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INCORPORATING THE ATLANTIC MULTIDECADAL OSCILLATION INTO THE WESTERN ATLANTIC BLUEFIN TUNA STOCK ASSESSMENT

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SUMMARY

Since the mid-1990s, the catch per unit effort (CPUE) for Atlantic bluefin tuna in the U.S. rod and reel fishery and the CPUE of the Canadian fleet, operating in the Gulf of St. Lawrence and Nova Scotian waters, have conflicting trends. In the 2017 Atlantic bluefin tuna stock assessment, exploratory analysis revealed correlations between these indices and the Atlantic Multidecadal Oscillation (AMO) index, which is a measure of cyclical sea surface temperature. The 2017 western bluefin tuna stock assessment included a sensitivity run that used the AMO as an environmental variable to modulate catchability of U.S and Canadian indices. Here, we re-examine correlations between indices and the AMO as well as an updated sensitivity run for the 2020 western Atlantic bluefin tuna stock assessment incorporating the AMO. Results indicate that the AMO remains correlated with U.S. and Canadian indices. Incorporating the AMO in the assessment model significantly improved model fit to U.S. and Canadian indices, while producing similar parameter estimates and trends as models that did not incorporate the AMO.

RÉSUMÉ

Depuis le milieu des années 1990, la prise par unité d'effort (CPUE) de thon rouge de l'Atlantique dans la pêche américaine à la canne et au moulinet et la CPUE de la flottille canadienne, opérant dans le golfe du Saint-Laurent et les eaux de la Nouvelle Écosse, présentent des tendances contradictoires. Dans l'évaluation du stock de thon rouge de l'Atlantique de 2017, une analyse exploratoire a révélé des corrélations entre ces indices et l'indice de l'oscillation atlantique multidécennale (OAM), qui est une mesure de la température cyclique de la surface de la mer. L'évaluation du stock de thon rouge de l'Ouest de 2017 comprenait un scénario de sensibilité qui utilisait l'OAM comme variable environnementale pour moduler la capturabilité des indices américains et canadiens. Le présent document examine les corrélations entre les indices et l'OAM ainsi qu'un scénario de sensibilité mis à jour pour l'évaluation du stock de thon rouge de l'Atlantique Ouest de 2020, qui intègre l'OAM. Les résultats indiquent que l'OAM reste corrélée avec les indices américains et canadiens. L'intégration de l'OAM dans le modèle d'évaluation a considérablement amélioré l'ajustement du modèle aux indices américains et canadiens, tout en produisant des estimations et des tendances de paramètres similaires à celles des modèles qui n'intégraient pas l'OAM.

RESUMEN

Desde mediados de los 90, la capturas por unidad de esfuerzo (CPUE) para el atún rojo del Atlántico en la pesquería de caña y carrete estadounidense y la CPUE de la flota canadiense, que operan en aguas del golfo de San Lorenzo y de Nueva Escocia, presentan tendencias contradictorias. En la evaluación del stock de atún rojo del Atlántico de 2017, los análisis exploratorios revelaron correlaciones entre estos índices y el índice de Oscilación Multidecadal del Atlántico (AMO), que es una medida de la temperatura cíclica de la superficie del mar. La evaluación del stock de atún rojo del oeste de 2017 incluía un ensayo de sensibilidad que utilizaba el AMO como variable medioambiental para modular la capturabilidad de los índices estadounidense y canadiense. En este documento se reexaminan las correlaciones entre los índices y el AMO, así como un ensayo de sensibilidad actualizado para la evaluación de stock de

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atún rojo del Atlántico occidental de 2020 que incorpora el AMO. Los resultados indican que el AMO continúa correlacionado con los índices estadounidense y canadiense. Incorporar el AMO en el modelo de evaluación mejoró significativamente el ajuste del modelo a los índices estadounidense y canadiense, aunque produciendo similares estimaciones de parámetros y tendencias que los modelos que no incorporaban el AMO.

KEYWORDS

Atlantic bluefin tuna, stock assessment, catch per unit effort, sensitivity run, environmental effects, Atlantic Multidecadal Oscillation (AMO)

1. Background

Climate, and oceanographic factors are important determinants of the spatial-temporal distribution of Atlantic bluefin tuna (*Thunnus thynnus*; Humston *et al*. 2000, Schick *et al*. 2004, Schick and Lutcavage 2009, Golet *et al*. 2013, Druon *et al*. 2016). Evidence of warming ocean conditions is apparent in the Atlantic Ocean, with some regions, such as the northwest Atlantic, experiencing relatively rapid increases in sea surface temperature in the last decade (e.g., Pershing *et al*. 2015). Substantial shifts in the spatial distribution of Atlantic bluefin tuna have been documented in response to changing ocean conditions (e.g., Golet *et al*. 2013, Fromentin *et al*. 2014, MacKenzie *et al*. 2014, Druon *et al*. 2016). For example, large quantities of Atlantic bluefin were caught off the coast of Brazil in the 1960s, a phenomenon that has been associated with shifts in oceanographic conditions (Fromentin *et al*. 2014). Similarly, recent catches of bluefin tuna in waters east of Greenland, outside its historical range, have been associated with rising ocean temperatures (MacKenzie *et al*. 2014).

Since the mid-1990s the catch per unit effort (CPUE) of bluefin tuna in the United States (U.S.) rod and reel fishery has shown a general pattern of decline while the CPUE of the Canadian fleet, operating in the Gulf of St. Lawrence and Nova Scotian waters, has simultaneously increased (**Figure 1**). It is hypothesized that changes in CPUE could be the result of changing spatial distribution due to changing oceanographic conditions and not abundance (as assumed in the current stock assessment model). Similar distributional shifts were identified for North Atlantic swordfish (*Xiphias gladius*) and were attributed to a distributional shift to areas of preferred temperature (Schirripa *et al*. 2017). Changes in swordfish CPUE corresponded with changes in the summer Atlantic Multidecadal Oscillation (AMO), a long-term mode of variability of North Atlantic sea surface temperature (Enfield *et al*. 2001; **Figure 2; Figure 3**).

The most recent ICCAT stock assessment of western bluefin tuna attempted to resolve conflicting trends in U.S. and Canadian CPUE indices (ICCAT 2017a) by accounting for preferred habitat shifts, measured by sea surface temperature metrics. At the time, the assessment group explored integrating the AMO to modulate the catchability of indices in the context of the stock assessment. Stock Synthesis, a widely used integrated statistical catch-at-age model (Methot and Wetzel 2013), as well as virtual population analysis (VPA 2-box) were both used to assess the western Atlantic bluefin tuna stock in 2017 (ICCAT 2017a). Integration of AMO was conducted using Stock Synthesis as this model allows for the integration of environmental and ecosystem factors to influence the population dynamics and observation processes over time. In 2017, Stock Synthesis model runs included two base scenarios (younger and older spawning-age) and eleven sensitivity runs. One of the sensitivity runs (run 8, ICCAT 2017a) included AMO as a covariate to inform time-varying catchability. Specifically, the AMO index was used to scale potential changes in the availability of bluefin tuna to the Canadian combined index, the Canadian acoustic index and U.S. rod and reel >177 cm index. For each year, an average of AMO values for July, August and September were used. Ultimately, model runs of Stock Synthesis using the AMO were not used as the basis for advice, and the indices were removed from the Virtual Population Analysis model, thereby eliminating information from important fisheries from the stock assessment.

The purpose of this research was to: 1) present analyses examining the relationships between environmental drivers and U.S. and Canadian fishery indices and 2) update the 2017 ICCAT stock assessment which incorporated the AMO as an environmental variable to modulate catchability for the Canadian combined index, the Canadian acoustic index and the U.S. rod and reel >177 cm index (i.e., Stock Synthesis run 8). These analyses are part of a broader investigation of the spatio-temporal distribution of Atlantic bluefin catches in U.S. and Canadian waters to understand the effects of changing ocean conditions on bluefin tuna catch rates.

2. Methodology

We updated the exploratory analysis that was developed during the 2017 ICCAT stock assessment that informed the inclusion of AMO in the stock assessment model (ICCAT 2017a). The updated analysis incorporated additional years of data (2016–2018) and used generalized linear models to examine the relationship between standardized indices and the AMO. We evaluated the relationship of CPUE residuals from the base assessment model and the AMO for U.S. and Canadian indices that extend through the 2000s (U.S. rod and reel > 177, U.S. rod and reel 115_144, U.S. rod and reel 66_114, Canadian acoustic survey, and Canadian combined index).

In 2020, the Stock Synthesis stock assessment for western Atlantic bluefin tuna was updated with new data (Tsukahara *et al*. 2020). The model extends from 1950–2018 and is fit to length composition data, conditional length at age, 13 indices of relative abundance and 13 fishing fleets (**Figure 4**; **Figure 5**). The assessment assumed a western Atlantic area structure (mixed stocks occurring West of 45º longitude) with fleet designations designed to capture spatial/temporal structure. All model specifications from the ICCAT 2017 stock assessment remained the same. Here we compare the results of the base model run (i.e., not incorporating AMO) to a sensitivity run using the AMO as an environmental variable to modulate the catchability of the Canadian combined index, the Canadian acoustic survey and U.S. rod and reel > 177 cm index. Besides the incorporation of the AMO, both model runs are the same and assume the older maturity-at-age schedule (100% at age 13). For more details on model set up see Tsukahara *et al*. (2020). Model comparisons were based on Akaike information criterion (AIC) to account for improved goodness of fit (i.e., likelihood) and the addition of three estimated parameters.

3. Results

3.1 Catch rates and the Atlantic Multidecadal Index (AMO)

Since the last assessment in 2017, the Canadian combined index has remained at a high level consistent with the trend, however, the Canadian acoustic survey and the U.S. rod and reel > 177 cm indices changed relative to the trend (**Figure 1**). During the ICCAT assessment meeting there was concern and discussion as to whether the 2018 estimate from the Canadian acoustic survey was representative of a decline in productivity or more likely reflected a shift in local availability. Ultimately, the 2018 year effect estimate for the Canadian acoustic survey was not included in the base case scenario for the 2020 assessment and thus was removed from the analysis presented here (see Tsukahara *et al*. 2020).

Since the 2017 ICCAT stock assessment, AMO values remained positive (**Figure 2**). Evaluation of the relationship between standardized indices and the AMO revealed U.S. rod and reel indices (U.S. rod and reel 66-144, U.S. rod and reel 115-144, U.S. rod and reel > 177 cm) exhibited moderate to weak negative correlations with the AMO that were not statistically significant (**Figure 6**). In contrast, both the Canadian acoustic and combined survey exhibited positive correlations with the AMO, with the relationship with the Canadian Acoustic survey non-significant and the relationship with the Canadian combined index statistically significant (**Figure 7**).

3.2 Stock Synthesis model results

The model run using the AMO had similar diagnostic performance as the model run not incorporating the AMO. Both runs exhibited a maximum gradient that was higher than desirable. However, none of the parameters hit bounds and most parameters had relatively low standard deviations relative to estimated values, indicating decent estimation (**Table 1; Table 2**).

In general, incorporating the AMO significantly improved total model fit and fit to U.S. and Canadian indices (AIC without AMO = 13509.8, AIC with AMO = 13446.6; (**Table 1; Figure 8**). However, neither model fit the U.S. rod and reel > 177 cm index particularly well early in the time series. The inclusion of AMO improved fit for the Canadian acoustic survey, particularly in the most recent years (**Figure 8**). For the Canadian combined index, both model runs had difficulty fitting to the index after 2008. However, the model run with the AMO had an improved fit with most year estimates falling inside observation error estimates. Both models demonstrated similar, relatively good fit to the length composition data (**Figure 9**).

Both models estimated similar trends, in which the stock decreased during the 1970s remaining relatively low during the 1980–2000 period with a pattern of steady population growth since 2000 (**Figure 10**). Recruitment trends were similar, with both models estimating interannual variation in recruitment (**Figure 11**).

4. Discussion

The goal of the AMO model run was to resolve conflicting CPUE trends between the U.S. and Canadian indices. Since the last assessment in 2017, Canadian indices have a positive correlation with the AMO, while U.S. indices have a negative correlation. Incorporating the AMO as a modulate for catchability improved stock assessment fit to U.S. and Canadian indices, while producing similar parameter estimates and trends as models that did not incorporate the AMO. These results agree with the 2017 Stock Synthesis assessment (Walter, *et al*., 2018), and indicate that a warming pattern in the northwest Atlantic might cause a shift in bluefin tuna distribution away from U.S. waters and towards Canadian waters. However, abundance trends in recent years have shifted, with increases in the U.S. rod and reel > 177 cm index and decreases in the Canadian acoustic survey. If similar trends continue or are observed in other indices the hypothesis of a northward shift in spatial distribution should be reexamined.

Similar to bluefin tuna, Atlantic swordfish are highly migratory, and it is hypothesized their distribution has shifted northwards (Schirripa *et al*. 2017). In the 2017 swordfish stock assessment, catchability for eight indices were made a function of the AMO, including a western Canadian longline index. Similar to the results presented here, modeling swordfish catchability as a function of the AMO improved stock assessment model fit (ICCAT 2017b).

In general, it is difficult to determine if changes in relative abundance are a function of catchability or productivity. The model run presented here, assumed the AMO is influencing catchability and not productivity, because productivity effects should influence the entire population and all abundance indices. If this assumption is incorrect the model could be inaccurately detrending abundance estimates when productivity is increasing. Tuna productivity has been correlated with sea surface temperature (Muhling *et al*. 2018) and the AMO could be used in Stock Synthesis to help inform recruitment estimates. Future work aims to further explore the relationship of western bluefin tuna CPUE indices to the AMO and other environmental indices (e.g., water temperature anomalies, North Atlantic Oscillation Index) at finer spatial scales. Results of this work are expected to help detangle the effects of environmental covariates on catchability and productivity so future assessment models can be accurately parametrized.

5. Conclusions

Canadian indices of abundance have a positive correlation with the AMO, while U.S. indices have a negative correlation. For the 2020 western bluefin tuna stock assessment, using AMO as an environmental modulate for catchability significantly improved model fit to U.S. and Canadian indices, while producing similar parameter estimates and trends as models that did not incorporate the AMO. Results help to reconcile conflicting U.S. and Canadian CPUE trends. Future work aims to improve understanding of the AMO and other environmental covariates on bluefin tuna catchability and productivity to better inform future stock assessments.

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Table 1. For the 2020 western bluefin tuna stock assessment, key diagnostics and likelihood components for models that did not incorporate the Atlantic Multidecadal Oscillation (AMO) and did incorporate the AMO.

Parameters	**No AMO**	**AMO**
AIC	13509.8	13446.6
Number of Parameters	107	110
Max gradient	0.0148904	0.0227846
Total Likelihood	6.65E+03	6.61E+03
Catch	1.73E-11	1.79E-11
Equil_catch	4.50E+00	4.41E+00
Indices	6.91E+02	6.61E+02
Length_comp	4.10E+03	4.09E+03
Age_comp	1.84E+03	1.84E+03
Recruitment	1.26E+01	1.23E+01
InitEQ_Regime	0.00E+00	0.00E+00
Forecast_Recruitment	0.00E+00	0.00E+00
Parm_priors	2.55E-01	2.55E-01
Parm_softbounds	1.10E-02	1.09E-02
Parm_devs	5.98E-01	5.98E-01
Crash_Pen	0.00E+00	0.00E+00

Table 2. For the 2020 western bluefin tuna stock assessment, estimated parameters for model run incorporating the Atlantic Multidecadal Oscillation (AMO).

Estimated Parameters	Value	Phase	Min	Max	Init	Status	Parm_StDev	Gradient	Pr_type	Prior	Pr_SD	Pr_Like	Afterbound
L_at_Amax_Fem_GP_1	264.074	4	2.00E+02	400	264.067	OK	7.51E-01	-9.73E-04	No_prior	NA	NA	NA	OK
VonBert_K_Fem_GP_1	0.301933	4	5.00E-02	0.4	0.302645	OK	8.97E-03	7.37E-03	No_prior	NA	NA	NA	OK
Richards_Fem_GP_1	-0.945559	4	-3.00E+00	3	-0.951164	OK	7.58E-02	1.69E-02	No_prior	NA	NA	NA	OK
CV_young_Fem_GP_1	0.0898458	3	5.00E-02	0.25	0.0900561	OK	5.58E-03	2.90E-04	No_prior	NA	NA	NA	OK
CV_old_Fem_GP_1	0.0697953	3	2.00E-02	0.25	0.0698243	OK	1.56E-03	8.02E-05	No_prior	NA	NA	NA	OK
SR_LN(R0)	6.37745	1	5.00E+00	10	7	OK	3.51E-02	2.25E-02	No_prior	NA	NA	NA	OK
SR_BH_steep	0.625599	2	2.00E-01	0.99	0.618617	OK	3.03E-02	2.02E-03	No_prior	NA	NA	NA	OK
SR_sigmaR	0.79231	6	2.00E-01	2	0.783987	OK	9.15E-02	-3.09E-03	No_prior	NA	NA	NA	OK
InitF_seas_1_flt_4USA_TRAP	0.0158075	5	1.00E-05	0.03	0.0157949	OK	2.41E-03	-1.32E-04	No_prior	NA	NA	NA	OK
LnQ_base_IDX5_US_RR_GT177(18)	-4.50979	1	-1.00E+01	-2	-4.43248	OK	7.04E-02	8.86E-05	No_prior	NA	NA	NA	OK
LnQ_base_IDX9_CAN_GSLNS(22)	-4.40168	1	-1.00E+01	-2	-4.38135	OK	6.23E-02	8.76E-05	No_prior	NA	NA	NA	OK
LnQ_base_IDX12_CAN_ACOUSTIC(25)	-5.59637	1	-1.00E+01	-2	-5.77869	OK	1.12E-01	1.01E-04	No_prior	NA	NA	NA	OK
LnQ_base_IDX5_US_RR_GT177(18)_ENV_mult	0.130048	3	-5.00E+00	5	0	OK	4.63E-02	-1.26E-04	No_prior	NA	NA	NA	OK
LnQ_base_IDX9_CAN_GSLNS(22)_ENV_mult	-0.277823	3	-5.00E+00	5	0	OK	3.71E-02	-1.29E-04	No_prior	NA	NA	NA	OK
LnQ_base_IDX12_CAN_ACOUSTIC(25)_ENV_mult	-0.0834657	3	-5.00E+00	5	0	OK	4.37E-02	-1.97E-04	No_prior	NA	NA	NA	OK
Size_DblN_peak_JAPAN_LL(1)	211.713	2	1.20E+02	230	211.961	OK	2.89E+00	9.51E-07	No_prior	NA	NA	NA	OK
Size_DblN_top_logit_JAPAN_LL(1)	-9.71816	2	-1.00E+01	3	-9.71893	OK	7.89E+00	2.15E-07	No_prior	NA	NA	NA	OK
Size_DblN_ascend_se_JAPAN_LL(1)	6.8374	3	-5.00E+00	9	6.83689	OK	1.55E-01	2.41E-06	No_prior	NA	NA	NA	OK
Size_DblN_end_logit_JAPAN_LL(1)	-12.0246	4	-2.00E+01	10	-12.0432	OK	1.01E+02	-1.96E-07	No_prior	NA	NA	NA	OK
Size_DblN_ascend_se_USA_CAN_PSFS(2)	3.72453	4	-4.00E+00	12	3.72305	OK	4.45E-01	-1.46E-03	Sym_Beta	0.5	0.1	1.16E-04	OK
Size_DblN_top_logit_USA_CAN_PSFB(3)	-2.39377	2	-5.00E+00	3	-2.41505	OK	3.33E-01	3.20E-05	No_prior	NA	NA	NA	OK
Size_DblN_ascend_se_USA_CAN_PSFB(3)	6.92014	3	-4.00E+00	8	6.92066	OK	7.26E-02	-3.82E-05	Sym_Beta	0.5	0.1	1.12E-01	OK
Size_DblN_end_logit_USA_CAN_PSFB(3)	-2.31982	4	-1.50E+01	5	-2.31435	OK	5.10E-01	8.59E-05	No_prior	NA	NA	NA	OK
Size_DblN_peak_USA_TRAP(4)	114.229	1	8.00E+01	150	114.232	OK	1.13E+01	2.00E-04	No_prior	NA	NA	NA	OK
Size_DblN_top_logit_USA_TRAP(4)	-1.89389	3	-5.00E+00	3	-1.89395	OK	6.28E-01	1.53E-04	Sym_Beta	-4	0.1	5.12E-03	OK
Size_DblN_ascend_se_USA_TRAP(4)	7.15967	3	-4.00E+00	8	7.15925	OK	4.76E-01	-2.35E-04	No_prior	NA	NA	NA	OK
Size_DblN_descend_se_USA_TRAP(4)	7.25171	3	-2.00E+00	10	7.25129	OK	5.08E-01	1.99E-04	Sym_Beta	1.2	0.1	3.48E-02	OK
Size_inflection_USA_CAN_HARPOON(5)	177.043	2	1.00E+02	220	177.017	OK	8.06E-01	4.08E-05	No_prior	NA	NA	NA	OK
Size_95%width_USA_CAN_HARPOON(5)	17.0545	2	1.00E+01	60	17.0455	OK	1.14E+00	-2.00E-06	No_prior	NA	NA	NA	OK
Size_DblN_peak_USA_RRFB(6)	192.757	1	1.40E+02	220	192.859	OK	8.16E-01	4.95E-05	Normal	190	50	1.52E-03	OK
Size_DblN_end_logit_USA_RRFB(6)	-0.866936	2	-1.50E+01	5	-0.902806	OK	3.13E-01	7.93E-05	No_prior	NA	NA	NA	OK
Size_DblN_peak_USA_RRFS(7)	106.401	1	8.00E+01	120	106.406	OK	6.08E-01	6.93E-06	Normal	106	40	5.03E-05	OK
Size_inflection_OTHER_ATL_LL(8)	157.076	2	1.00E+02	200	157.006	OK	2.11E+00	2.45E-05	No_prior	NA	NA	NA	OK
Size_95%width_OTHER_ATL_LL(8)	46.2025	2	1.00E+01	100	46.1926	OK	2.07E+00	-8.33E-06	No_prior	NA	NA	NA	OK
Size_inflection_CAN_HOOKLINE(9)	194.689	2	1.50E+02	250	194.535	OK	1.37E+00	-4.46E-06	No_prior	NA	NA	NA	OK
Size_95%width_CAN_HOOKLINE(9)	32.8141	2	3.00E+01	50	32.698	OK	1.53E+00	3.31E-07	No_prior	NA	NA	NA	OK
Size_inflection_GOM_LL_US_MEX(10)	213.828	2	1.50E+02	250	213.499	OK	2.14E+00	4.62E-07	No_prior	NA	NA	NA	OK
Size_95%width_GOM_LL_US_MEX(10)	38.8435	2	2.00E+01	50	38.5612	OK	2.28E+00	-3.85E-07	No_prior	NA	NA	NA	OK
Size_inflection_JLL_GOM(11)	200.132	2	1.50E+02	250	200.062	OK	3.98E+00	2.27E-05	No_prior	NA	NA	NA	OK
Size_95%width_JLL_GOM(11)	22.3709	2	1.00E+01	50	22.3399	OK	4.86E+00	-1.41E-06	No_prior	NA	NA	NA	OK
Size_inflection_CAN_TRAP(12)	253.087	2	2.30E+02	300	252.908	OK	3.90E+00	3.42E-06	No_prior	NA	NA	NA	OK
Size_95%width_CAN_TRAP(12)	55.1176	2	4.00E+01	80	55.2127	OK	2.72E+00	-1.08E-06	No_prior	NA	NA	NA	OK
Size_inflection_CAN_GSL1(13)	255.518	2	2.00E+02	300	255.399	OK	1.73E+00	-4.50E-05	No_prior	NA	NA	NA	OK
Size_95%width_CAN_GSL1(13)	19.1309	2	1.00E+01	50	19.4575	OK	2.24E+00	1.69E-06	No_prior	NA	NA	NA	OK
Size_DblN_top_logit_JAPAN_LL(1)_BLK1repl_1950	-4.12972	5	-1.00E+01	1	-4.18893	OK	7.47E-01	2.19E-04	No_prior	NA	NA	NA	OK
Size_DblN_ascend_se_JAPAN_LL(1)_BLK1repl_1950	7.59617	5	-1.00E+00	9	7.59601	OK	3.27E-02	-1.15E-03	No_prior	NA	NA	NA	OK
Size_DblN_end_logit_JAPAN_LL(1)_BLK1repl_1950	-4.60501	5	-2.00E+01	1	-4.62704	OK	7.82E-01	3.50E-04	No_prior	NA	NA	NA	OK
Size_DblN_peak_USA_RRFS(7)_BLK3repl_1950	88.4597	4	6.00E+01	110	88.457	OK	7.96E-01	3.09E-04	Normal	88	30	1.17E-04	OK

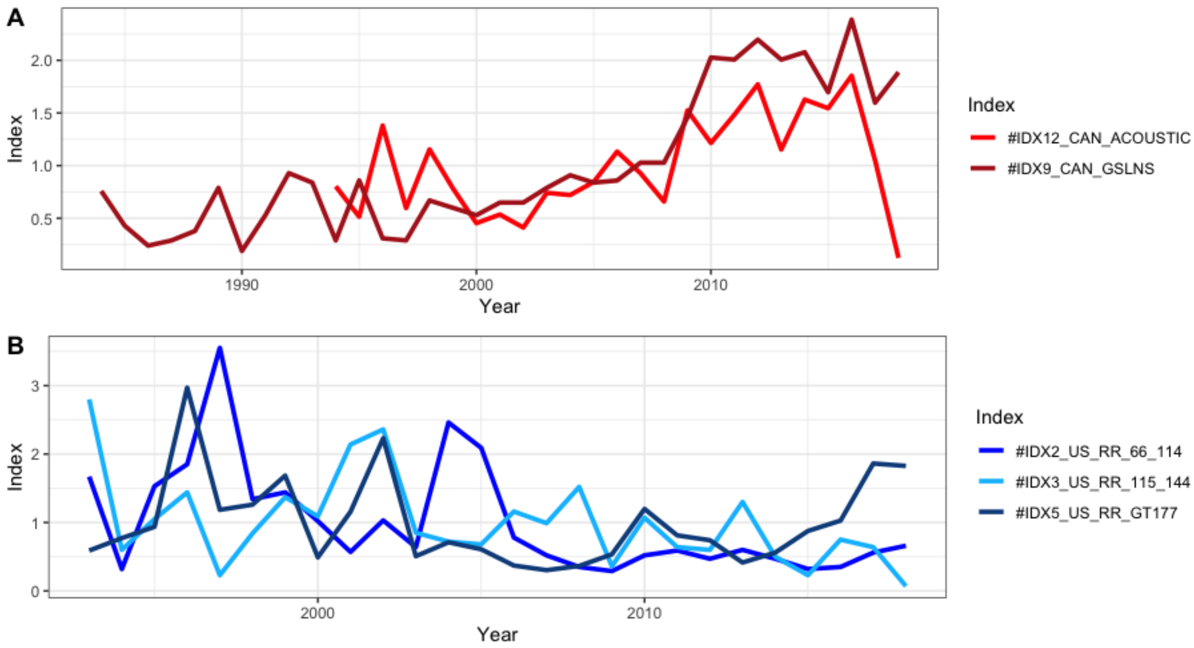

Figure 1. Canadian (A) and United States (B) indices of abundance used in 2020 western Atlantic bluefin tuna stock assessment. The 2018 year effect estimate from the Canadian acoustic survey was not used in the base stock assessment model run.

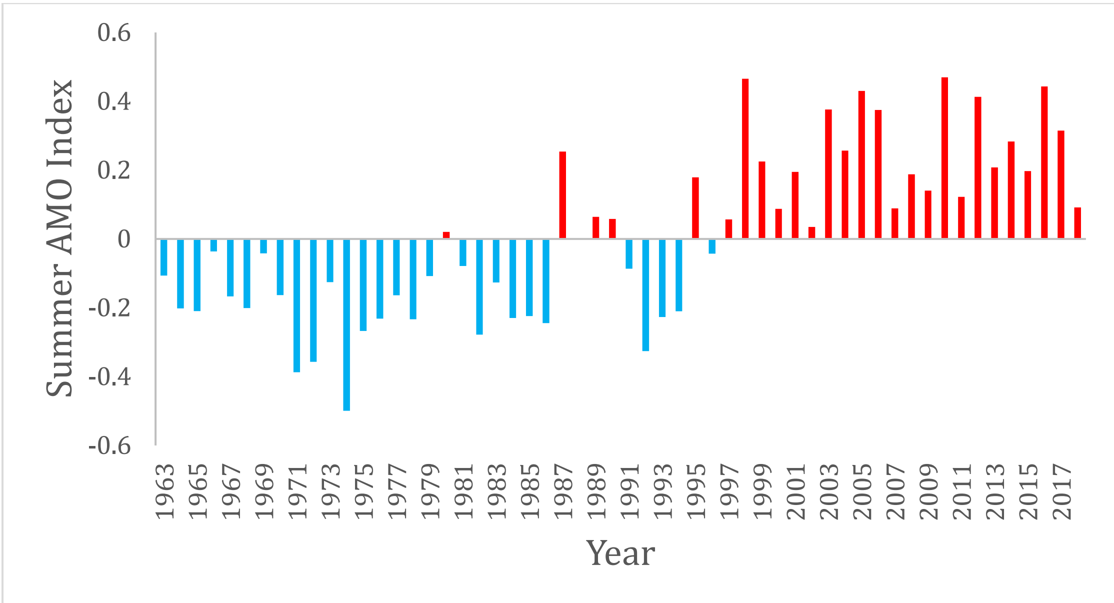

Figure 2. Average Atlantic Multidecadal Oscillation (AMO) values for July, August, and September.

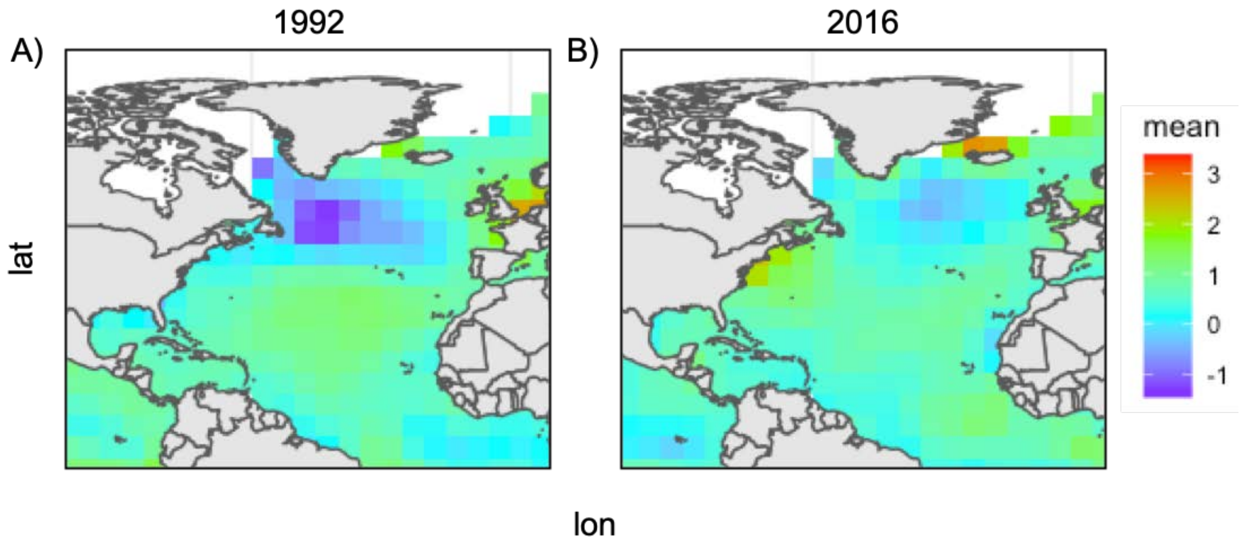

Figure 3. Spatial comparison for cold (1992) and warm years (2016) of average Atlantic Multidecadal Oscillation (AMO) values for July, August, and September. Spatial resolution is 5x5 ° grid from Kaplan extended sea surface temperature version 2 (NOAA, 2020).

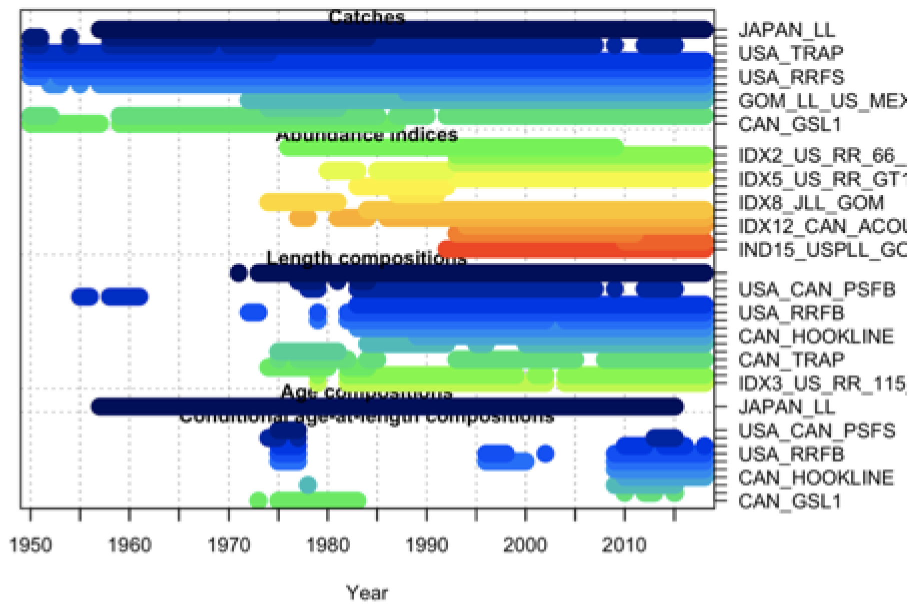

Figure 4. For the 2020 western bluefin tuna stock assessment, data presence by year for each fleet and data type.

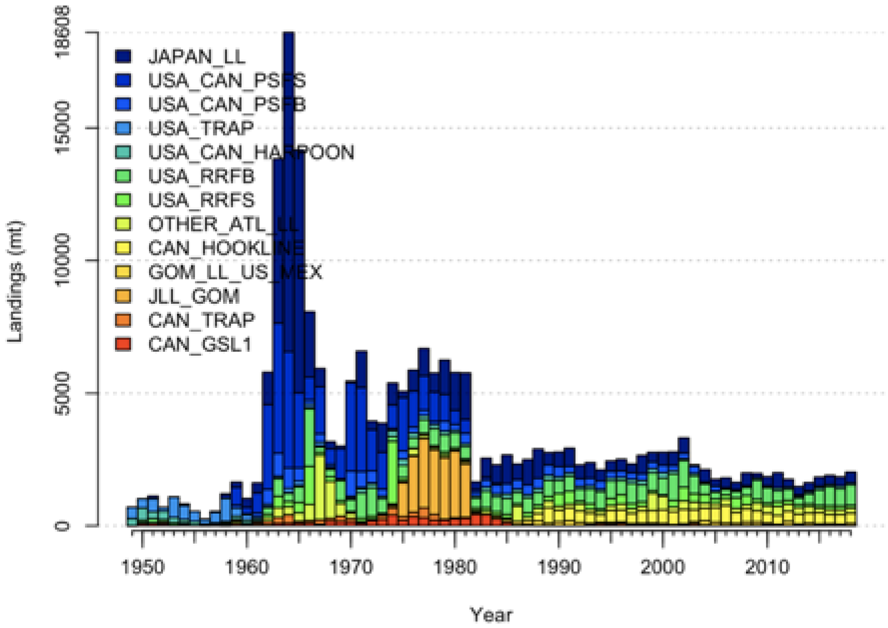

Figure 5. Landings by fleet for western Atlantic bluefin tuna.

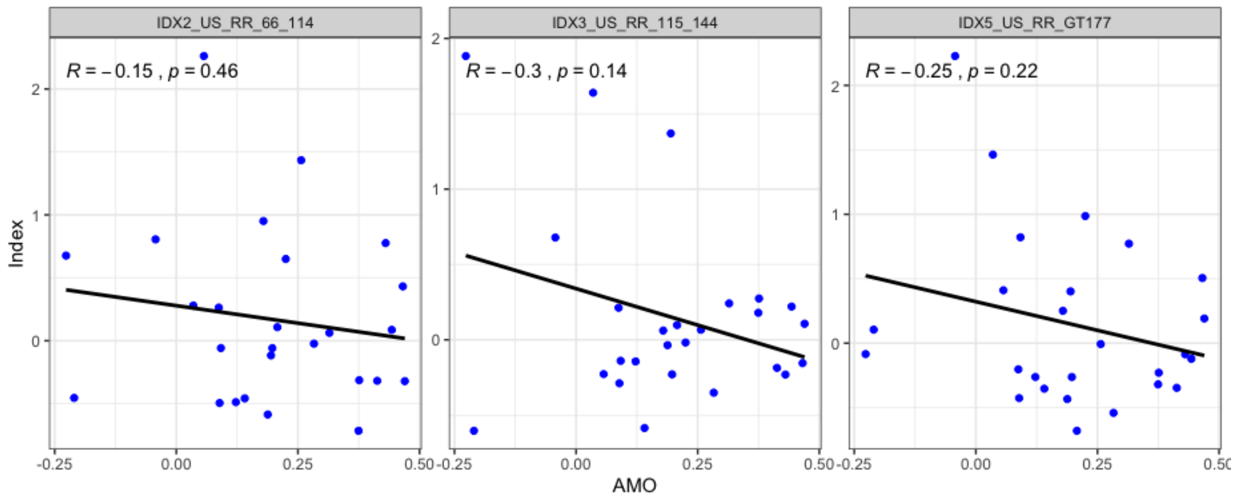

Figure 6. Correlation between United States rod and reel indices and the Atlantic Multidecadal Oscillation (AMO) index.

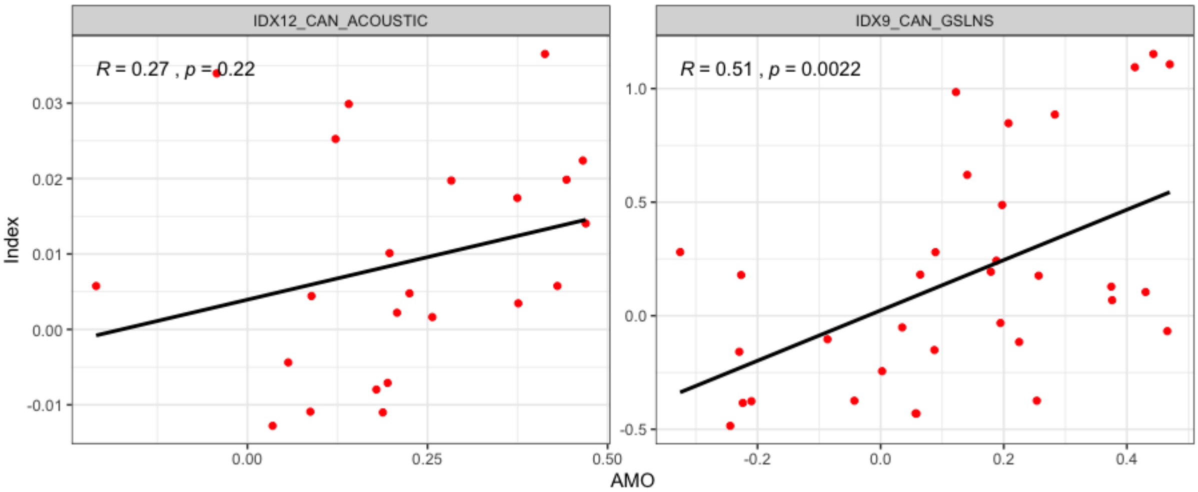

Figure 7. Correlation between Canadian indices and the Atlantic Multidecadal Oscillation (AMO) index. The 2018 year effect estimate from the Canadian acoustic survey is not included in this analysis.

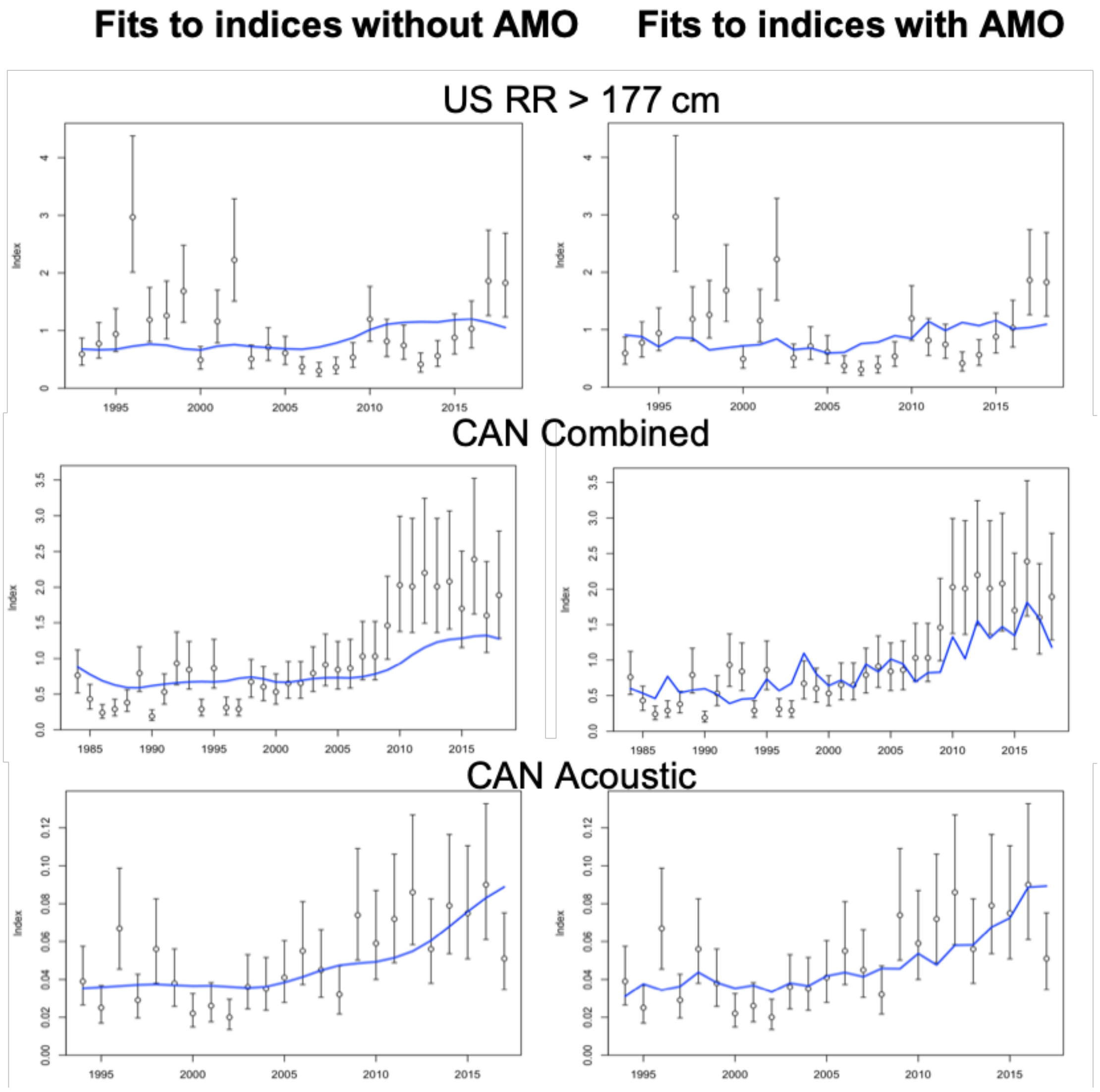

Figure 8. Fit of different stock assessment runs to the U.S. rod and reel > 177 cm index, Canadian combined index and the Canadian acoustic survey. Panels on the left are from a model run not using the Atlantic Multidecadal Oscillation (AMO) index and panels on the right are from a model run using the AMO.

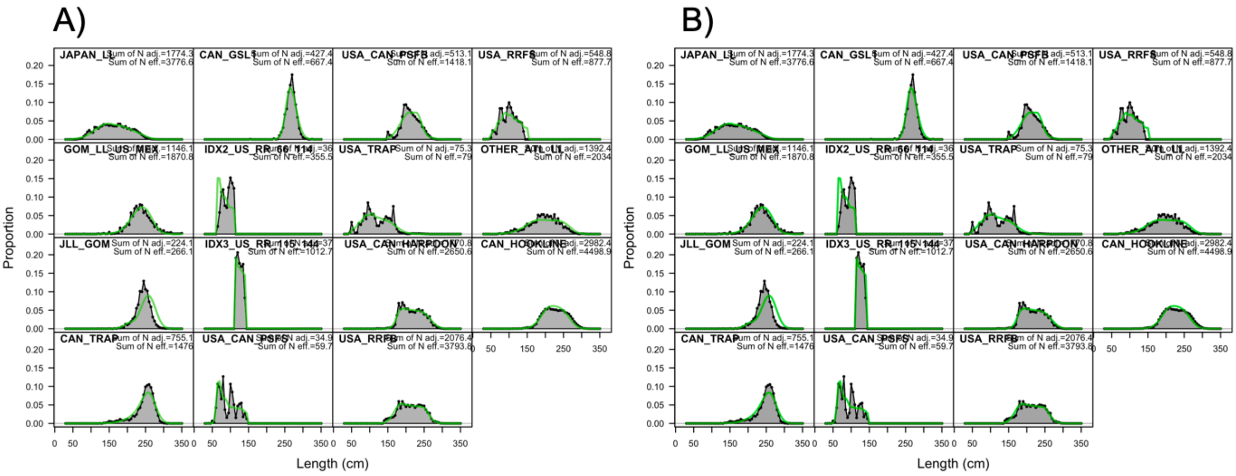

Figure 9. Fits to length composition data aggregated across time by fleet for model runs not incorporating the Atlantic Multidecadal Oscillation index (AMO; A) and the AMO (B).

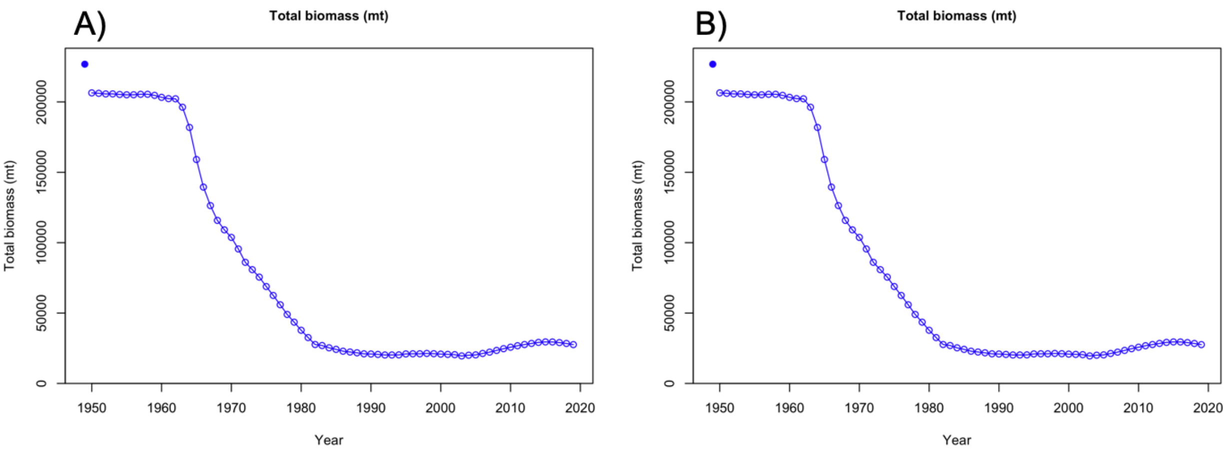

Figure 10. Total biomass trends for model runs not incorporating the Atlantic Multidecadal Oscillation index (AMO; A) and the AMO (B).

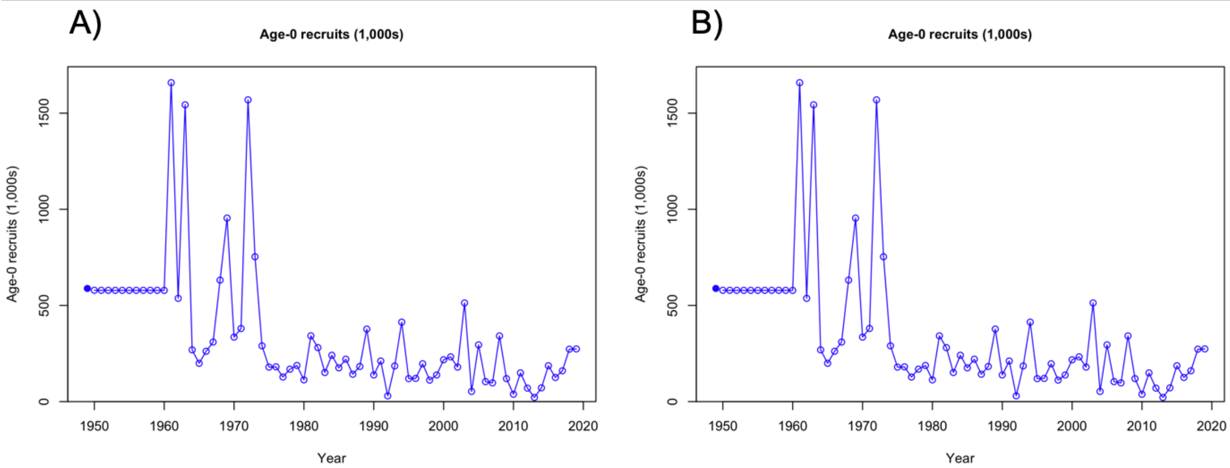

Figure 11. Recruitment estimates from model runs not incorporating the Atlantic Multidecadal Oscillation index (AMO; A) and the AMO (B).