachus)*, recruitment and environmental variables in New Zealand. Env Bio Fish. 61: 315-328.

Chen DG, Ware DM. 1999. A neural network model for forecasting fish stock recruitment. Can J Fish Aquat Sci. 56: 2385-2396.

Chen DG, Hargreaves NB, Ware DM, Liu Y. 2000. A fuzzy logic model with genetic algorithm for analyzing fish stock-recruitment relationships. Can J Fish Aquat Sci. 57: 1878-1887.

Chen DG. 2001. Detecting environmental regimes in fish stock-recruitment relationships by fuzzy logic. Can J Fish Aquat Sci. 58: 2139-2148.

Daskalov G. 1999. Relating fish recruitment to stock biomass and physical environment in the Black Sea using generalized additive models. Fish Res 41: 1-23.

Dreyfus-Leon M, Chen DG. 2007. Recruitment prediction with genetic algorithms with application to the Pacific herring fishery. Eco Modeling 203: 141-146.

Hastie TH, Tibshirani RJ. 1990. Generalized Additive Models. Chapman and Hall. New York.

Hoss DE, Hettler WF, Coston LC. 1974. Effects of thermal shock on larval estuarine fish ecological implications with respect to entrainment in power plant cooling systems. Pages 357-371 *in* Blaxter JHS, ed. The Early Life History of Fish. Springer-Verlag, Berlin-Heidelberg-New York.

Johns DM, Howell WH. 1980. Yolk utilization in summer flounder (*Paralichthys dentatus*) embryos and larvae reared at two temperatures. Mar Ecol Pro Ser 2: 1-8.

Johns DM, Howell WH, Klein-MacPhee G. 1981. Yolk utilization and growth to yolk-sac absorption in summer flounder (*Paralichthys dentatus*) larvae at constant and cyclic temperatures. Mar Bio 63: 301-308.

Jones PD, Jonsson T, Wheeler D. 1997. Extension to the North Atlantic Oscillation using early pressure observations from Gibraltar and South-West Iceland. Int J Climat. 17: 1443-1450.

Keefe M, Able KW. 1992. Habitat quality in New Jersey estuaries: habitat-specific growth rates of juvenile summer flounder in vegetated habitats. Fin Rep NJ Dep EPE.

Malloy KD, Targett TE. 1991. Feeding, growth and survival of juvenile summer flounder (*Paralichthys dentatus*): experimental analysis of the effects of temperature and salinity. Mar Eco Prog Ser 72(3): 213-223.

Malloy KD, Targett TE. 1994. Effects of ration limitation and low temperature on growth, biochemical condition and survival of juvenile summer flounder from two Atlantic coast nurseries. Trans Am Fish Soc 123(3): 182-193.

Megrey BA, Lee Y, Macklin SA. 2005. Comparative analysis of statistical tools to identify recruitment-environment relationships and forecast recruitment strength. ICES J Mar Sci. 62: 1256-1269.

Mountain DG. 2004. Variability of the water properties in NAFO Subsreas 5 and 6 during the 1990s. J NW Atl Fish Sci. 34: 101-110.

O'Brien L, Burnett J, Mayo RK. 1993. Maturation of nineteen species of finfish off the northeast coast of the Untied States, 1985-1990. NOAA Technical Report NMFS 113. US DOC Springfield, Virginia.

Smith WG. 1973. The distribution of summer flounder, *Paralichthys dentatus,* eggs and larvae on the continental shelf between Cape Cod and Cape Lookout 1956-1966. Fish Bull. U.S. 71(2): 527-548.

Southern Demersal Working Group (SDWG) 2007. Summer flounder stock assessment summary for 2007. 15 p.

Szedlmayer ST, Able KW, Rountree RA. 1992. Growth and temperature-induced mortality of young-of-the-year summer flounder (*Paralichthys dentatus*) in southern New Jersey. Copeia 1:120-128.

Terceiro M. 2006a. Stock assessment of summer flounder for 2006. NEFSC Ref Doc. 06-17. 119 p.

Terceiro M. 2006b. Summer flounder assessment and biological reference point update for 2006. http://www.nefsc.noaa.gov/nefsc/saw/2006FlukeReview/BRP2006_Review.pdf

Williams EH, Quinn TJ II. 2000. Pacific herring, *Clupea pallasi*, recruitment in the Bering Sea and north-east Pacific Ocean, II: relationships to environmental variables and implications for forecasting. Fish Ocean 9:4: 300-315.

Table 1. Summer flounder Spawning Stock Biomass (SSB; 000s metric tons), recruitment at age 0 (VPA0; million of fish), Recruit-Spawner ratios (RS), and Recruit-Spawner Anomalies (RSA), from the SDWG (2007) F07_ALL VPA run configuration. Note that estimates differ from the SDWG (2007) F07_1 VPA run used for official status determination.

| Year | SSB | VPA0 | RS | RSA |
|---|---|---|---|---|
| 1983 | 22.582 | 80.3 | 3.556 | 1.552 |
| 1984 | 24.435 | 48.4 | 1.981 | -0.025 |
| 1985 | 21.870 | 48.6 | 2.222 | 0.216 |
| 1986 | 19.853 | 53.4 | 2.690 | 0.687 |
| 1987 | 18.391 | 43.9 | 2.387 | 0.383 |
| 1988 | 19.082 | 13.0 | 0.681 | -1.322 |
| 1989 | 10.883 | 27.3 | 2.508 | 0.501 |
| 1990 | 7.025 | 30.4 | 4.327 | 2.316 |
| 1991 | 9.940 | 28.7 | 2.887 | 0.881 |
| 1992 | 8.743 | 32.3 | 3.694 | 1.691 |
| 1993 | 9.905 | 33.2 | 3.352 | 1.343 |
| 1994 | 12.287 | 35.3 | 2.873 | 0.864 |
| 1995 | 15.099 | 38.7 | 2.563 | 0.557 |
| 1996 | 18.972 | 28.3 | 1.492 | -0.515 |
| 1997 | 20.065 | 28.0 | 1.395 | -0.560 |
| 1998 | 20.381 | 31.3 | 1.536 | -0.469 |
| 1999 | 22.141 | 30.0 | 1.355 | -0.650 |
| 2000 | 22.491 | 33.7 | 1.498 | -0.505 |
| 2001 | 25.940 | 36.8 | 1.419 | -0.585 |
| 2002 | 32.145 | 39.6 | 1.232 | -0.774 |
| 2003 | 38.879 | 28.0 | 0.720 | -1.284 |
| 2004 | 45.873 | 36.1 | 0.787 | -1.218 |
| 2005 | 46.451 | 12.2 | 0.263 | -1.742 |
| 2006 | 47.956 | 32.2 | 0.671 | -1.334 |
| Mean | 22.558 | 35.4 | 2.004 | 0.000 |

Table 2. Significant correlations of environmental factors with metrics of summer flounder recruitment success. See text for meaning of acronyms; Spearman *r* is a correlation coefficient; *p* level indicates probability that correlation (*r*) is due to random chance.

| Recruitment metric | Environmental Factor | Spearman *r* | *p* |
|---|---|---|---|
| RSA (Recruit-Spawner Anomaly) | NAO_WIN | 0.59 | <0.01 |
| | MAN_BT1 | -0.43 | 0.04 |
| VPA0 (age 0 stock size) | NAO_FAL | 0.34 | 0.09 |
| | NAO_FAL_1 | 0.35 | 0.09 |
| | MAS_BT2 | 0.38 | 0.08 |

Table 3. Summary General Additive Model (GAM) results for relationship between environmental factors and summer flounder recruitment metrics with significant linear model component fits ($p < 0.20$).

***Regression model using NAO_WIN and RSA***

**Parameter Estimates**

| Parameter | Parameter Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | -0.36404 | 0.21224 | -1.72 | 0.1018 |
| Linear(NAO_WIN) | 0.52255 | 0.15453 | 3.38 | 0.0030 |

**Fit Summary for Smoothing Components**

| Component | Smoothing Parameter | DF | GCV | Num Unique Obs |
|---|---|---|---|---|
| Spline(NAO_WIN) | 0.990281 | 3.000000 | 0.959966 | 24 |

***Regression model using NAO_WIN, NAO_FAL_1, MAS_BT2 and VPA0***

**Parameter Estimates**

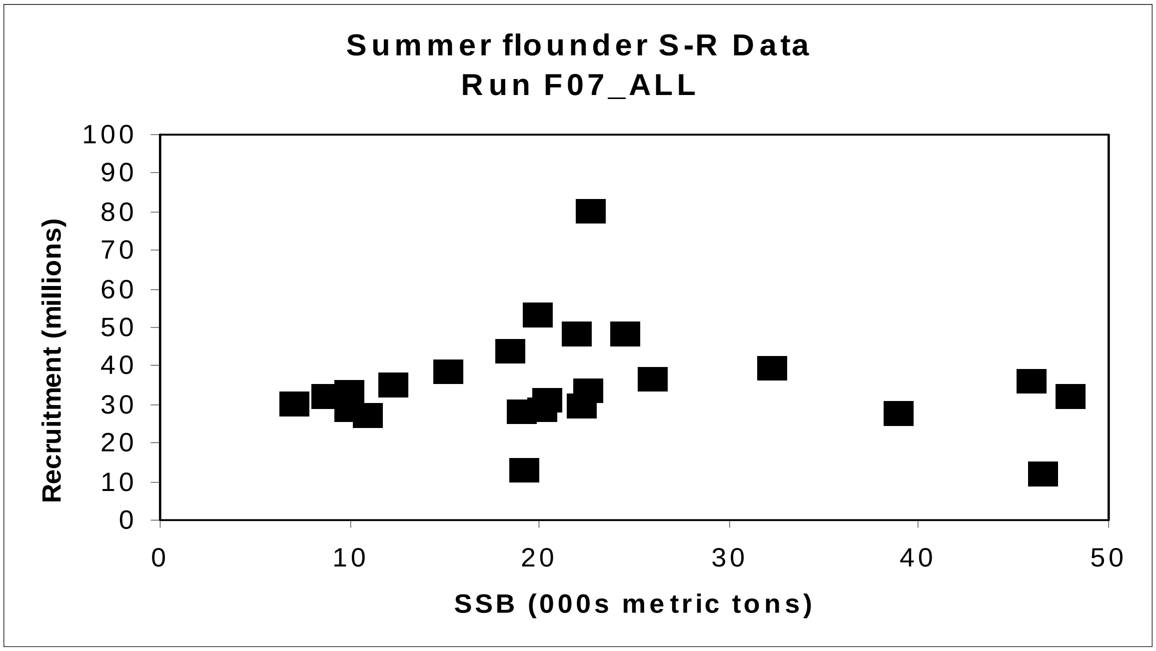
| Parameter | Parameter Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 32.30060 | 3.15681 | 10.23 | <.0001 |
| Linear(NAO_WIN) | 5.56656 | 1.91828 | 2.90 | 0.0124 |
| Linear(NAO_FAL_1) | 4.57488 | 2.82983 | 1.62 | 0.1299 |
| Linear(MAS_BT2) | 4.02419 | 1.87632 | 2.14 | 0.0514 |

**Fit Summary for Smoothing Components**

| Component | Smoothing Parameter | DF | GCV | Num Unique Obs |
|---|---|---|---|---|
| Spline(NAO_WIN) | 0.988675 | 3.000000 | 99.148877 | 23 |
| Spline(NAO_FAL_1) | 0.978174 | 3.000000 | 99.276403 | 19 |
| Spline(MAS_BT2) | 0.989486 | 3.000000 | 99.148669 | 23 |

Table 4. Summary diagnostics for summer flounder ADAPT VPA runs F07_ALL (all available survey indices included), F07_ALL_GAM2 (same as F07_ALL, but including environmental factors MAS_BT2, NAO_WIN, and NAO_FAL_1 as age 0 calibration indices), F07_GAM2_ONLY (including only the environmental factors MAS_BT2, NAO_WIN, and NAO_FAL_1 as age 0 calibration indices), and F07_MD0_MAS_BT2 (including only the MD DNR age 0 survey index and the environmental factor MAS_BT2 as age 0 calibration indices). MSR = Mean Squared Residual. Age 0 (recruitment) stock sizes (VPA0) in thousands of fish.

| Run ID | MSR | Age 0 1983 N | Age 0 1988 N | Age 0 2005 N | Age 0 2006 N |
|---|---|---|---|---|---|
| F07_ALL | 0.846 | 80,323 | 13,033 | 12,209 | 33,167 |
| F07_ALL_GAM2 | 0.943 | 80,323 | 13,033 | 13,432 | 34,419 |
| F07_GAM2_ONLY | 1.017 | 80,323 | 13,033 | 15,912 | 35,185 |
| F07_MD0_MAS_BT2 | 0.924 | 80,323 | 13,033 | 13,479 | 36,225 |



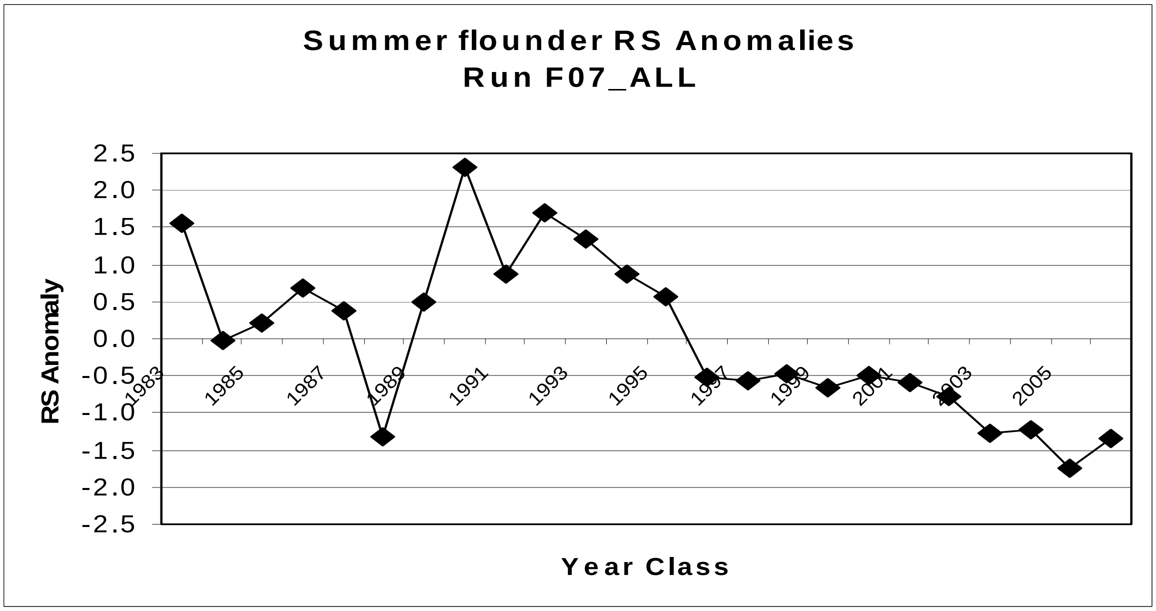


Figure 1. Summer flounder Spawning Stock Biomass (SSB; 000s metric tons) and Recruitment (Age 0 fish; millions) estimates (top) and Recruit-Spawner Anomalies (RSA; bottom) from the SDWG (2007) F07_ALL VPA run for the 1983-2006 year classes. Note that estimates differ from the SDWG (2007) F07_1 VPA run used for official status determination.

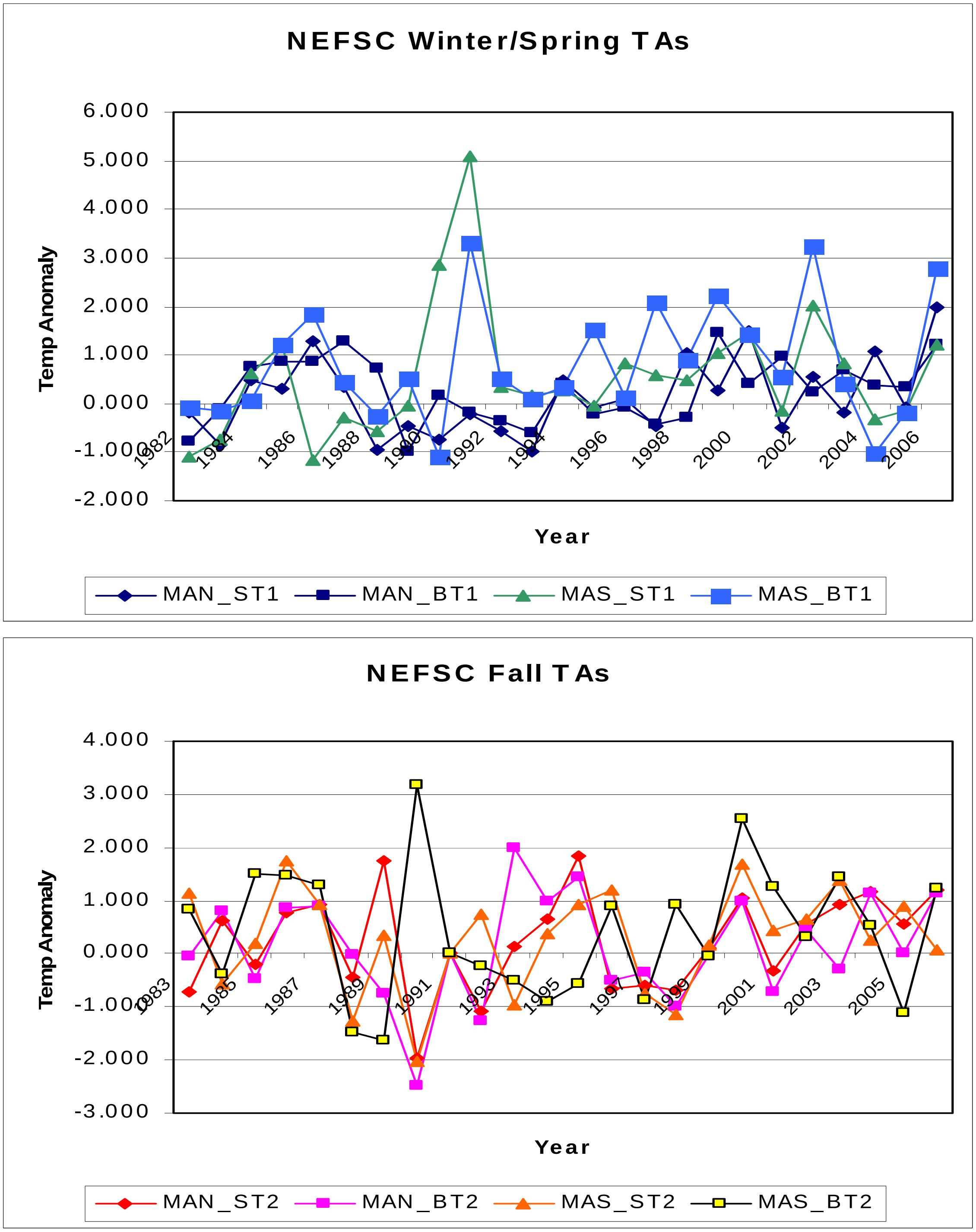
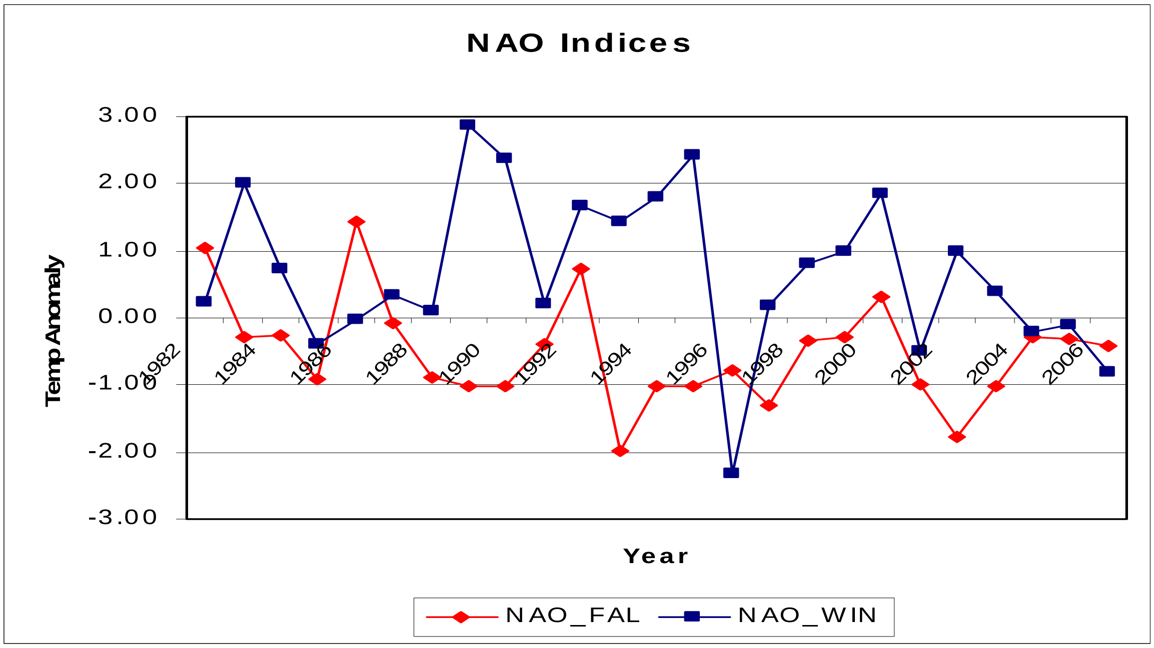


Figure 2. NEFSC survey Temperature Anomalies (TAs). Fall season anomalies are forward lagged to the next calendar year for correspondence with year class designation. MAN = Mid-Atlantic Bight North, MAS = Mid-Atlantic Bight South); ST = Surface Temperature, BT = Bottom Temperature; 1 = Winter/Spring= January-June, 2 = Fall= July-December.



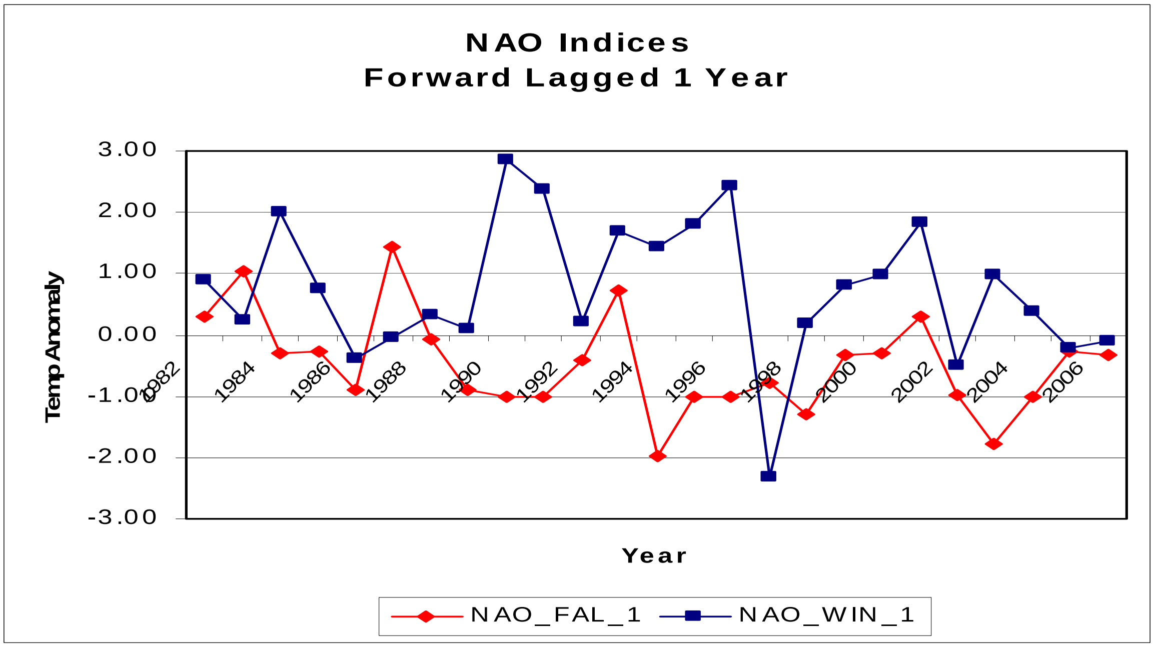


Figure 3. North Atlantic Oscillation (NAO) climate indices. Winter indices (NAO_WIN) are December-March. Fall (NAO_FAL) indices are September-November. Indices are also forward lagged one (_1) and two (_2) years because the NAO can produce both contemporary local and time-lagged, broad-scale physical changes.

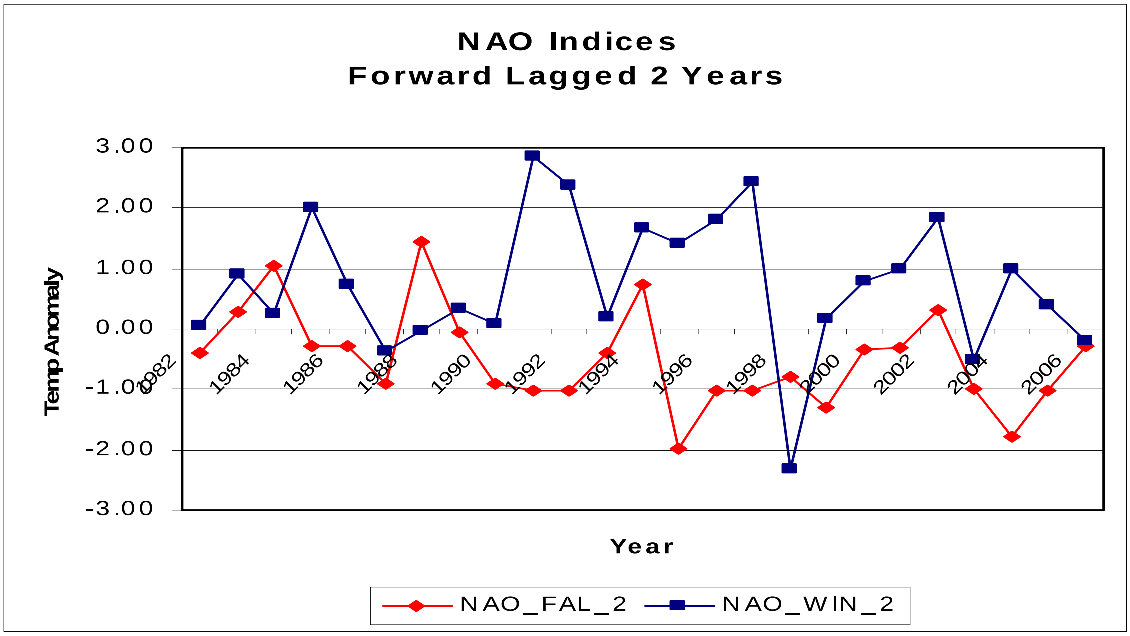
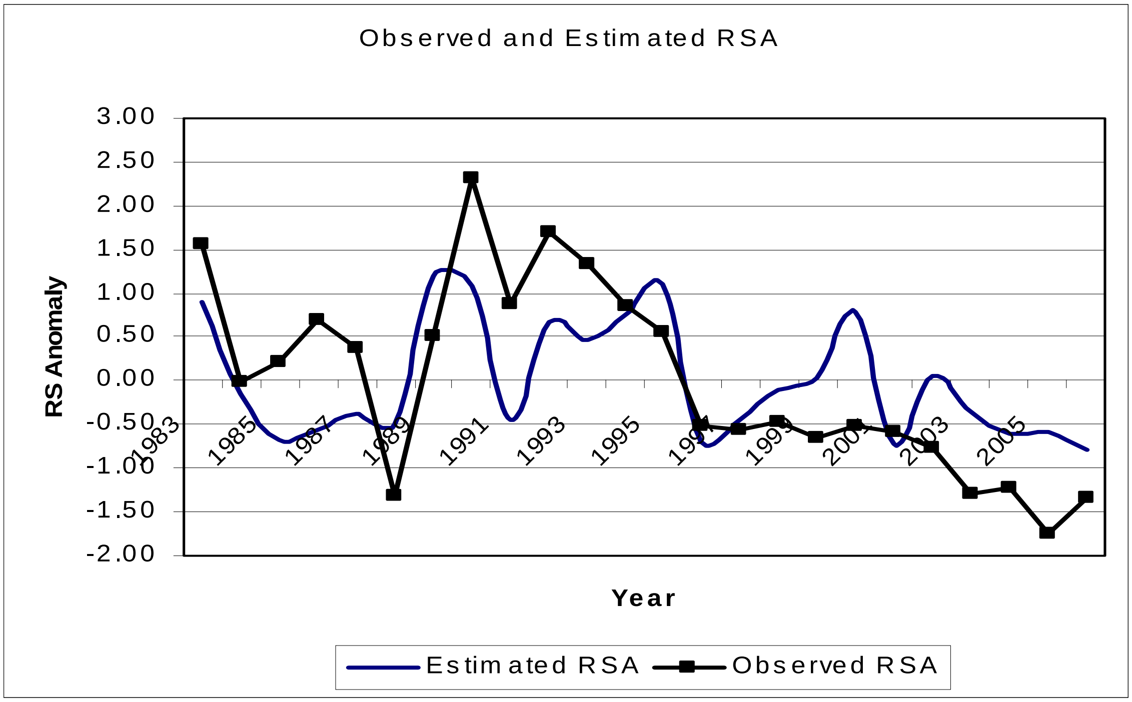


Figure 3 Continued.



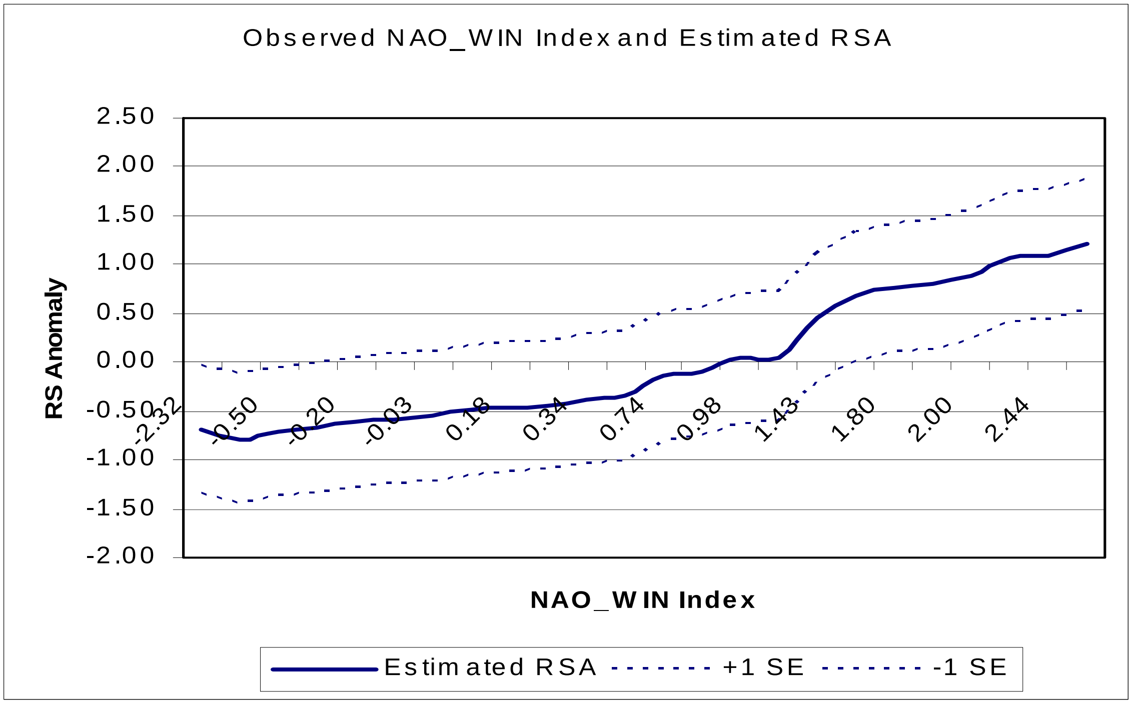


Figure 4. Results from the GAM1 regression and smoothing model of NAO_WIN climate index and Recruit-Spawner Anomaly (RSA).

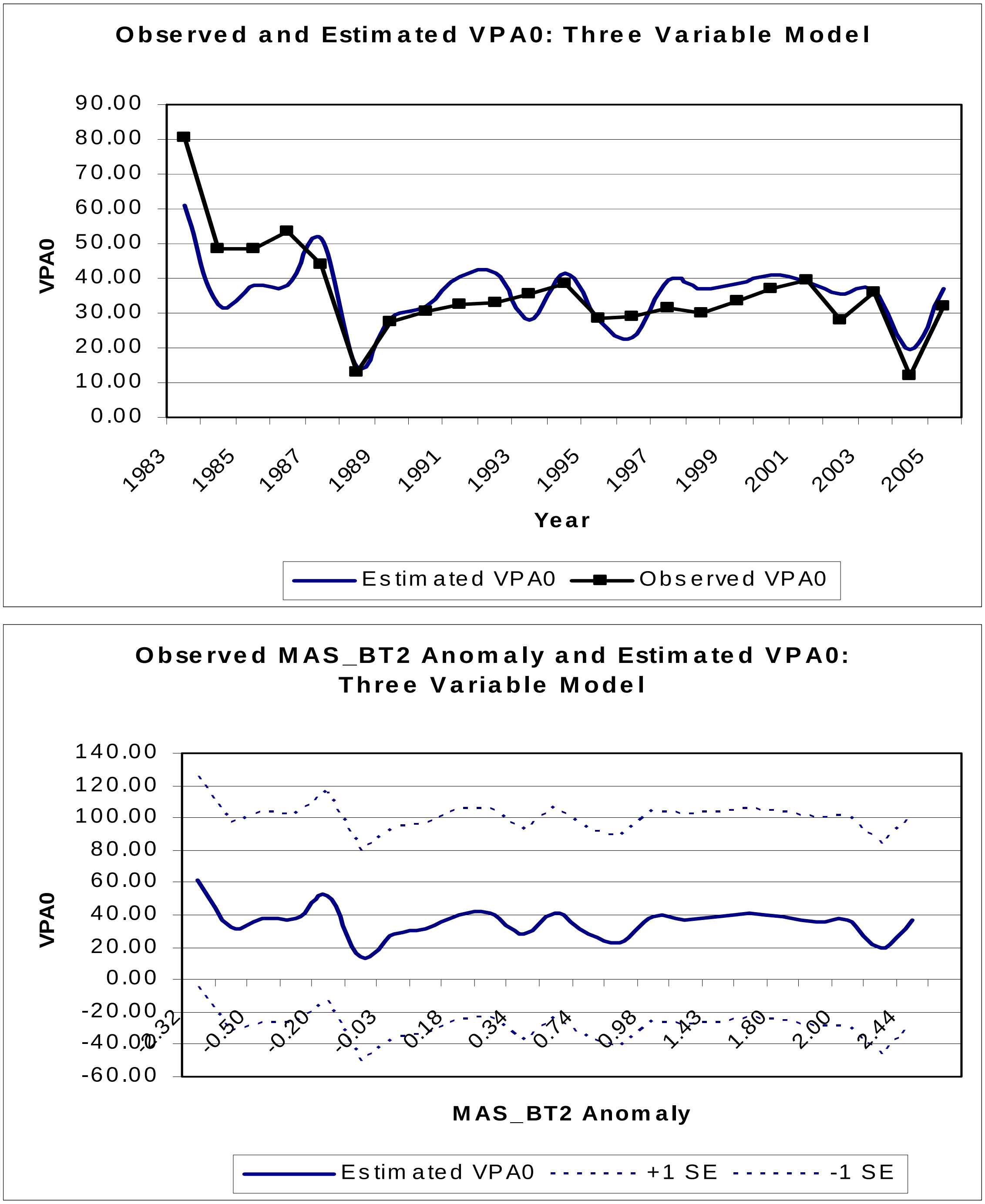


Figure 5. Results from the GAM2 regression and smoothing model of NAO_WIN and NAO_FAL_1 climate indices and MAS_BT2 temperature anomaly and Age 0 recruitment (VPA0).

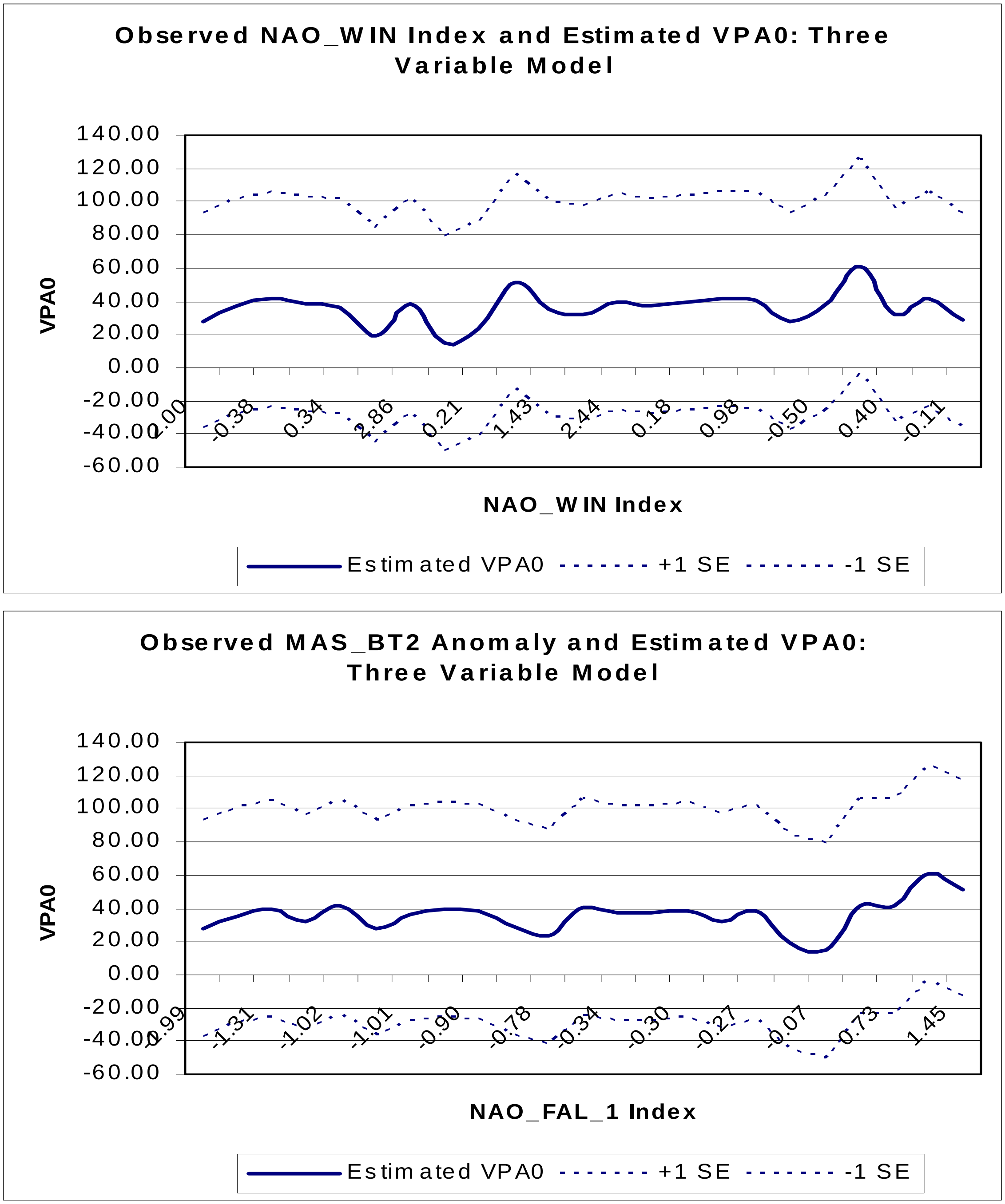


Figure 5 continued.

### SAW 47 Working Paper 12 (TOR 6) – Wavelet Analysis

# Wavelet Analysis of Trends in Summer Flounder YOY and Spawner-Recruit Relationships

by Eric Powell

## Introduction

Two climatic signals are most significant in affecting oceanographic and estuarine processes in the Mid-Atlantic Bight, the North Atlantic Oscillation (NAO) and the Pacific North American (PNA). The NAO is closely related to the Arctic Oscillation (AO) and primarily affects temperature. The PNA has a well-described teleconnection with the El Niño-Southern Oscillation (ENSO) and is dominantly an effector of precipitation and, thus, freshwater inflow, in the northeast region. The NAO has a well-described 8-year cycle and indications of a 4-yr periodicity that are superimposed on longer-term trends. These periodicities are known to profoundly effect estuarine oyster populations, including recruitment and mortality.

## Methods

*Meteorological Data Sets*

Monthly values for the NAO and PNA indices were obtained from the National Weather Service Climate Prediction Center [1]. Both are obtained from a rotated principal component analysis using the monthly standardized 500-mb height anomalies obtained from the CDAS in the analysis region 20° N-90° N. Details are provided at the NOAA web site.

Analytical Approach

The time series technique of wavelet analysis was used. Application of this technique to oyster populations is described in Soniat et al. (2006), who reference a wide range of other applications of this technique. Wavelet analysis resolves localized variations in the strength of a signal (i.e., the wave) within a time series. With this approach, the original time series is decomposed into a time-frequency space, which allows the dominant components (i.e., the wavelets) that make up the wave to be identified. Soniat et al (2006) provide references to source the mathematical details of the technique. Earlier analyses by our group have evaluated the use of a number of mother wavelets (e.g., Paul, Morlet). The Morlet wavelets have good frequency resolution, but smear the dominant signals in the time domain. The Paul wavelets provide good time resolution, but smear the signals in the frequency domain. Comparison of the two show that, for applications of the type that follow, the Morlet wavelet provides adequate time resolution and superior frequency resolution over the results obtained from the Paul wavelet. As a consequence, the Morlet wavelet is used here.

---

[1] www.cpc.ncep.noaa.gov/products/precip/CWlink

*Fisheries data*

The fisheries data used are the spawning stock biomass (SSB) and recruitment estimates (VPA0) for summer flounder obtained as described by Terceiro[2].

## Results

Four wavelet analyses are reported as representative of a number of different analyses. Each is a cross-wavelet analysis, equivalent to a cross-correlational analysis, comparing either the NAO or PNA to either the VPA0 or VPA0/SSB (labeled `SR' on the plots that follow) index.

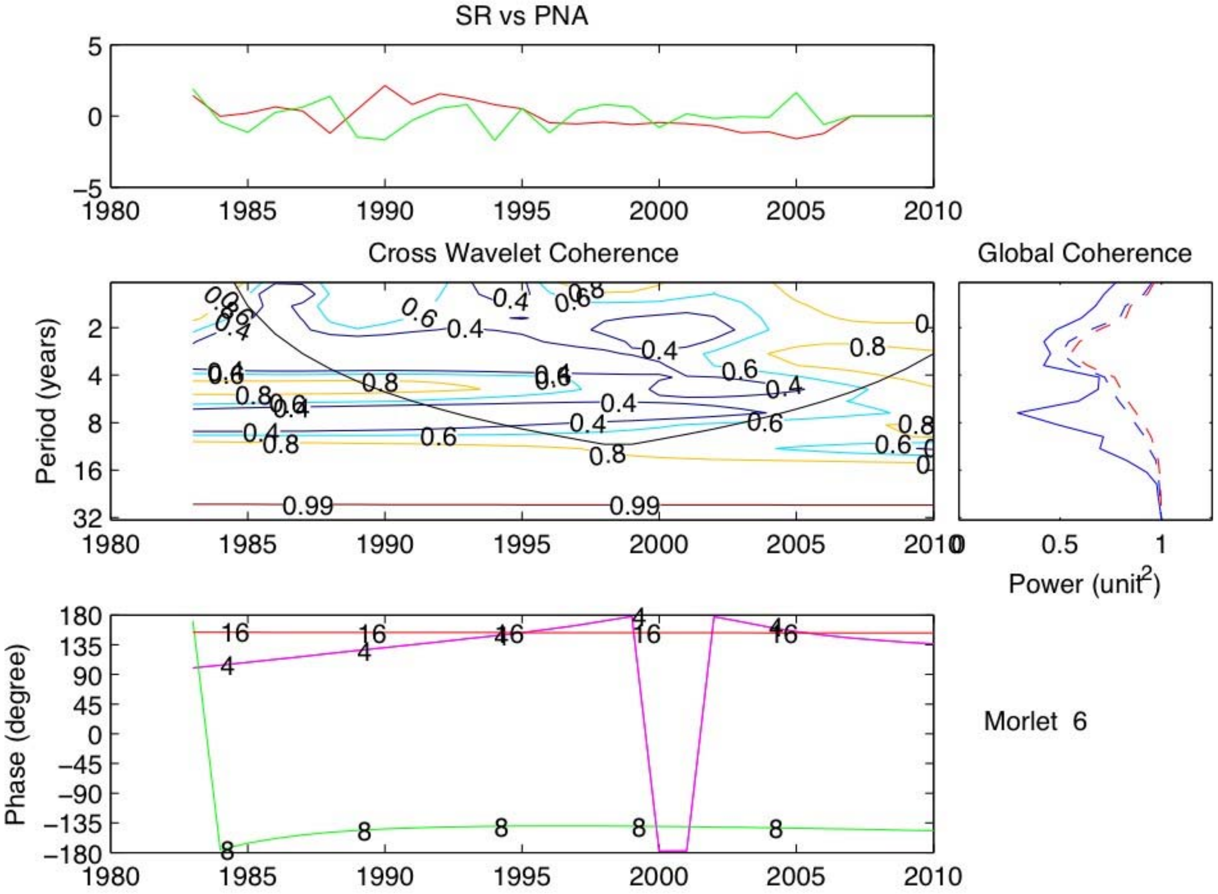


**Figure 1.** Cross-wavelet analysis between the VPA0/SSB (spawner-recruit) index and the PNA (Pacific North American) index.

Figure 1 shows the cross-wavelet analysis between the spawner-recruit index and the PNA. The top graph reports the data time series standardized to a mean of zero. The middle righthand graph labeled `global coherence' reports the significance of periodicities from <1 to >16 years. The dashed lines on this graph identify the significance at the $\alpha = 0.10$ (left dashed line) and $\alpha = 0.05$ (right dashed line) levels. The time series is 24 years long. A rule-of-thumb is

---

[2] Working Paper: Modeling environmental factors and summer flounder recruitment success.

that no periodicity can be safely identified with a period that exceeds half the time series length, so that results exceeding 12 years should be ignored. In the case of the PNA and the spawner-recruit relationship, no significant periodic interaction is found. Other analyses, not figured here, also failed to find any relationship with the PNA and recruitment (VPA0).

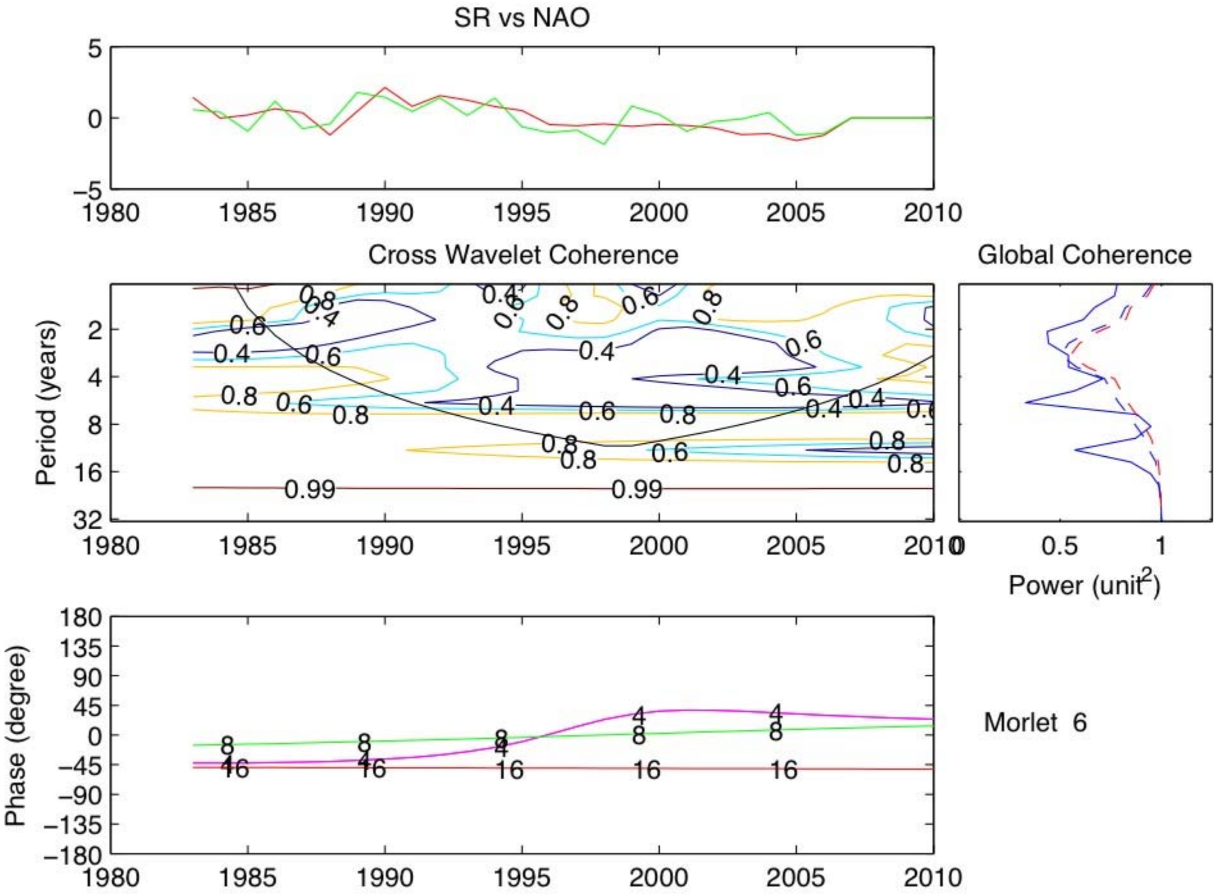


**Figure 2.** Cross-wavelet analysis between the VPA0/SSB (spawner-recruit) index and the NAO (North American Oscillation) Index.

Figure 2 shows results of the cross-wavelet analysis for the spawner-recruit index and the NAO. The analysis shows two significant coherences, at 4 years and 8 years (middle, right plot labeled `global coherence'). These same two periodicities are significant in other species we have examined such as oysters. The lower plot shows the phase relationships, with the first variable leading the second. Thus, the 8-year periodicity has a phase of near 0. Highs in NAO and the spawner-recruit index more or less coincide. The 4-yr periodicity shows a strong shift in phase between 1995 and 2000. Prior to 1995, the phase was –45°. That is, NAO led the spawner-recruit relationship by
4 x ( 45° / 360 ° ) = 0.5 yr. After 2000, the two periods were nearly synchronous.

Figure 3 shows the results of cross-wavelet analysis between the VPA0 index and NAO. The 8-year signal is significant and the 4-yr signal barely so. The phase shift in the 4-year signal is dramatic.

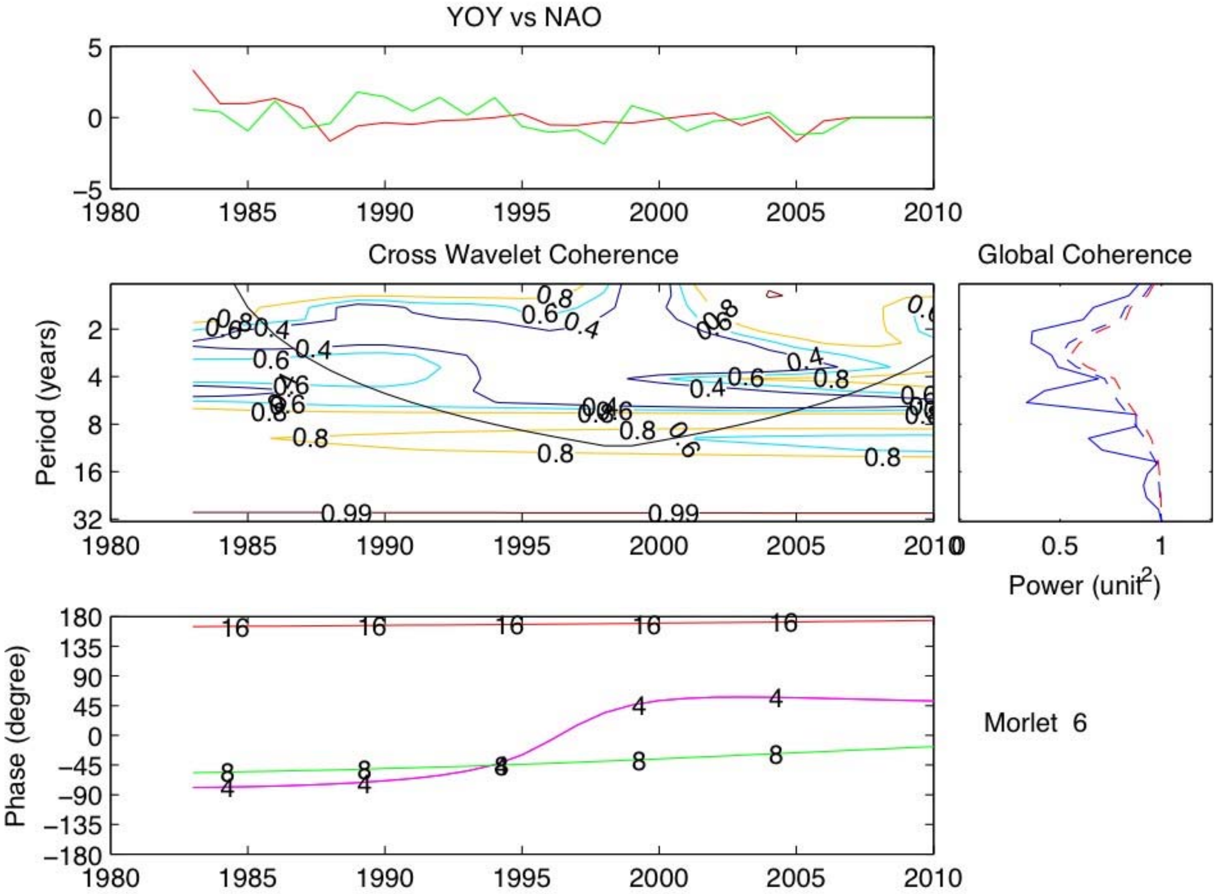


**Figure 3**. Cross-wavelet analysis between the VPA0 index and the NAO (North American Oscillation) Index.

The spawner-recruit index has a long-term downward trend that might affect the wavelet analysis. A final analysis was conducted with this trend in the spawner-recruit relationship removed prior to analysis. Figure 4 shows that the 8-year periodicity remains strongly significant. The 4-year periodicity is no longer significant, although the phase shift remains apparent.

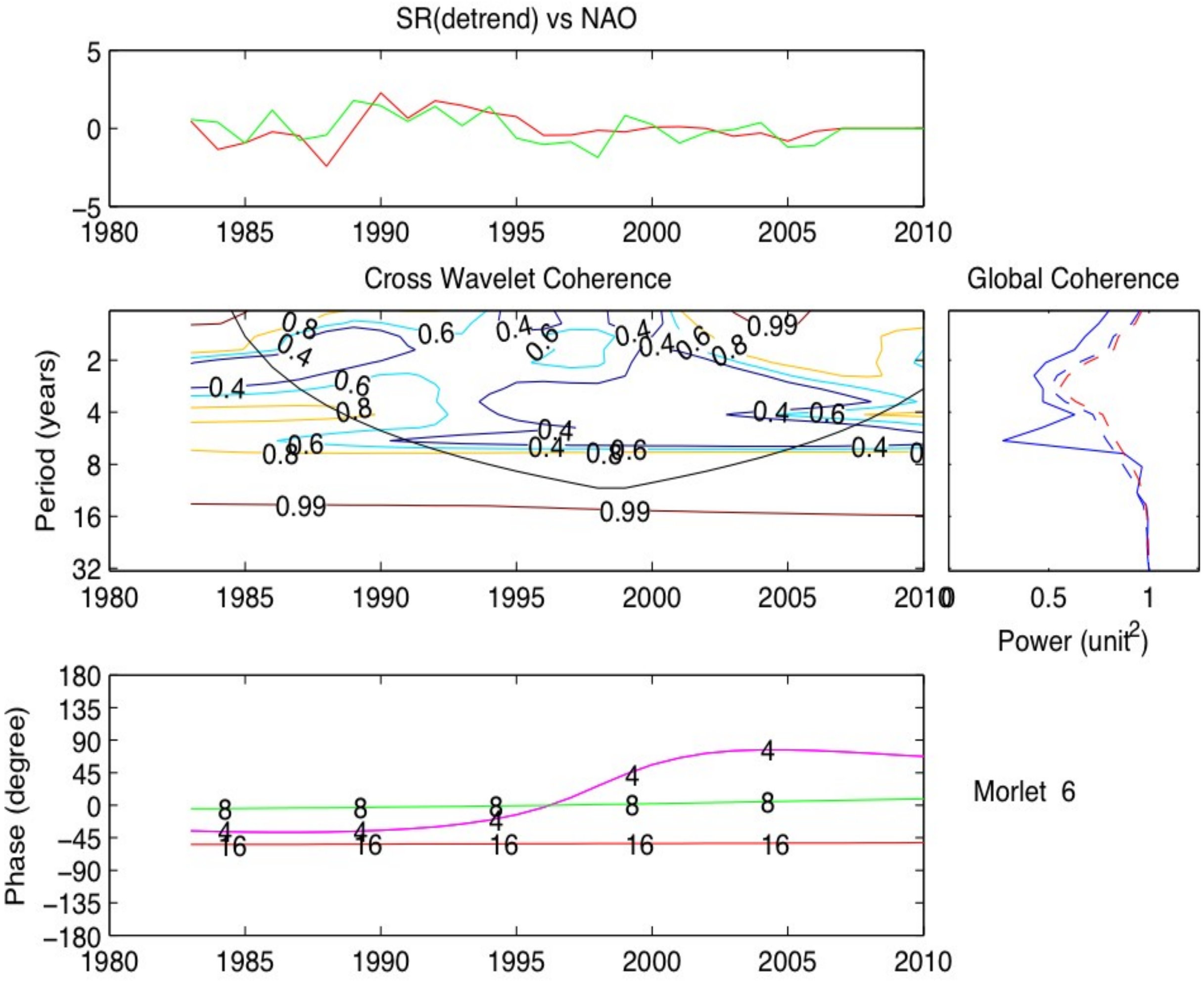


**Figure 4.** Cross-wavelet analysis between the VPA0/SSB index and the NAO (North American Oscillation) Index, with the spawner-recruit relationship de-trended prior to analysis.

## Conclusions

No evidence exists for a relationship between the PNA and summer flounder recruitment. On the other hand, a relationship between the NAO and summer flounder recruitment is strongly supported. The 8-year periodicity, the dominant periodicity in the NAO, is identified as significantly correlated with an 8-year periodicity in the recruitment indices in all analyses. The significance level consistently exceeds α = 0.05. No substantive phase shift occurs. The two periodicities are in near-synchrony so that high NAO and high recruitment indices occur more or less simultaneously.

In most analyses, a 4-year periodicity also occurs, although sometimes at a weaker level of significance. This interaction is consistently associated with a phase shift between 1995 and 2000. Such phase shifts are frequently associated with substantive long-term changes in population dynamics. However, this periodicity was no longer significant after the long-term trend in the spawner-recruit data was eliminated. This suggests that the interaction of the two time series was primarily associated with subsets of the time series record. A detailed examination of the coherence over the time series suggests that the 4-year periodicity was stronger pre-1995 and post-2000 and that the phase shift was coincident with a decline in the significance of this periodicity during the intervening years.

The NAO is consistently associated with temperature shifts in the North Atlantic. The present analysis suggest that some portion of the variability in summer flounder recruitment since 1982 can be explained by this climate forcer and its expression in changes in the temperature regime experienced by the fish.

I have not included a long list of references. Those interested in further information on wavelet analysis are directed towards the references contained in Soniat et al. (2006) [Soniat, T.M., J.M. Klinck, E.N. Powell and E.E. Hofmann. 2006. Understanding the success and failure of oyster populations: Climatic cycles and *Perkinsus marinus. J. Shellfish Res.* 25:83-93]. A recent review of the NAO/AO that provides access to this literature is Cohen and Barlow (2005) [Cohen, J. and M. Barlow. 2005. The NAO, the AO, and global warming: how closely related? *J. Climate* 18:2298-4513].