Re-evaluating the effect of wind on recruitment in Gulf of Maine Atlantic Cod (*Gadus morhua*) using an environmentally-explicit stock recruitment model

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Abstract

A previous study documented a correlation between Atlantic Cod (*Gadus morhua*) recruitment in the Gulf of Maine and an annual index of the north component of May winds. This correlation was supported by modeling studies that indicated unusually strong recruitment of Gulf of Maine Atlantic Cod results from high retention of spring-spawned larvae in years when winds were predominately out of the north, which favor downwelling. We re-evaluated this relationship using updated recruitment estimates and found that the correlation decreased between recruitment and wind. The original relationship was largely driven by two recruitment estimates, one of which (2005 year class) was highly uncertain because it was near the terminal year of the assessment. With additional data, the updated assessment estimated lower recruitment for the 2005 year class, which consequently lowered the correlation between recruitment and wind. We then investigated whether an environmentally-explicit stock recruit function that incorporated an annual wind index was supported by either the original or updated assessment output. Although incorporation of the annual wind index produced a better fitting model, the uncertainty in the estimated parameters and the implied unexploited conditions were not appropriate for providing management advice. These results suggest the need for caution in the development of environmentally-explicit stock recruitment relationships, in particular when basing relationships and hypotheses on recruitment estimates from the terminal years of stock assessment models. More broadly, this study highlights a number of sources of uncertainty that should be considered when analyses are performed on the output of stock assessment models.

Introduction

There are a range of approaches to include environmental and ecosystem information in stock assessments from extended single species models (e.g., environmentally-explicit stock-recruitment models) to highly complex ecosystem models (Townsend et al. 2008, Stock et al. 2011). Despite the relative simplicity of environmentally-explicit single-species models, there are still relatively few examples of their use in stock assessments. Myers (1998) conducted a meta-analysis and found that only a few environment-recruitment correlations held up when re-tested with new data. Further, Myers (1998) cited only 1 of 42 studies where the environment-recruitment relationship was used to modify management advice (Pacific Sardine) (Jacobson and MacCall 1995) and this relationship has since been scrutinized (Jacobson and McClatchie 2013). In a review of modeling studies that link environmental variability to fishery population dynamics, Keyl and Wolff (2008) identified seven potential causes for "breaking relationships" between the environment and population dynamics: non-linearity, multi-dimensionality, direct and indirect effects, temporal lags, spatial considerations, effect of population structure, and spurious regressions. In all but the last cause, the environment-population link is real and masked by other factors. In the case of spurious regressions, the environment-population link is not real and is an artifact of limited sample size or auto-correlated time series (Pyper and Peterman 1998, Granger et al. 2001). Owing to the well-documented occurrence of "breaking relationships", before environment-recruitment relationships are used in stock assessment, they should have a mechanistic basis and be supported by hypothesis testing and re-testing of the relationship with cross-validation and new data (Myers 1998, Francis 2006, Keyl and Wolff 2008).

Churchill et al. (2011) proposed that recruitment of Gulf of Maine Atlantic Cod was a function of transport from spawning grounds to nursery habitats in the Gulf of Maine. The focus of the Churchill et al. (2011) hypothesis was spring spawning in the western Gulf of Maine (Figure 1), which is concentrated in the area of Ipswich Bay and near Cape Anne from April to June with peak activity in May (Howell et al. 2008). Based on the results of particle-tracking models, Churchill et al. (2011) hypothesized that during periods of northward winds (out of the south; upwelling favorable), eggs and larvae tend to be flushed out of the western Gulf of Maine and away from local nursery habitats. Conversely, during periods of southward winds (out of the north; downwelling favorable), eggs and larvae tend to be advected onshore and successfully transported to juvenile habitats in the western Gulf of Maine (Howe et al. 2002). Supporting this hypothesis, Churchill et al. (2011) found that recruitment for western Gulf of Maine Atlantic Cod, as estimated in the 2008 stock assessment (Mayo et al. 2009), was higher in years with downwelling favorable winds (southward winds) during May and lower in years with upwelling favorable winds (northward winds) during May.

Our purpose was to further investigate the influence of spring winds on recruitment of Gulf of Maine Atlantic Cod (*Gadus morhua*) and to evaluate the resulting environmentally-explicit stock recruitment function for potential use in stock assessments. We re-evaluated the Churchill et al. (2011) environment-recruitment correlation using data from a more recent stock assessment conducted in 2011 (NEFSC 2012). We first refined the analyses of Churchill et al. (2011) to improve the empirical relationship between wind and Atlantic Cod recruitment estimated from the 2008 stock assessment (Mayo et al. 2009). We then repeated the analysis with updated recruitment estimates from a 2011 stock assessment. After re-evaluating the relationship between wind and recruitment, we fit environmentally-explicit stock recruit relationships that incorporated the annual wind index as a covariate. We also examined the effect of different sources of uncertainty on the estimated environmentally-explicit stock recruitment relationships.

Material and Methods

Our analyses consisted of four parts: 1) refinement of the wind index and correlation analysis with recruitment estimates from the 2008 stock assessment, 2) re-testing the correlation using recruitment estimates from the 2011 stock assessment, 3) calculation of standard and environmentally-explicit stock recruitment relationships using recruitment estimates from both the 2008 and 2011 stock assessments, and 4) analyses of uncertainty in the environmentally-explicit stock recruitment relationship including: model configuration, length of data series included, and uncertainty in input data.

Recruitment and Spawning Stock Biomass Estimates

Recruitment and spawning stock biomass estimates were derived from two stock assessment models (Table 1): one completed in 2008 (Mayo et al. 2009) and one completed in 2011 (NEFSC 2012). The stock area extends across the western two-thirds of the Gulf of Maine from the coast of Massachusetts to the U.S.-Canadian border (Figure 1). Both assessment models were based on virtual population analysis (VPA), which is a cohort-reconstruction technique that uses age-specific removals from fishing and is tuned to fishery-independent indices of abundance. The loss of fish from a cohort is an estimate of total mortality. Assuming values of natural mortality, fishing mortality can be estimated (Quinn and Deriso 1999). Recruitment was defined as the number of age-1 fish in a given year. In the 2008 VPA assessment model, commercial and recreational landings were included for 1982-2007, as well as commercial discards for years 1999-2007. In the 2011 VPA assessment model, the model inputs from the 2008 model were updated and a full time series of both commercial and recreational discards was estimated for years 1982-2010. Natural mortality was assumed to be 0.2 for all years and ages in both assessment models. Accounting for the 1 year lag between spawning and recruitment, estimates of spawning stock biomass and recruits were available for 1982-2006 and 1982-2009 for the 2008 and 2011 models, respectively (Table 1).

The VPA model used here was not the final model from the 2011 stock assessment; the final model was based on the Age-Structured Assessment Program (ASAP; Legault and Restrepo 1998). We used results from the VPA model so that any differences in analyses performed on the model output (comparing the 2008 and 2011 models) are due solely to differences is model output and are not due to application of a different model structure. The estimates of recruitment and spawning stock biomass from the final 2011 ASAP model were very similar to the 2011 VPA model estimates used here (NEFSC 2012).

Wind Data

Churchill et al. (2011) examined the relationship between recruitment and wind averaged over the month of May. Wind data were from National Data Buoy Center buoy 44013, which is in the western Gulf of Maine, east of Boston, Massachusetts (Figure 1). This location is proximate to major spawning and nursery locations of the western Gulf of Maine Atlantic Cod. The data record from this buoy starts in 1985 and extends over almost all of the assessment period, which begins in 1982 (there is no wind data to match with recruitment data in 1982, 1983, and 1984). Three refinements were made to the wind index used in the original analysis of Churchill et al (2011): a) missing data in the wind data series were statistically estimated using nearby wind measurements; b) the orientation of wind vectors leading to the maximum correlation between wind and recruitment was calculated; and c) the period over which wind data were averaged leading to the maximum wind and recruitment correlation was determined.

There are gaps in the data series from buoy 44013 that reduce the number of years for comparison between wind and recruitment estimates. Importantly, the year 2006 was missing from the analyses of Churchill et al. (2011); 2006 was the last year for which recruitment estimates were available from the 2008 VPA assessment model. To estimate missing wind data for buoy 44013, we used wind data from buoy 44029, which is located ~20 km to the north-northeast of buoy 44013 and just south of Cape Ann, Massachusetts (Figure 1). We calculated linear regressions on the daily north and east components of wind with data from buoy 44029 as the independent variable and data from buoy 44013 as the dependent variable. The regressions for both north and east wind components were highly significant ($p<0.001$) and explained much of the variance in buoy 44013 data ($r^2=0.91$ for both). Using the regression equations, we estimated the missing data from buoy 44013. The wind record for 1988 could not be estimated, as data were missing from the records of both buoys 44013 and 44029.

Re-evaluation of Wind-Recruitment Relationship

We evaluated whether the correlation between wind and recruitment could be improved by changing the period over which the winds were averaged and by altering the orientation of the wind used in the correlation. We used recruitment estimates from the 2008 VPA assessment model in these analyses. Churchill et al. (2011) tested the wind-recruitment relationship using north wind stress averaged over May. Using the estimated wind vectors, we calculated the correlation between wind and recruitment for wind orientations ranging from -90^o to $+90^o$ relative to north winds (at 10 degree intervals; positive is counterclockwise) and for winds averaged over different time periods that bracket peak spawning: 15 April – 15 May, 1 May – 31 May, and 15 May – 15 June. Southwest winds (northeastward) averaged over May were found to have the greatest negative correlation with recruitment (Figure 2). This wind direction is aligned with the dominant axes of the Maine coastline and would be expected to be most effective in driving offshore Ekman transport, which would presumably carry larvae offshore and away from local nursery habitats. This is indicated in the modeling analyses of Churchill et al. (2011) (their Figure 11).

We re-examined the wind-recruitment correlation using recruitment estimates from the 2011 VPA assessment model. A Pearson correlation coefficient was calculated between the original and revised wind index and recruitment estimated from the 2011 VPA assessment model. This represents a “re-test” of the wind-recruitment correlation described by Churchill et al. (2011) with additional and updated recruitment estimates.

Environmentally-Explicit Stock Recruitment Modeling

Beverton-Holt stock recruit models were fit to estimates of spawning stock biomass (SSB) and age-1 recruitment from both the 2008 and 2011 VPA assessment models. In addition, the two wind indices described above (north-south oriented wind and northeastward-southwestward oriented wind) were used to develop environmentally-explicit Beverton-Holt stock recruit models (Table 1). Both the standard and environmentally-explicit Beverton-Holt stock recruitment relationships (see below) were fit using AD Model Builder (http://admb-project.org/, Fournier et al. 2012) assuming a lognormal error and using maximum likelihood estimation. The models fit easily and no parameter bounds were needed.

$$R = \frac{aSSB}{(1 + bSSB)} \qquad \text{Standard Model} \qquad \text{eq. 1}$$

$$R = \frac{ae^{cW}SSB}{(1 + bSSB)} \qquad \text{Environmental Model} \qquad \text{eq. 2}$$

Recruitment (R) and spawning stock biomass (SSB) are derived from the 2008 and 2011 stock assessment, wind (W) is either the northward or northeastward wind index (Table 1). The estimated values (a, b, and c) are parameters derived through the model fitting. Years with no wind data (1982, 1983, 1984) and missing wind data (1988) were excluded from both the standard and the environmental model fitting. Akaike Information Criteria with correction for small sample size (AICc) and AICc weights were used to assess model fits (Burnham and Anderson 1998). Variance explained (r^2) was estimated from the model estimated recruitment and the observed recruitment:

$$r^2 = 1 - \frac{SS_{err}}{SS_{tot}} \qquad eq. 3$$

where SS_{err} is the sums-of-squares error term and SS_{tot} is the sums-of-squares total term from the model fit. AICc was used to compare the fit of the models and r^2 was used to estimate approximately how much variance in recruitment is explained by the different models. It should be recognized, however, that the r^2 estimate will be inflated as more independent variables are added (i.e., the inclusion of the environmental term).

From the parameter estimates of the stock recruitment relationship (a, b, and c), steepness (h), virgin recruitment (R_0), and virgin spawning stock biomass (S_0) were also calculated. These parameters are useful for comparing between stocks, and for calculating reference points used in stock assessments (Myers et al. 1999, He et al. 2006). It is straightforward to derive a translation between the present parameterization (a, b, and c) and one which uses h, R_0, and S_0

$$h = \frac{0.2 \cdot \alpha \cdot sr_0}{0.8 \cdot \beta + 0.2 \cdot \alpha \cdot sr_0} \qquad eq. 4$$

$$R_0 = \frac{\alpha \cdot sr_0 - \beta}{sr_0} \qquad eq. 5$$

$$\alpha = \frac{a}{b} \quad or \quad \alpha = \frac{a \cdot e^{c\acute{W}}}{b} \qquad eq. 6$$

$$\beta = \frac{1}{b} \qquad eq. 7$$

$$sr_{0,year} = \frac{SSB_0}{R_0} = \sum_{age=1}^{maxage} f_{age,year} \prod_{i=1}^{age-1} e^{-M_{i,year}} \qquad eq. 8$$

where sr_0 is unexploited spawning stock biomass per recruit, $f_{age,year}$ is fecundity at age in a given year, and $M_{i,year}$ is the natural mortality at age in a given year. To calculate sr_0, we take the mean of the most recent five years for each biological parameter for each assessment. This gives sr_0 values of 21.81 and 22.53 for the 2008 and 2011 VPA models. Note that in eq. 8, fecundity-at-age was calculated as the product of maturity-at-age and weight at age.

Evaluation of Uncertainty

Our approach of using assessment model output to estimate stock-recruitment models can be problematic. There are errors associated with assessment model estimates of both spawning stock biomass and recruitment that are not accounted for in the subsequent stock-recruitment models; this creates bias in the parameter estimates of stock recruitment models (Ludwig and Walters 1981, Walters and Ludwig 1981, Quinn and Deriso 1999). Depending on the degree of bias, the underlying relationship between spawning stock biomass and recruitment could be masked such that it is not apparent that a relationship even exists (Quinn and Deriso 1999).

To evaluate the effect of uncertainty in the assessment models estimates of spawning stock biomass and recruitment on the fits of the stock-recruitment functions, we used two approaches: 1) bootstrapped estimates of spawning stock biomass and recruitment from both assessment models and 2) retrospective estimates of spawning stock biomass and recruitment from both assessment models. The output of the bootstrapped and retrospective assessment models were subjected to the same methods of model fitting described above. The bootstrap model runs were used to examine the uncertainty in parameter estimates of both the standard and environmental stock recruitment models, while the retrospective model runs were used to evaluate how sensitive any estimated stock recruitment relationships were to the time series of spawning stock biomass and recruitment estimates and the time series of environmental data.

The bootstrapping approach was used for both the 2008 and 2011 VPA models on data through 2005 so that both models had the same length of time series and only differed in model configuration. For this exercise, 500 new input files were generated for the assessment models in which the residuals from each of the relative abundance index fits were standardized and randomly sampled to generate "new" relative abundance indices. Both the 2008 and the 2011 VPA assessment models were then fit to each of these new input files resulting in bootstrapped estimates of spawning stock biomass and recruitment. Because of the convergent property of the VPA, only a handful of the most recent years will show variability in the spawning stock biomass and recruitment estimates. Nevertheless, the bootstrap runs were evaluated in lieu of simply adding noise to the assessment model estimates because adding noise would have required a subjective decision about the error distribution and coefficient of variation (CV), as well as the degree of correlation in errors added to the two time series.

The retrospective analysis evaluated the effect of incorporating additional years of data on the spawning stock biomass and recruitment estimates. These estimates can vary depending on the length of the assessment time series; in particular, more recent estimates of recruitment are often highly sensitive to the amount of information on which they are based. For example, the estimate of recruitment in 2005 likely will be different if the VPA includes data through 2010 instead of through 2007. When the data are available only through 2007, then the 2005 estimate of recruitment is based on limited information from one or two data points per fisheries-independent surveys because that year-class has yet to recruit to the fishery. When data through 2010 are incorporated into the model, then there are five years of observations from surveys and several years of catch from which to estimate the cohort size. Retrospective analyses successively drop 1, 2, 3, …, n years of data from the time series in the VPA model. The estimates of spawning stock biomass and recruitment in year *y* can then be examined for each retrospective model to evaluate the stability of the spawning stock biomass and recruitment estimates, and to determine their dependence on additional years of data. These retrospective analyses were conducted by removing data back to 2000 for both the 2008 and the 2011 VPA assessment models.

Results

Test of the Wind-Recruitment Relationship

The correlation between the original northward wind index derived by Churchill et al. (2011) and recruitment from the 2008 VPA assessment model was -0.67 ($p<0.01$). The correlation between the estimated northward wind index, which included data from an additional year, was -0.62 ($p<0.01$). The correlation between the estimated and rotated northeastward wind index was -0.71 ($p<0.001$). Thus, utilizing winds with an orientation coincident with the along-shore axis, as opposed to the north-south direction, resulted in a greater degree of correlation between wind and recruitment as estimated in the 2008 VPA assessment model. When recruitment estimates from the 2011 VPA assessment model were analyzed, the correlation between wind and recruitment decreased substantially. The correlation between the northward wind stress and recruitment was -0.26 ($p>0.05$), and the correlation between the northeastward wind stress and recruitment was -0.34 ($p>0.05$).

The difference between the recruitment estimates from the two assessment models was largely caused by a decrease in the estimated recruitment of the 2005 year class from the 2008 to the 2011

VPA assessment model (Table 1). The 2008 VPA assessment model estimates of spawning stock biomass were generally higher than the 2011 VPA assessment model estimates, and the estimates of recruitment were generally lower (Figure 3). Compared to the 2011 VPA, the 2008 VPA assessment model estimated higher spawning stock biomass in 2006 and substantially higher recruitment in 2005. The differences between the results of the two assessments can primarily be attributed to changes in the underlying data (e.g., incorporation of additional sources of catch and discards) and incorporation of additional years of data (NEFSC 2012).

Environmentally-Explicit Stock Recruitment Models

2008 VPA Assessment Model - The environmental stock-recruitment models fit the spawning stock biomass and recruitment estimates better than the standard model. The environmental model formulation using northeastward winds fit better than the formulation using northward winds. Most of the AICc weight was associated with the environmental model using northeastward winds (weight = 0.77) and ~54% of the variance in recruitment was explained with northeastward wind model compared to ~0% with the standard model.

The environmental models estimated slightly lower steepness and a larger estimate of unexploited recruitment (R_0) than the standard model (Table 2). Over a range of ± 1 standard deviation of the mean wind, the environmental models predict different stock-recruitment relationships, with both a higher slope at the origin and higher recruitment with greater northward and northeastward winds (Figure 4). Comparison of the recruitment residuals from the standard model compared to wind illustrate the wind effect. As northward winds increase, recruitment decreases even after accounting for spawning stock biomass (Figure 4).

2011 VPA Assessment Model - Based on the spawning stock biomass and recruitment estimates determined from data through 2010, the environmental models fit the spawning stock biomass and recruitment data better than the standard model. However, the amount of recruitment variance explained from the 2011 model estimates is approximately half of that explained from the 2008 model estimates. The parameters of the stock-recruitment function changed as well, with the 2011 VPA assessment model estimates leading to changes in the estimates of steepness and unexploited recruitment compared with the 2008 VPA assessment model (Table 2, Figure 5). The recruitment residuals from the standard model compared to wind illustrate the wind effect. As northward winds increase, recruitment decreases even after accounting for spawning stock biomass, but the correlation is lower based on the recruitment estimates from the 2011 VPA Assessment compared to the 2008 VPA Assessment (Figure 5).

Comparison of the 2008 and 2011 VPA Assessment Models - The relationship between northeastward wind stress and recruitment developed by Churchill et al. (2011) and modified here explained ~50% of the variance in the recruitment estimates originating from the 2008 VPA assessment model (Mayo et al. 2009). With the updated 2011 VPA assessment model, recruitment of the 2005 year-class was estimated to be less and subsequently the relationship between northeastward wind stress and recruitment was less, explaining ~17% of the variance in estimated recruitment.

Most estimated parameters (a, b, S_0, and R_0) for both the Standard and Environmental model had extremely high coefficients of variation (Table 2), which indicates that the data are not sufficiently informative with respect to these parameters. Examining the fit over the implied range of recruits and spawning biomass (from the origin to unexploited conditions), it is apparent that there is no data to inform unexploited conditions (i.e., the asymptote of the curve), nor is there any data to inform the rate of descent to the origin (Figure 6). With such a limited range in estimated spawning biomass and the large range of estimated recruitment, the large CVs on estimated parameters are to be expected. Consequently, even the “best” fitting model is unreasonable.

Evaluation of Uncertainty

Model Configuration - To evaluate the effect of model configuration on the estimates of spawning stock biomass and recruitment, we used data from 1982 to 2007 in both the 2008 and 2011 VPA assessment models. As noted previously, the 2005 year-class was estimated to be unusually large in the 2008 VPA assessment model (with data from 1982 to 2007) but was estimated to be about average in the 2011 VPA assessment model (with data from 1982 to 2009). Using input data from 1982 to 2007, the 2008 and 2011 VPA assessment models produced similar estimates of recruitment in 2005 (Figure 7). This demonstrates that the decrease in the estimate of the 2005 year-class size was due primarily to considering additional years of data in the model and was not related to the set-up of the 2011 VPA assessment model. However, the 2011 VPA assessment model included updated landings and discards estimates (NMFS 2012).

Bootstrapping Input Time Series - The bootstrapping analyses revealed differences between the stock-recruitment parameters estimated from the two assessment models with input data from 1982-2005; the b parameter was slightly lower and there was less variance in parameter estimates for the 2011 VPA assessment model compared to the 2008 VPA assessment model (Figure 8). Yet, the model fits were very similar with the majority of AIC weights being assigned to the environmentally-explicit stock-recruitment model for both assessment models. These results support the conclusion that configuration of the assessment model was not responsible for the decreased fit of the environmentally-explicit stock recruitment function estimated from the 2011 VPA assessment model.

Evaluation of the stock recruitment relationship (eq 1 and 2) parameters from the bootstrapped assessment model estimates shows the two parameters (a and b) are highly correlated but vary among stock-recruitment models (eq. 1 and eq 2) and assessment models (2008 and 2011) (Figure 9). The environmental model (eq. 2) parameters are lower and less variable than the standard model (eq 1) parameters.

Retrospective Analysis of Model Outputs - The retrospective analyses indicated that the length of the data series included in the assessment models played an important role in the estimates of spawning stock biomass and recruitment (Figure 10). As an example, for the 2011 VPA assessment model, the 2006 estimate of spawning stock biomass decreased with each year of additional data included in the assessment model. Similarly, the 2005 estimate of recruitment decreased with each year of additional data included in the assessment model. This recruitment estimate is of particular interest because the change in this estimate resulted in the decrease in the correlation between wind and recruitment.

Discussion

Wind and Atlantic Cod Recruitment

The work of Churchill et al. (2011) suggested a possible relationship between northward wind stress and recruitment, which prompted our exploration of environmentally-explicit stock recruitment relationships for use in deriving biological reference points. Based on the 2008 VPA assessment estimates of spawning stock biomass and recruitment, the environmentally-explicit stock recruitment relationship explained a large amount of variance in recruitment (~54%, Table 2). The re-calculation of the correlation between northeastward wind-stress and recruitment with additional years of data provided a re-test of the Churchill et al. (2011) hypothesis *sensu* Myers (1998). Using the 2011 VPA assessment model estimates, the explained variance of the environmentally-explicit stock recruitment model was ~17% (Table 2). This decrease in explained variance was due to the lowering of the 2005 recruitment estimate in the 2011 relative to the 2008 VPA assessment model. These results suggest caution when using the output of a stock assessment as data in subsequent analyses; specifically it is important to include the uncertainty in the estimates resulting from a stock assessment in any subsequent analyses.

The retrospective analysis conducted here supports an explanation for the decrease in correlation between wind stress and recruitment; specifically, highly uncertain estimation of recruitment in the terminal years of the 2008 VPA assessment model. The high 2005 recruitment estimate resulted from two survey tows that caught a very large number of fish from that year class, one in the spring of 2007 and one in the spring of 2008 (NEFSC 2012). The 2008 VPA assessment model included only the mean catch from the 2007 and 2008 trawl surveys and did not account for the large variance (or imprecision) around these means caused by these two very large catches (NEFSC 2012). The VPA models explored during the 2011 VPA assessment, which did account for the imprecision of these observations, did not exhibit severe retrospective patterns (NEFSC 2012). Reduced retrospective patterns were also found for the statistical catch-at-age (ASAP) model that was ultimately adopted during the 2011 assessment (NEFSC 2012). Further, the 2011 VPA assessment incorporated three additional years of survey observations of the 2005 year class, as well as observations of discards and landings of that year class from the commercial and recreational fisheries. None of the additional data showed any evidence that the year class was exceptionally large. In general, imprecision in terminal year estimates of recruitment is a well-known phenomenon, and many assessments constrain terminal year estimates to be closer to the mean of whatever process is used to model recruitment. When attempting to fit a stock recruitment model outside of the assessment model, the possibility of greater uncertainty in the terminal year estimates of both spawning stock biomass and especially recruitment needs to be considered.

The examination of the Churchill et al. (2011) hypothesis of a relationship between wind stress and recruitment in Gulf of Maine Atlantic Cod is complicated by considerations of stock structure. The Gulf of Maine Atlantic Cod stock is composed of fish captured throughout the Gulf of Maine (see Figure 1). The hypothesis of Churchill et al. (2011) applies to the spring-spawning Atlantic Cod in the western Gulf of Maine, which is only a portion of the Gulf of Maine Atlantic Cod stock. Recent genetic evidence and an interdisciplinary stock structure analysis suggests at least two sub-populations in the western Gulf of Maine: winter-spawning and spring spawning (Kovach et al. 2010, Kerr et al. 2014, Zemeckis et al. 2014). Spring and winter spawning sub-populations were not differentiated in the assessment models analyzed here. Further, the distribution of Atlantic Cod has contracted from east to west, with numbers decreasing over-time in the eastern Gulf of Maine (Alexander et al. 2011, NEFSC 2013). An explanation for the lack of correlation between springtime northeastward wind stress and recruitment could be due to a changing ratio over time of recruits resulting from winter and spring spawning and changing importance of spawning locations. This possibility highlights the general need to better understand the spatial structure of marine fish populations and their relationship to the environment (see Cadrin and Secor 2009, Goethel et al. 2011).

Although the correlation between northeastward wind stress and recruitment decreased with the inclusion of new data, there remains evidence supporting the Churchill et al. (2011) hypothesis. The environmental model fits better than the standard model (Table 2). It is possible that wind stress has a significant impact on egg and larval survival by affecting supply to juvenile nurseries, but that other processes are also important in determining recruitment (Rothschild et al. 2005, Lough and O'Brien 2012, Friedland et al. 2013). If data were available on the abundance of eggs, larvae and juveniles at multiple points within that first year of life, and if the associated selectivity (or catchability) were available for each data source, then one could use a multi-stage Beverton-Holt model that incorporated interval-specific survival within the first year (Brooks and Powers 2007). Such an approach would require explicit hypotheses about which intervals in that first year of life feature density dependent mortality. Further, a juvenile abundance index or recruitment estimate that can be segregated on the basis of spawning time and location would allow for a more focused test of the Churchill et al. (2011) hypothesis.

Reference Points

Biological reference points are used to determine the status of a stock. Stock assessments are used to estimate the current spawning stock biomass ($B_{current}$) and fishing rate ($F_{current}$), which are then compared to the biological reference points. Two common reference points that can be derived from a stock recruitment relationship are biomass at maximum sustainable yield (B_{MSY}) and the fishing rate that produces maximum sustainable yield (F_{MSY}). Typically, if $B_{current}$ is less than 0.5 B_{MSY} the stock is classified as overfished and if $F_{current}$ is greater than F_{MSY} the stock is classified as experiencing overfishing. These classifications are then followed by changes in management and regulation. During the 2008 VPA assessment of Gulf of Maine Atlantic Cod, deriving reference points from the stock recruitment relationship was rejected owing to the poor fit of the standard stock-recruitment model (see Table 2). Instead, management advice was based on using F40% as a proxy for F_{MSY} (NEFSC 2008). The biological parameters (weights-at-age, maturity-at-age) and fishery selectivity-at-age were averaged over the period 2003-2007 and used to calculate $F_{40\%}$.

Although the environmentally-explicit stock recruitment model provided a better fit than the standard stock-recruitment model, the estimated steepness, unexploited SSB, and unexploited R were high, and similar to the standard stock recruitment model. In addition most of the parameters had very high coefficients of variation indicating poor precision (Table 2). Thus, the results from the environmental model are inappropriate for application to management advice. Steepness estimated from the environmental model is comparable to estimated steepness for gadids (0.81 compared to 0.79) (Myers et al. 1999) but questions remain about the validity of wind-recruitment hypothesis. The strong correlation between the parameters of the stock-recruitment relationship also presents problems for defining reference points, but the parameter space and correlation between parameters was smaller for the environmental model. Furthermore, the unexploited spawning stock biomass was estimated between 460,000 – 570,000 t compared to the current range of ~7,000-26,000 t. Although higher spawning stock biomasses are inferred from studies of historical catches (Alexander et al. 2011), a ~50 fold increase in spawning stock biomass is difficult to envision. An additional concern is that there are no observations anywhere near S_0 and R_0, meaning that those values are extrapolations well beyond the range of observed values; this likely contributed to the extremely large CVs on those parameters. Without strong evidence for the northeastward wind stress effect on recruitment and questions regarding the credibility of the fitted relationship, the use of the environmentally-explicit stock recruitment relationship developed here to define reference points and provide management advice for Gulf of Maine Atlantic Cod is not currently justified.

Uncertainty

Our study highlights the importance of recognizing the various sources of uncertainty associated with assessment model output. Ecological, oceanographic, and ecosystem studies frequently treat the output from single-species stock assessments as data (Hare and Able 2007; Churchill et al., 2011). However, there are at least three sources of uncertainty to recognize: 1) the uncertainty in the assessment model estimates; 2) the fact that estimates are conditional on the length of time-series used in the assessment model; and 3) the estimates are conditional on the assessment model structure. In addressing the first form of uncertainty, we explored the fit of stock recruit models to the bootstrapped output. This analysis demonstrated the effect of recruitment uncertainty on the resulting stock recruit relationship.

Uncertainty due to the length of time series was highlighted by the change in correlation of wind and recruitment between the 2008 and 2011 VPA assessments, as well as the decrease in explained variance of the environmentally-explicit stock recruit function. This is due in part to the greater uncertainty in these terminal years of the assessment because there is the least amount of data for estimating the size of these year-classes. With subsequent years of data, as year classes recruit to the fishery and are observed in the catch-at-age and in the surveys at multiple ages, the estimates of their abundance stabilize. The largest difference between the 2008 and 2011 VPA assessment models was the data included, with the 2011 model having longer time series and more complete catch data.

Between-model uncertainty can arise due to different model structures, including different assumptions about parameter values or distributions. Ralston et al. (2011) demonstrated that between-model uncertainty could be greater than within model uncertainty. In the present study, we compared bootstrapped distributions from the 2008 and 2011 model run on the same length of time series, and found them to be similar, indicating that between model differences were not a significant source of uncertainty.

Environment-Recruitment Relationships

Keyl and Wolff (2005) developed a list of explanations for spurious correlations in stock recruitment relationships. To this list, uncertainty in the estimation of spawning stock biomass and recruitment should be added. Estimating the relationship within the assessment can potentially avoid this problem. If internal estimation of a stock recruit function is not possible, one approach to reduce the influence of uncertain estimates is to exclude recent estimates of recruitment and spawning stock biomass from environment-recruitment analyses. Another approach might be to use a jackknife to evaluate the influence of individual observations on the stock-recruitment relationship (Efron 1981). Performing retrospective analyses might suggest the number of years that need to be excluded. Alternatively, one could set a general rule of thumb to exclude year classes that have not yet appeared in the fishery catch at age.

Whatever the approach taken to estimate stock recruit relationships, a thorough consideration of model diagnostics is necessary. For instance, in the present example, simply examining AICc would suggest that the environmental model provides the best fit. Model convergence was supported by gradients that were generally $<10^{-5}$. However, the CVs for the estimated parameters indicate minimal confidence in the stock recruitment models and plotting the predicted function over the entire implied domain identified just how limited the observed range was. These results indicate that the stock-recruitment models are not adequate for management recommendations.

The potential of spurious environmental relationships due to retrospective patterns does not negate the utility of exploring the inclusion of environmental information in stock assessments. However, Myers (1998), Keyl and Wolff (2008), and our study indicate that caution is needed. Further, Haltuch et al. (2009) and Haltuch and Punt (2011) offer examples where inference about reference points can be riskier when environmental data are included, and Francis (2006) demonstrated less accurate recruitment predictions when based on a spurious environmental-recruit relationship. Careful examination is needed of the estimated stock-recruitment relationship in the context of steepness, virgin spawning stock biomass and virgin recruitment. These results indicate that stock assessment scientists, oceanographers, and ecologists need to work closely in the translation of oceanographic and environmental information into stock assessments and ultimately management advice.

Acknowledgments

We wish to thank the participants of the 2011 Gulf of Maine Atlantic Cod stock assessment working group for their comments and input during the development of this work. We also thank the NMFS Fisheries and the Environment program which funded the initial work of Churchill et al. (2011) (FATE Project 08-02) and funded Hare (FATE Project 10-08) to examine environmentally-explicit stock recruitment models. We also thank Richard Langton and three anonymous reviewers for comments on an earlier draft of this manuscript. We thank Rich Bell for advice regarding the fitting of environmentally-explicit stock recruitment relationships in R. We also acknowledge the contributions of James Ianelli (NMFS AFSC) who reviewed the manuscript and provided code for the environmentally explicit stock recruitment models in ADMB; our initial efforts were with MatLab and R. Acknowledgment of the above individuals does not imply their endorsement of this work; the authors have sole responsibility for the content of this contribution. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its sub-agencies.

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Table 1. Estimates of spawning stock biomass (SSB) and corresponding age-1 recruits for both the 2011 and 2008 VPA assessment models. The two wind indices also are included (northward wind index, and northeastward wind index). Recruits have been lagged by 1 year so that for a given row, the value of SSB aligns with the resultant number of age-1 fish.

Year	SSB (t) 2011 (Year)	Recruits (000s) 2011 (Year+1)	SSB (t) 2008 (Year)	Recruits (000s) 2008 (Year+1)	Northward Wind	Northeastward Wind
1982	26,581	12,861	25,269	7,824	NA	NA
1983	20,601	13,832	19,234	10,454	NA	NA
1984	16,877	11,703	16,984	6,591	NA	NA
1985	15,522	14,612	16,941	10,124	0.46	0.28
1986	14,072	17,226	19,077	12,552	0.57	-0.42
1987	13,473	32,911	15,583	24,233	-0.61	-0.62
1988	12,835	5,079	16,153	4,189	NA	NA
1989	17,068	5,640	21,656	4,076	1.87	1.61
1990	23,016	9,227	28,014	6,834	0.46	0.40
1991	20,210	9,315	19,650	6,245	1.18	0.67
1992	12,559	11,389	11,681	9,004	-0.62	0.24
1993	8,924	3,885	10,096	3,148	0.55	0.19
1994	7,565	4,243	10,484	3,771	-0.11	-0.43
1995	8,395	3,602	13,319	3,513	0.39	0.33
1996	9,190	5,583	11,742	5,195	0.96	0.68
1997	7,811	5,711	9,707	4,414	1.70	0.66
1998	7,246	11,085	10,699	7,731	-0.64	-0.19
1999	8,077	7,323	11,138	3,956	-0.05	0.37
2000	11,368	1,754	14,133	1,170	0.28	0.53
2001	15,813	8,178	17,624	4,869	-0.19	0.03
2002	15,525	2,547	18,387	1,653	1.05	0.44
2003	12,515	8,597	16,236	10,794	-0.92	-0.21
2004	10,635	5,420	13,398	6,613	0.57	0.43
2005	9,197	8,107	10,684	23,571	-2.80	-2.02
2006	8,284	6,662	18,688	4,741	-1.01	-0.44
2007	10,714	7,664	NA	NA	-0.43	-0.55
2008	12,650	4,033	NA	NA	-0.08	-0.26
2009	13,800	1,811	NA	NA	1.12	1.10

Table 2. Estimated parameters and fit statistics for the standard (eq 1) and environmental (eq 2) Beverton Holt stock recruitment model based on spawning stock biomass and age-1 recruitment estimates from the 2008 and 2011 VPA assessment models. Two environmental models were fit: one using northward winds and one using northeastward winds. For the environmental model, the mean wind index was used to calculate S_0 and R_0 (see equation 6). The coefficient of variation (CV) of the parameter estimates are provided, which is the ratio of the standard deviation of the parameter estimate in relation to the parameter estimate.

	Parameter	Standard Model		Environmental Model (Northward Winds)		Environmental Model (Northeastward Winds)	
		Estimate	CV	Estimate	CV	Estimate	CV
2008 VPA Assessment Model	a	4.663	6.50	0.985	1.16	0.858	0.91
	b	7.334E-04	7.12	9.002E-05	2.04	6.652E-05	1.85
	c			-0.398	0.34	-0.671	0.28
	h	0.963	0.24	0.840	0.18	0.817	0.16
	S0	1.419E+05	0.59	2.214E+05	0.85	2.531E+05	0.91
	R0	6.298E+03	0.59	9.826E+03	0.85	1.123E+04	0.91
	AICc	53.003		48.587		45.916	
	w	0.022		0.204		0.774	
	r2	-0.084		0.381		0.541	
2011 VPA Assessment Model	a	1.476	1.17	0.850	0.63	0.795	0.56
	b	1.374E-04	1.90	3.719E-05	2.04	2.791E-05	2.21
	c			-0.289	-0.46	-0.481	-0.38
	h	0.893	0.13	0.821	0.11	0.809	0.10
	S0	2.348E+05	0.72	4.658E+05	1.40	5.704E+05	1.64
	R0	1.042E+04	0.72	2.067E+04	1.40	2.532E+04	1.64
	AICc	54.891		53.518		51.649	
	w	0.124		0.247		0.629	
	r2	-0.023		0.101		0.171	

Figure Captions

Figure 1. Map showing the Gulf of Maine Atlantic Cod stock area and the locations of Atlantic Cod spawning and local nursery habitats in the western Gulf of Maine. Locations of buoys used for wind data are marked.

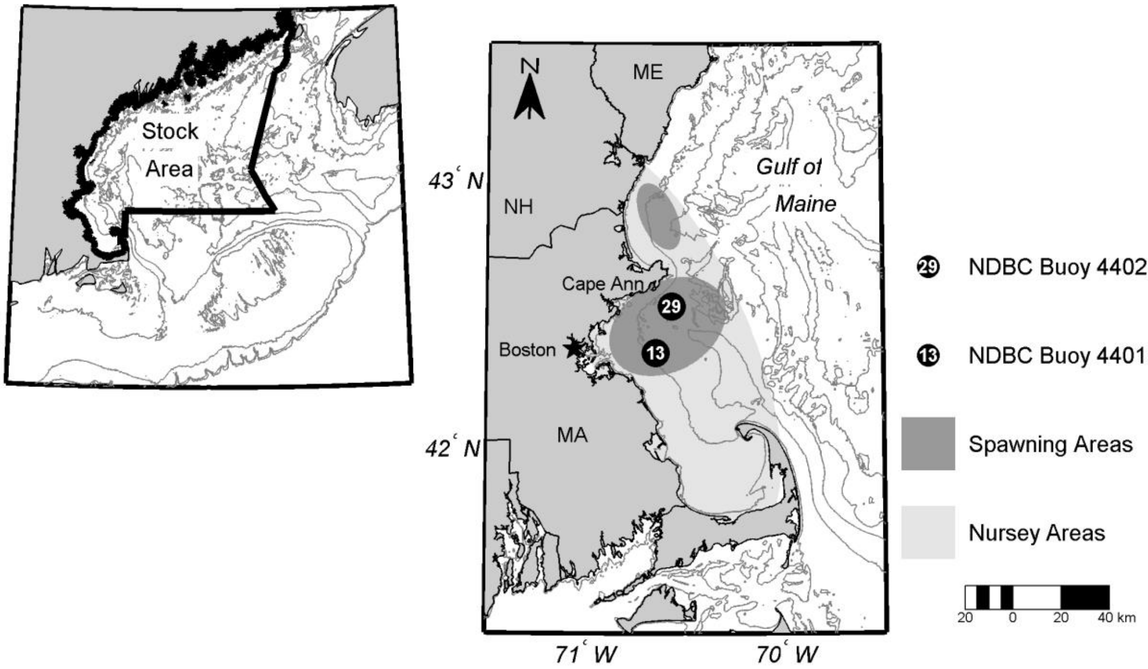

Figure 2. Correlation between recruitment and wind speed as a function of wind orientation and the period over which winds were averaged. Prior to analyses, missing data from NODC Buoy 44013 were estimated with data from NODC Buoy 44029 (see Figure 1). These values were then correlated with the recruitment estimates from the 2008 VPA assessment model. The correlation between the May winds without estimating missing values ("unfilled") and recruitment is also shown.

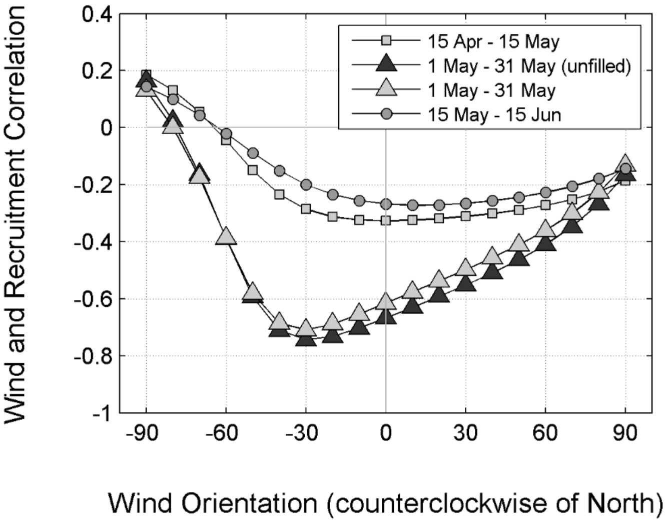

Figure 3. Comparison of spawning stock biomass and recruitment estimates from the 2008 and 2011 VPA assessment models. Spawning stock biomass from 2006 is highlighted as is recruitment of the 2005 year-class. These two estimates exhibit the greatest difference between the two assessment models.

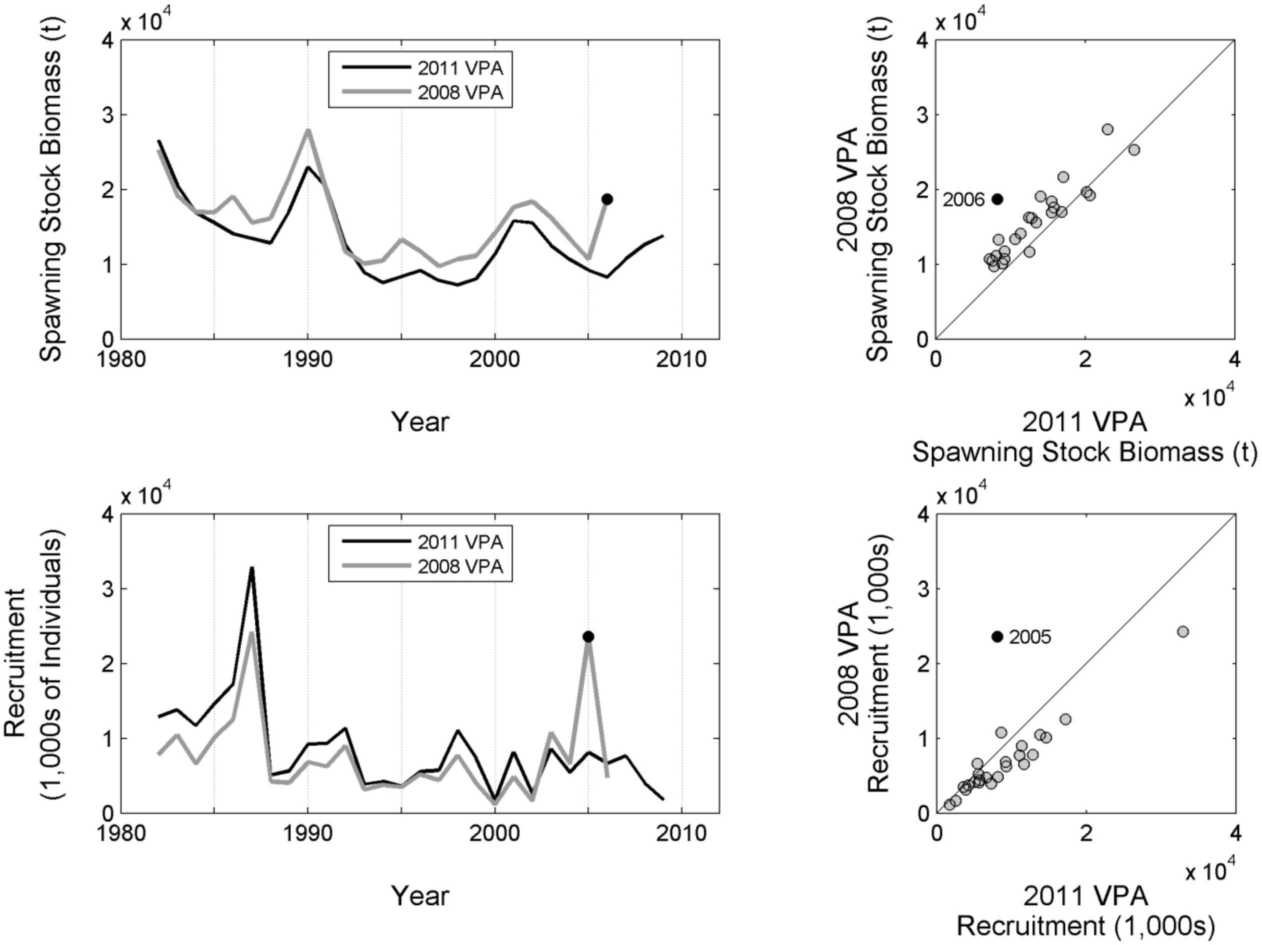

Figure 4. Environmentally-explicit stock-recruitment relationships based on the 2008 VPA assessment model. Two environmental formulations are shown: 1) the original Churchill et al. (2011) formulation but with an estimated data series (labeled Northward Winds, panel A, C, E) and 2) estimated data series with Northward Winds rotated -30^{o} counterclockwise of north (labeled Northeastward Winds, panel B, D, F). A, B) The stock-recruitment estimates and model fit for the standard model (eq.1) and the environmentally-explicit model (eq. 2) at the mean wind index. The shading of the stock-recruitment pairs reflects the strength of the wind. C, D) The environmentally-explicit model fit at the mean wind index and at +/- 1 standard deviation. E, F) Scatterplot of the wind index and the residuals from the standard stock recruitment model (eq. 1).

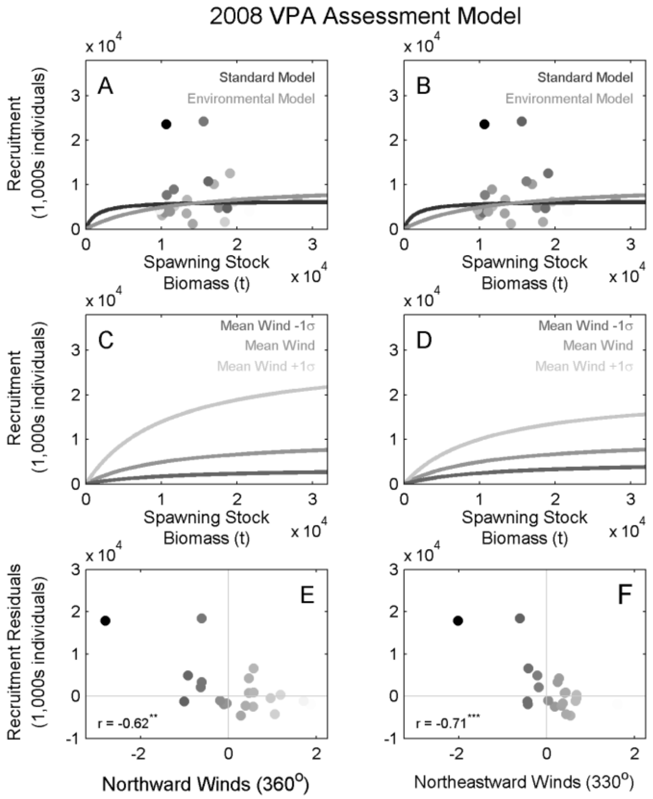

Figure 5. Environmentally-explicit stock-recruitment relationships based on the 2011 VPA assessment model. Two environmental formulations are shown: 1) the original Churchill et al. (2011) formulation but with an estimated data series (labeled Northward Winds, panel A, C, E) and 2) estimated data series with Northward Winds rotated -30^{o} counterclockwise of north (labeled Northeastward Winds, panel B, D, F). A, B) The stock-recruitment estimates and model fit for the standard model (eq.1) and the environmentally-explicit model (eq. 2) at the mean wind index. The shading of the stock-recruitment pairs reflects the strength of the wind. C, D) The environmentally-explicit model fit at the mean wind index and at +/- 1 standard deviation. E, F) Scatterplot of the wind index and the residuals from the standard stock recruitment model (eq. 1).

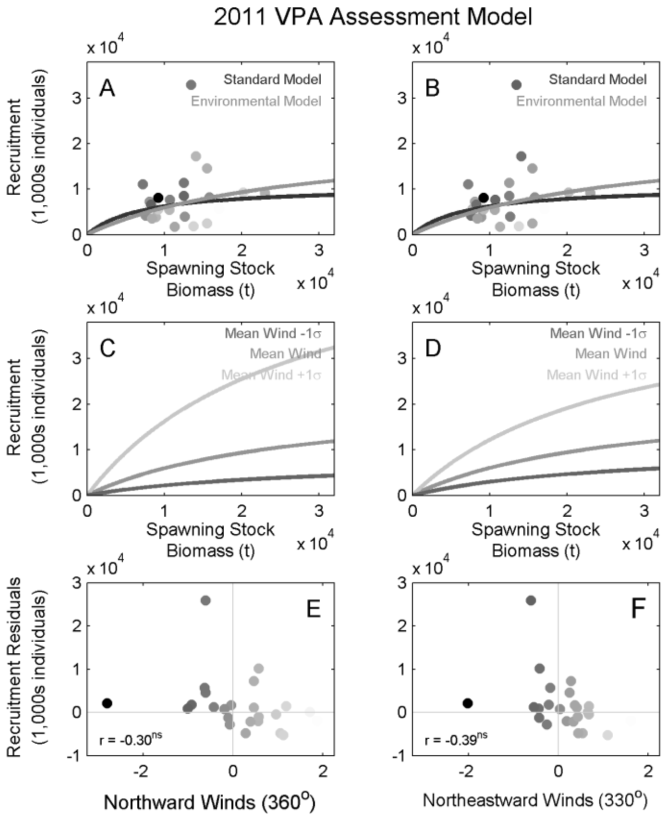

Figure 6. Environmentally-explicit stock-recruitment relationships based on the 2008 (A) and 2011 VPA (B) assessment model. The environmental model includes Northeastward Winds. The stock-recruitment estimates and model fit for the standard model (eq.1) and the environmentally-explicit model (eq. 2) at the mean wind index. The shading of the stock-recruitment pairs reflects the strength of the wind. The data and functions are the same as shown in Figures 4B and 5B. Where the replacement line (thin black line) intersects the functions represents estimated “virgin conditions”. There is no data to support the estimates of “virgin conditions” and the lack of contrast in spawning stock size is one factor contributing to the highly variable parameter estimates derived from fitting the stock recruitment relationships (Table 2).

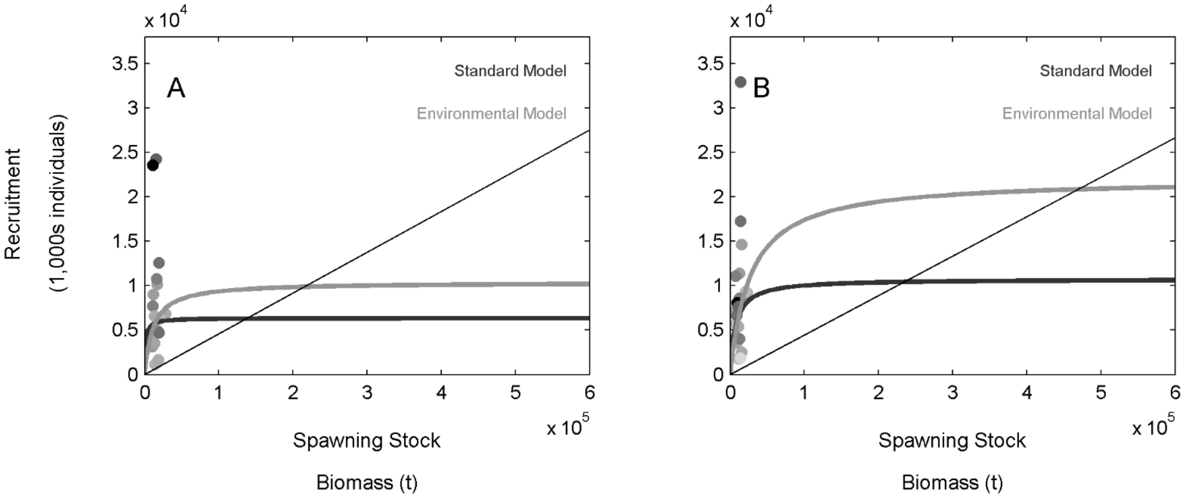

Figure 7. Comparison of the bootstrapped 2005 spawning stock biomass and recruitment estimates from the 2008 and 2011 VPA assessment models. Both models were fit with 1982 to 2005 data (from the retrospective analysis) as a comparison of assessment model configuration.

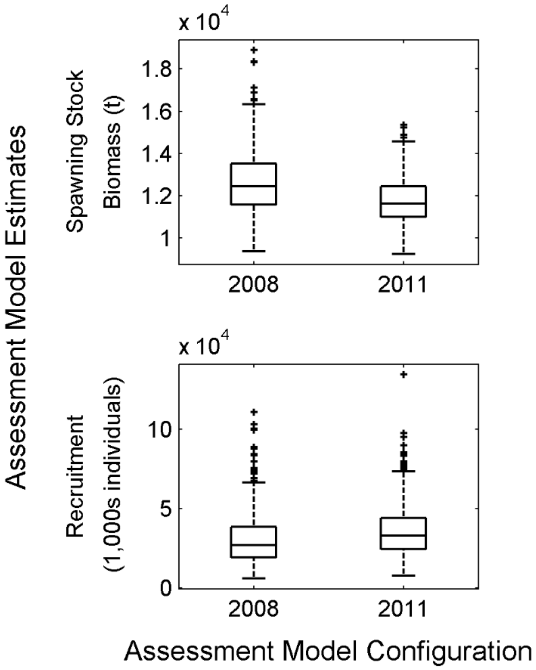

Figure 8. Comparison of the bootstrapped stock-recruitment parameters from the 2008 and 2011 VPA assessment models. Both models were fit with 1982 to 2005 data (from the retrospective analysis) as a comparison of assessment model configuration. Parameters from both the standard (eq 1, SM) and the environmentally-explicit (eq. 2 EM) stock recruitment functions are provided.

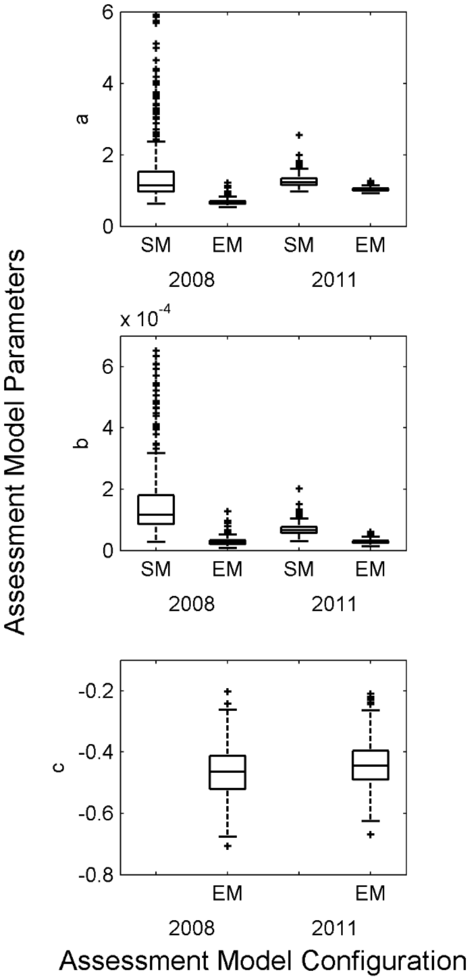

Figure 9. Comparison of the relationship of bootstrapped stock-recruitment parameters from the 2008 and 2011 VPA assessment models. Both models were fit with 1982 to 2005 data (from the retrospective analysis) as a comparison of assessment model configuration. Parameters from both the standard (eq 1, SM) and the environmentally-explicit (eq. 2 EM) stock recruitment functions are provided. It is important to note that these values are not directly comparable to those presented in Table 2, because the values shown here are based on the same data input: 1982-2005.

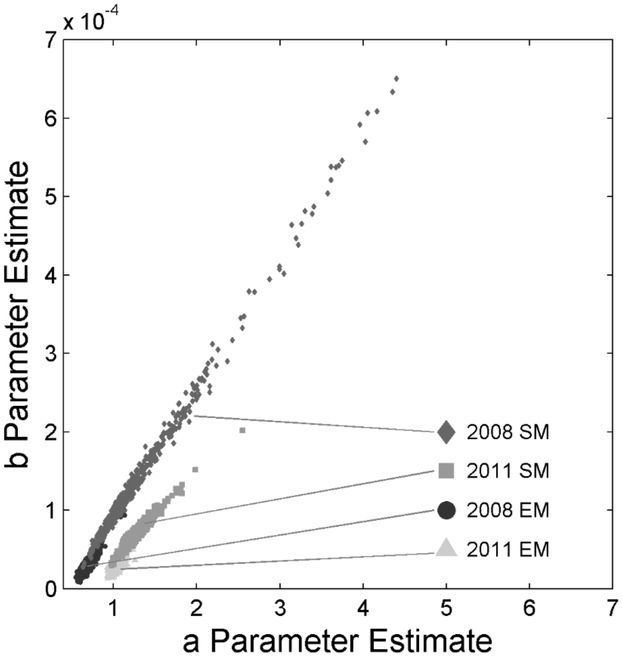

Figure 10. Retrospective analysis of spawning stock biomass and recruitment from the 2008 and 2011 VPA model estimates. Error bars represent the standard deviation in the estimate based on 1000 bootstrapped estimates of the indices used in the assessment model. The last few years of each retrospective assessment are shown. Retrospective analyses use the same model configuration but vary the years included in the model.