Online Appendix

Forecasting the Dynamics of a Coastal Fishery Species Using a Coupled Climate-Population Model.

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1. Background on global climate models

Minimum winter air temperatures were derived from two prominent global climate models: the NCAR Community Climate System Model (CCSM) 3.0 (Collins et al. 2006, Meehl et al. 2007), and the GFDL Climate Model (CM) 2.1 (Delworth et al. 2006, Meehl et al. 2007). The resolution of atmosphere in the CCSM is 1.4° latitude and 1.4° longitude with 25 levels. The resolution of the atmosphere in the CM2.1 is 2.0° latitude by 2.5° longitude with 34 levels. The resolution of the ocean in both models is approximately 1° longitude; the resolution in latitudes varies between 1° in the extratropics to ~1/3° in the tropics to resolve equatorial waves associated with El Niño. The influence of subgrid scale processes (e.g., turbulence in the boundary layer, thunderstorms and ocean eddies) are parameterized based on large-scale conditions, i.e., variables that are simulated on the model's coarse grid. Even at coarse resolution, the models are run on super computers as the temperature, moisture, salinity, winds, ocean currents, etc., are predicted at hundreds of thousands of grid boxes.

Global coupled models can be verified by comparing their output to the recent past, e.g., how simulated and observed temperatures changed over the 20th century. An exact match between observations and model simulations in a given period is not expected because of random fluctuations in the climate system. However, these models should simulate the statistics of natural variability, replicate the long-term trends driven by greenhouse gases and other external forcing, and reproduce the spectral properties of observations. To overcome the influence of random fluctuations in climate, the output of an ensemble of model runs (as opposed to a single model run) is generally compared to observations. Nine NCAR CCSM3.0 and three GFDL CM2.1 simulations were conducted for the 20th century. Minimum winter temperature for the grid cell over southern Chesapeake Bay was extracted from the ensemble model runs and compared with observed minimum winter temperatures for Virginia. The GFDL CM2.1 mean was about 0.5^{o}C lower and the standard deviation was slightly greater than observed (Fig. A1). The NCAR CCSM3.0 had a +3.0^{o}C bias but the standard deviation was nearly identical to observations (Fig. A1). These mean differences between the climate models and observations were used to bias correct the minimum winter air temperatures estimated in the GFDL CM2.1 and NCAR CCSM3.0 climate models. The smoothed observations indicate a long-term cycle in minimum winter air-temperature with high temperatures in the 1940's and low temperatures in the 1970's; these warm and cool periods have been linked to the Atlantic Multidecadal Oscillation. (Kerr 2000, 2005). The modeled temperatures do not match this long-term trend in observed temperature, but the modeled temperatures due seem to exhibit a cycle of similar duration and magnitude as observed. A comparison of spectral properties indicates that variability in observations generally matched variability in the simulations (Fig. A2). At the longer periods, there is good agreement between the models and observations. At shorter periods, the GFDL model exhibited higher variability at 3-4 year periods and lower variability at 5-7 year periods than the observations. Confidence intervals (CI) from the NCAR CCSM3.0 model included the observations at all frequencies, but there were more ensembles, so it is likely that with more GFDL ensembles, the CI would enclose the observations. Based on these comparisons of historical model runs and observations, the GFDL CM2.1 and NCAR CCSM3.0 appear to capture the long-term dynamics of minimum winter temperature in the mid-Atlantic region.

Prior studies have also shown that climate models, including CCSM3 and CM2.1, generally reproduce the continental-scale trends (Randall et al. 2007) and some regional trends (Knutson et al. 2006, Seager et al. 2007). The CM2.1 reproduces the observed warming over the 20th century in the subtropical North Atlantic and continental U.S. when anthropogenic forcing is included, but over-estimates warming for the southeast US (Knutson et al. 2007). All climate models have biases and several factors may lead to model-data differences including model error, inadequate representation of regional processes (e.g., aerosol loading, deforestation/reforestation, irrigation), and natural variability (i.e,. the atmospheric circulation over the southeast United States is influenced by El Nino and the Atlantic Multidecadal Oscillation). While there are differences between the CM2.1 and the observed annual temperature trends in the southeast U.S., there is general agreement between the simulated and observed minimum winter temperature in the mid-Atlantic region (Fig. A1 and A2).

Although, the analyses above suggest that the climate models reasonably capture the minimum winter air temperatures in coastal Virginia, a potential concern is that the coupled climate-population model results are specific for this model grid cell. However, there is strong concordance in the time series of minimum winter air temperature over the eastern seaboard of the United States (Fig. A3) in historical observations, climate model hindcasts, and climate model forecasts (Table A1). This concordance is expected since prior studies have documented strong concordance in interannual winter air temperature over the eastern U.S. (Joyce 2002), estuarine water temperatures in the mid-Atlantic (Hare and Able 2007), coastal water temperatures (Nixon et al. 2004), and sea surface temperature in the western North Atlantic (Friedland and Hare 2007). Additionally, minimum winter air temperature is closely related to minimum winter water temperature in estuaries along the mid-Atlantic coast (Hettler and Chester 1982, Hare and Able 2007) owing to the efficient heat exchange between atmosphere and water in these shallow systems (Roelofs and Bumpus 1953). Thus, minimum winter air temperatures from Virginia can serve as a proxy for coast-wide variability in minimum winter water temperatures.

2. Choice of a stock-recruitment function

A number of functions have been used historically to model the relationship between fish population size and subsequent recruitment (Hilborn and Walters 2004). There also are a number of extensions of these functions that include the effect of the environment on recruitment (Hilborn and Walters 2004). We evaluated two common stock recruitment functions (Beverton-Holt and Ricker) and several extensions of these functions that include environmental effects (Table A2). The Akaike Information Criterion (AIC) was used to choose the best formulation to use in the coupled climate-population model. Spawning stock biomass and recruitment data were obtained from a recent stock assessment of Atlantic croaker (ASMFC 2005) and minimum winter air temperature in Virginia (http://www.sercc.com/climateinfo_files/monthly/Virginia_temp.html) was used as a proxy for water temperature during the estuarine juvenile stage (Hare and Able 2007).

The stock-recruitment functions were initially fit with non-linear algorithms, but these algorithms rarely converged. As a result, linear forms of the stock recruitment functions (model 1 and 4, see Table A2) were fit using least-squares regression. The environmental extensions of the Ricker stock-recruitment model are easily linearized (models 5-11, see Table A2) and these models were also fit using least-squares. The environmental forms for the Beverton-Holt model (models 2 and 3) are not easily linearized. To fit these models, the standard Beverton-Holt terms (a and b) were estimated using the linearized version of the model (model 1), and then a non-linear fitting algorithm was used to estimate the environmental parameter (c) with the standard parameters (a and b) fixed at the appropriate values. Because the linearized forms of the models used different dependent variables (1/R for Beverton and Holt and ln[R/S] for Ricker), AIC was estimated based on the models predictions of R using the non-linearized forms of the equations, with the terms derived from the linearized models. In this way, AIC was calculated based on the residual sums of squares of estimated R and observed R. The strength of evidence of the alternative models was calculated following (Burnham and Anderson 1998).

The Ricker stock-recruitment model with a temperature term was the best-supported model evaluated (Table A2), with the highest strength of evidence (w=0.619). The models with environmental terms were far superior to the standard stock-recruitment models. The relative likelihood of the environmental Beverton and Holt model (model 2) compared to the standard

Beverton and Holt model was ~6000 to 1 ($w_{model\ 2}$ / $w_{model\ 1}$). For the environmental Ricker (model 5) compared to the standard Ricker (model 4), the relative likelihood was ~10000 to 1. Based on these results, model 5 was chosen for use in the population model. Temperature-dependent Ricker models with higher order terms (model 8 and 9) had moderate strengths of evidence (w=0.137 and w=0.181). These models potentially create non-linearities that could amplify the effect of climate at higher minimum winter temperatures. However, over the range of temperatures forecasted in the climate models, the higher order models predict very similar recruitment compared to the linear model, so non-linear effects are minimal, and thus these were not included in the final model.

3. Distribution model based on logistic regression

As an alternative approach to multiple regression for modeling distribution, a logistic regression was developed that used the presence / absence at individual trawl stations. First, trawl stations were screened to remove stations that sampled deeper than 45 m; this value was based on the 5% level of a logistic regression of catch on depth. The logistic regression model was used in a form similar to the average distance model. Catch at station *s* in year *Y* was modeled as the distance of station *s* in year *Y*, spawning stock biomass (*S*) in year *Y*, and minimum winter temperature in year *Y*:

$$catch_{sY} = a + b \cdot dist_{sY} + c \cdot SSB_Y + d \cdot T_Y + e \cdot SSB_Y^{\ 2} + f \cdot T_Y^{\ 2} \qquad (6)$$

The model was fit using the glm [family=binomial(link="logit")] function in R (http://www.r-project.org/) and an Akaike multi-model inference was used to determine the model parameters. The model was then used to forecast Atlantic croaker distribution estimating the distance to the 50% and 10% catch probability. The results were qualitatively similar to those from the average distance approach, with distances decreasing with increasing *F* and increasing with increasing CO_2 emissions; we choose to present the results of the multiple regression model.

4. Results for NCAR CCSM 3.0 model runs

The NCAR CCSM3.0 climate model provided qualitatively similar results as the GFDL CM2.1 model. The most striking difference was that the NCAR CCSM3.0 B1 and A1B runs predicted similar long-term minimum winter temperatures, which resulted in similar spawning stock forecasts (Fig. A4) and distribution forecasts (Fig. A4). However, the relative effect of climate compared to fishing was similar between the NCAR CCSM3.0 and GFDL CM2.1 (Fig. A4). Similarly, the overall forecasts of Atlantic croaker distribution were very similar between the NCAR CCSM3.0 and the GFDL CM2.1; the NCAR CCSM3.0 predicted less change between the B1 and A1B scenarios (Fig. A4). Owing to the similarity between the temperature forecasts for the NCAR CM3.0 between the B1 and A1B scenarios, the predicted effects of climate on fishery benchmarks were less for the A1B scenario than predicted under the GFDL model (Fig. A5, Table A3).

5. References

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Table A1. Kendall's concordance (W) for time series of minimum winter air temperatures from locations indicated in Fig. A3. Calculations were made for each of the models considered. Kendall's concordance is a non-parametric test that measures the degree of agreement between multiple series of data.: 0 indicates no agreement; 1 indicates perfect agreement

Model	W	p	Year
GFDL 20th Century	0.63	$p<0.001$	1861-2000
NCAR 20th Century	0.75	$p<0.001$	1870-1999
NCEP Reanalysis	0.73	$p<0.001$	1948-2006
GFDL Commit	0.74	$p<0.001$	2001-2100
GFDL B1	0.69	$p<0.001$	2001-2200
GFDL A1B	0.74	$p<0.001$	2001-2200
NCAR Commit	0.79	$p<0.001$	2000-2099
NCAR B1	0.73	$p<0.001$	2000-2349
NCAR A1B	0.74	$p<0.001$	2000-2349

Table A2. Akaike Information Criteria values for various models fit to stock (S) and recruitment (R) data for the mid-Atlantic stock of Atlantic croaker. Values provided for corrected Akaike Information Criteria (AIC_c), number of parameters in the model including the error term (k), the delta-AIC_c, which is scaled to the minimum observed AIC_c, and the model weights (w), which range from 0 to 1.

No.	Model	Linearized Model	AIC_c	k	ΔAIC_c	*W*
1	$R = \frac{S}{b + aS}$	$\frac{1}{R} = a + \frac{b}{S}$	309.1	3	24.6	0.000
2	$R = \frac{e^{cT} S}{b + aS}$	Not linearized	291.5	4	7.0	0.019
3	$R = \frac{S}{b + e^{cT} aS}$	Not linearized	294.6	4	10.1	0.004
4	$R = Se^{a+bS}$	$\ln(\frac{R}{S}) = a + bS$	303.4	3	18.9	0.000
5	$R = Se^{a+bS+cT}$	$\ln(\frac{R}{S}) = a + bS + cT$	284.5	4	0.0	0.619
6	$R = Se^{a+bS+dT^2}$	$\ln(\frac{R}{S}) = a + bS + dT^2$	306.2	4	21.7	0.000
7	$R = Se^{a+bS+eST}$	$\ln(\frac{R}{S}) = a + bS + eST$	293.4	4	8.9	0.007
8	$R = Se^{a+bS+cT+dT^2}$	$\ln(\frac{R}{S}) = a + bS + cT + dT^2$	287.5	5	3.0	0.137
9	$R = Se^{a+bS+cT+eST}$	$\ln(\frac{R}{S}) = a + bS + cT + eST$	287.0	5	2.5	0.181
10	$R = Se^{a+bS+dT^2+eST}$	$\ln(\frac{R}{S}) = a + bS + dT^2 + eST$	295.8	5	11.3	0.002
11	$R = Se^{a+bS+cT+dT^2+eST}$	$\ln(\frac{R}{S}) = a + bS + cT + dT^2 + eST$	290.5	6	6.0	0.031

Table A3. Maximum sustainable yield (*MSY*) and fishing rate at maximum sustainable yield (F_{MSY}) based on three CO_2 emission scenarios simulated with two global climate models. Also, provided are the values based on the most recent stock assessment; the values presented here are slightly different than those presented in the assessment for Atlantic croaker (37) because the model form used here (an environmentally-explicit Ricker stock-recruitment function) is different than that used in the stock assessment (a standard Beverton-Holt function)

Scenario	F_{MSY}	Yield (*MSY*) (kg)
A1B	0.81	3.36×10^7
B1	0.75	3.08×10^7
Commit	0.59	2.41×10^7
Observed	0.48	1.87×10^7

Figure Legends

Fig. A1. Time series of observations and ensemble predictions from GFDL CM2.1 and NCAR CCSM3.0 climate models (top row). Distributions of observed and modeled reanalysis minimum winter air temperatures and comparison of observed and predicted means and standard deviations of temperature (middle row). Smoothed observations and predictions, with the predictions corrected by the mean difference between model and observations (bottom row). The climate model forecasts coupled with the population model were also adjusted by the mean difference. In all cases, temperature as an axis label refers to minimum winter air temperature in Virginia.

Fig. A2. Spectral analysis of observations and model reanalysis ensembles. In top panels, shading indicates the 95% confidence intervals of model runs calculated from the ensemble runs. In bottom panel, results for each model run are presented.

Fig. A3. Time series of minimum winter air temperatures from the NCEP Reanalysis for grid cells nearest the locations indicated on the map. These data were significantly concordant: the pattern of interannual variability was coherent across the time series.

Fig A4. Forecasts of the effects of climate change on Atlantic croaker abundance and distribution along the mid-Atlantic coast of the United States based on the NCAR CCSM3.0 global climate model. A) Forecast mean spawning stock biomass (2010 to 2100) for three climate scenarios (commit, B1, and A1B) and a range of fishing mortality rates. Spawning stock biomasses are significantly different among climate scenarios at most levels of fishing mortality rate. B) Contours of the ratio of the partial derivatives of S to F ($\frac{\partial S}{\partial F}$) and S to temperature ($\frac{\partial S}{\partial T}$); this ratio is a measure of the relative effect of climate compared to fishing. The average minimum winter air temperature from 2010 to 2100 for climate model scenario is shown by the colored triangles on the left of panel B. C) Forecasts of mean population location, D) northern extent of the range (mean + 2 standard deviations), and E) percent of years when northern extent of the population is north of the New York apex (distance 600). Inset shows location of various distance marks along the continental shelf. The historical values (1972-2004) of mean location (~240 km), northern extent (~420 km), and proportion of years with the measure of northern extent exceeding 600 km (0.09) are shown as grey contours in C, D and E. Arrows along the x-axis indicate the level of current fishing mortality rate. The average minimum winter air temperature from 2010 to 2100 for climate model scenario is shown by the colored triangles on the left of panel E.

Fig. A5. Yield curves based in the temperature dependent Ricker stock recruitment model and three climate scenarios using the NCAR CCSM3.0 climate model. The current management benchmark (based on a Ricker function) of the fishing rate to maintain the maximum sustainable yield is 0.48. This benchmark is calculated for the three climate scenarios

Figure A1

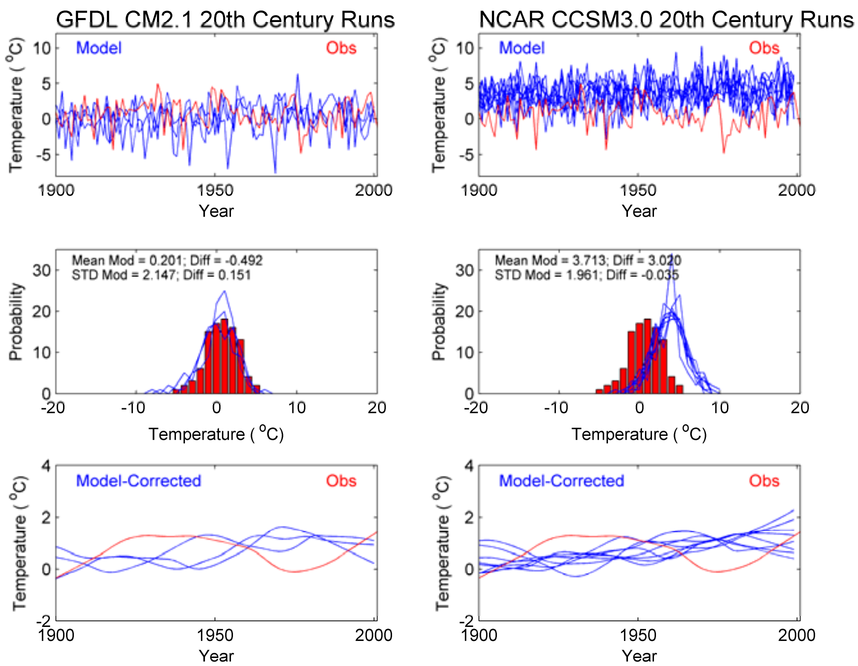
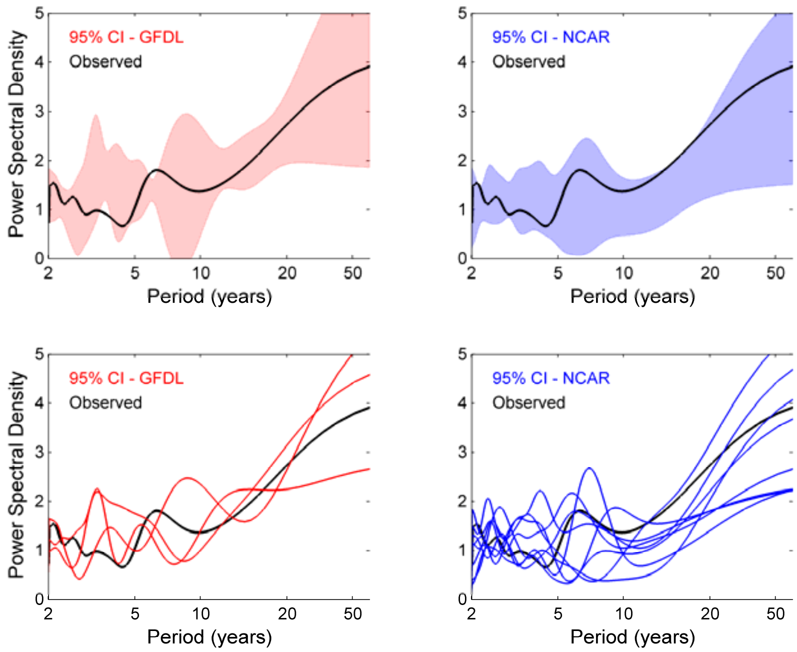
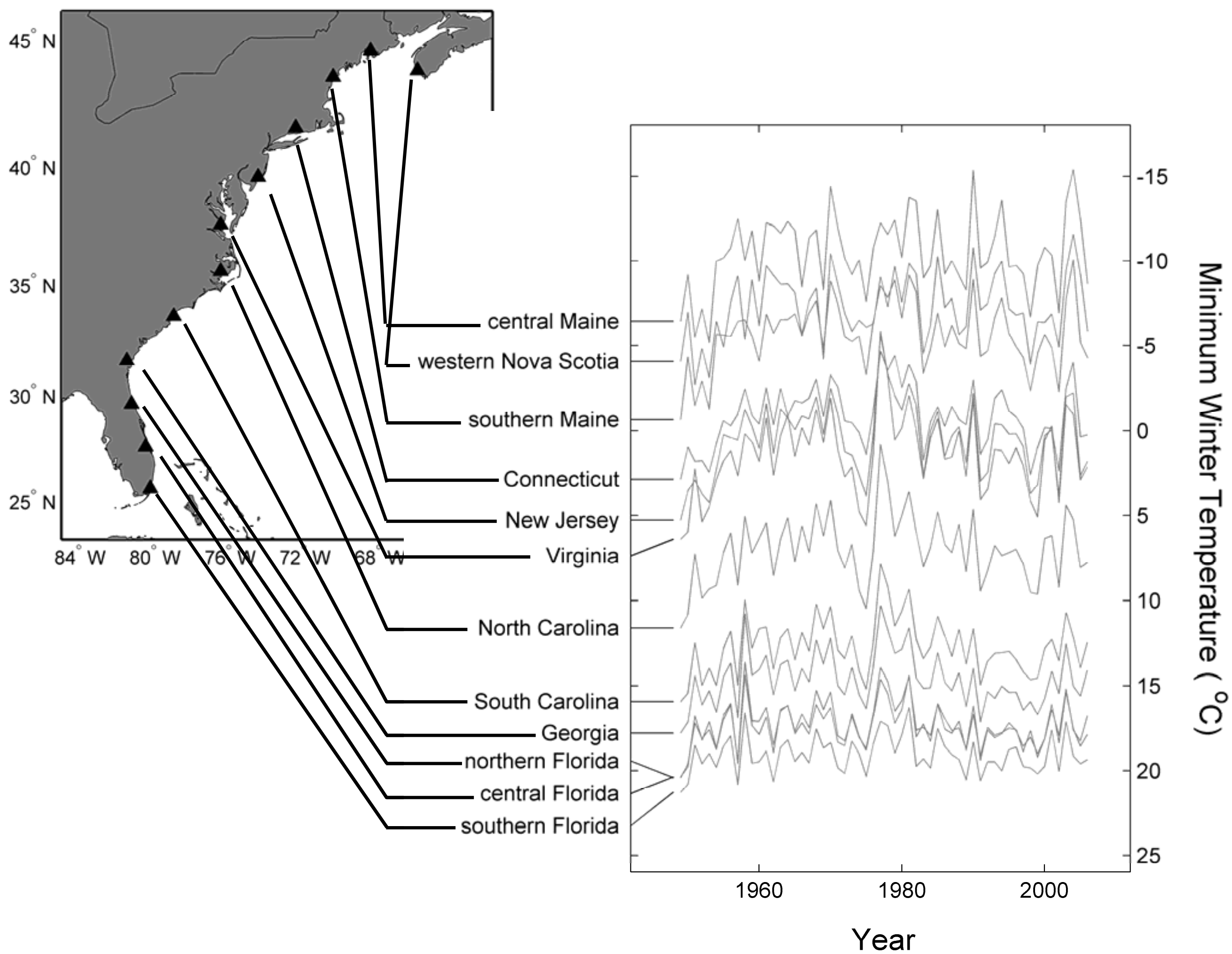

GFDL CM2.1 20th Century Runs
NCAR CCSM3.0 20th Century Runs
Model
Obs
Temperature (°C)
Year
Probability
Temperature (°C)
Mean Mod = 0.201; Diff = -0.492
STD Mod = 2.147; Diff = 0.151
Mean Mod = 3.713; Diff = 3.020
STD Mod = 1.961; Diff = -0.035
Model-Corrected

Figure A2



95% CI - GFDL
Observed
Power Spectral Density
Period (years)
95% CI - NCAR
Observed
Period (years)
95% CI - GFDL
Observed
Power Spectral Density
Period (years)
95% CI - NCAR
Observed
Period (years)

Figure A3



45° N
40° N
35° N
30° N
25° N
84° W
80° W
76° W
72° W
68° W
central Maine
western Nova Scotia
southern Maine
Connecticut
New Jersey
Virginia
North Carolina
South Carolina
Georgia
northern Florida
central Florida
southern Florida
-15
-10
-5
0
5
10
15
20
25
Minimum Winter Temperature (°C)
1960
1980
2000
Year

Figure A4

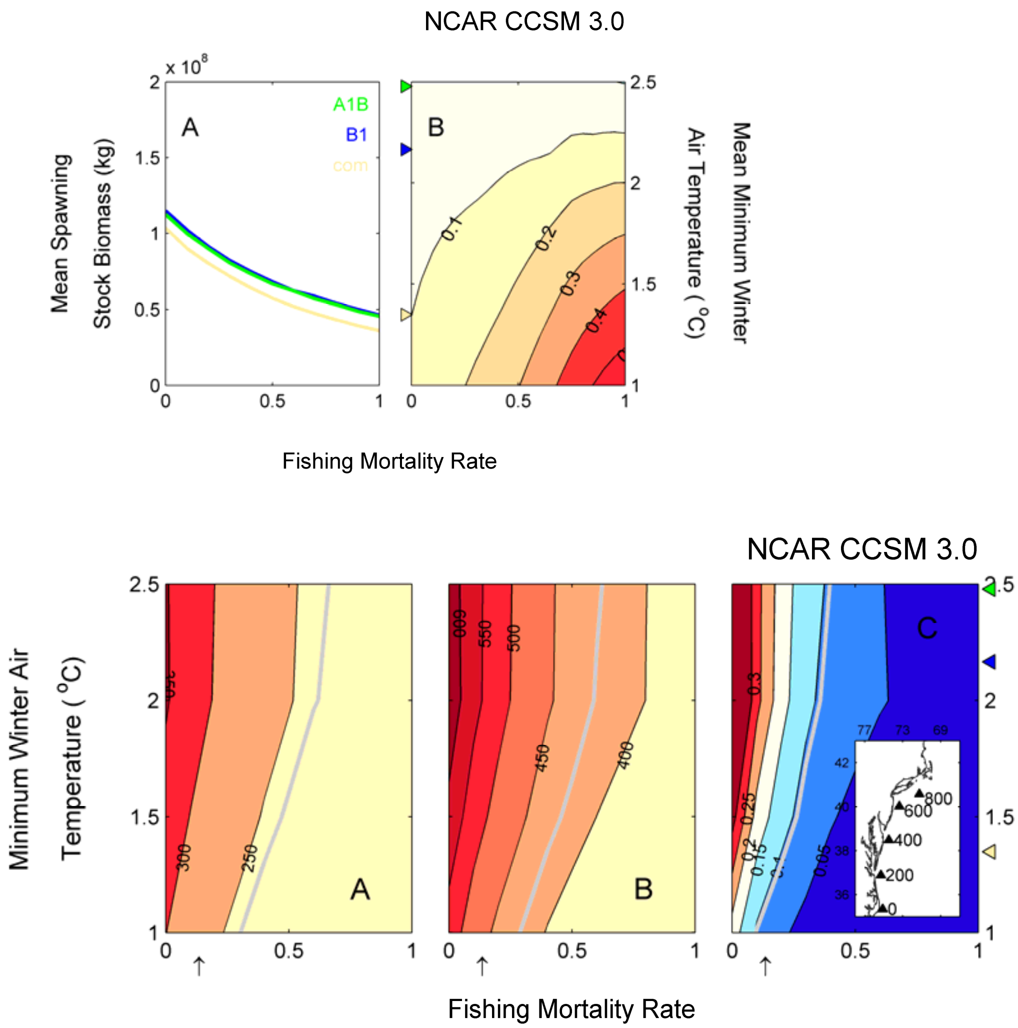
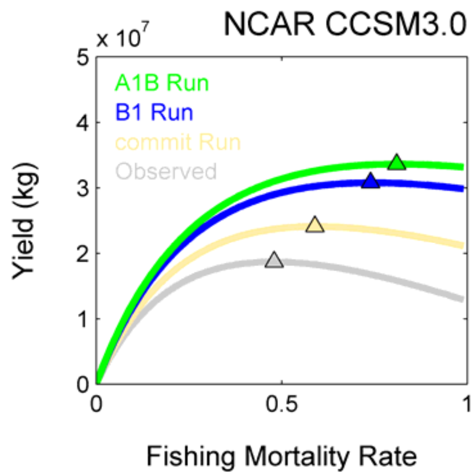

NCAR CCSM 3.0
x 10^8
Mean Spawning Stock Biomass (kg)
A
A1B
B1
com
B
0.1
0.2
0.3
0.4
Mean Minimum Winter Air Temperature (°C)
Fishing Mortality Rate
NCAR CCSM 3.0
Minimum Winter Air Temperature (°C)
300
250
A
600
550
500
450
400
B
C
0.3
0.25
0.2
0.15
0.1
0.05
77
73
69
42
40
38
36
800
600
400
200
0
Fishing Mortality Rate

Figure A5



NCAR CCSM3.0
x 10^7
A1B Run
B1 Run
commit Run
Observed
Yield (kg)
Fishing Mortality Rate
0
1
2
3
4
5
0
0.5
1