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LONGLINE DATA SIMULATION: INTEGRATING 3-D SPECIES HABITAT WITH OCEANOGRAPHIC DATA AND DEPTH DISTRIBUTIONS OF PELAGIC LONGLINE HOOKS

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SUMMARY

The ICCAT Working Group on Stock Assessment Methods (WGSAM) has recommended the use of simulated data sets with known values of underlying population trends to test the robustness of CPUE standardization methods. This recommendation was furthered by the swordfish working group and the Sub-Committee on Ecosystems who both recommended that oceanographic variability be formally used in CPUE standardization. Here we use a habitat suitability model (HSM) to investigate the size and 3-D spatial distribution of blue marlin habitat using weighted habitat volume (H). H was estimated from monthly average oceanographic data partitioned by 1° of latitude and 1° of longitude in 50 layers from the surface to a depth of 1200m. Fluctuations in habitat volume contribute to seasonal and longer-term fluctuations in CPUE that are independent of population abundance and add uncertainty to abundance indices used to estimate population benchmarks. The results highlight the need to expand stock assessments to include annual climatology to account for changes in habitat volume and global warming. The HSM-based model offers a way to validate analytical methods for using longline CPUE to monitor populations.

RÉSUMÉ

Le groupe de travail sur les méthodes d'évaluation des stocks de l'ICCAT (WGSAM) a recommandé d'utiliser des jeux de données simulées avec des valeurs connues des tendances sous-jacentes de la population afin de tester la solidité des méthodes de standardisation de la CPUE. Cette recommandation a été secondée par le groupe d'espèces sur l'espadon et le Sous-comité des écosystèmes qui ont tous deux recommandé d'utiliser officiellement la variabilité océanographique pour standardiser la CPUE. Le présent document décrit l'utilisation d'un modèle de qualité de l'habitat (HSM) pour étudier la taille et la distribution spatiale en trois dimensions de l'habitat du makaire bleu en appliquant le volume de l'habitat pondéré (H). H a été estimé à partir des données océanographiques moyennes mensuelles divisées par 1° de latitude et 1° de longitude en 50 couches entre la surface et une profondeur de 1.200 m. Les fluctuations du volume de l'habitat contribuent aux fluctuations saisonnières et à long terme de la CPUE qui sont indépendantes de l'abondance de la population et ajoutent une incertitude aux indices d'abondance utilisés pour estimer les points de référence de la population. Les résultats mettent en évidence la nécessité d'élargir les évaluations des stocks et d'y inclure la climatologie annuelle afin de tenir compte des changements du volume de l'habitat et du réchauffement climatique. Le modèle fondé sur HSM offre un moyen de valider les méthodes analytiques afin d'utiliser la CPUE palangrière pour contrôler les populations.

RESUMEN

El Grupo de trabajo ICCAT sobre métodos de evaluación de Stock (WGSAM) recomendó que se utilicen conjuntos de datos simulados con valores conocidos de las tendencias subyacentes de la población para probar la robustez de los métodos de estandarización de la CPUE. Esta recomendación fue respaldada por el grupo de especies de pez espada y el Subcomité de ecosistemas que recomendaron ambos la utilización formal de la variabilidad oceanográfica en la estandarización de la CPUE. En este documento se utiliza un modelo de idoneidad de hábitat

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(HSM) para investigar el tamaño y distribución espacial tridimensional del hábitat de la aguja azul por mes, usando el volumen de hábitat ponderado (H). H se estimó a partir del promedio mensual de datos oceanográficos, desglosados en cuadrículas de 1º latitud x 1º de longitud, en 50 capas desde la superficie hasta una profundidad de 1.200 m. Las fluctuaciones en el volumen de hábitat contribuyen a las fluctuaciones estacionales y, más a largo plazo, a las de la CPUE. Estas fluctuaciones son independientes de la abundancia de la población y agregan incertidumbre a los índices de abundancia utilizados para estimar niveles de referencia de la población. Los resultados resaltan la necesidad de ampliar las evaluaciones de stock para incluir la climatología anual para tener en cuenta los cambios en el volumen de hábitat y el calentamiento global. El modelo basado en HSM ofrece una manera de validar métodos analíticos para el uso de CPUE de palangre para hacer un seguimiento de la población.

KEYWORDS

Environmental effects, Habitat, Fishery oceanography, Spatial distribution, Pelagic Longlines, Population models, Stock assessment, Climate change, Simulation models

1. Introduction

Previously, the ICCAT Working Group on Stock Assessment Methods (WGSAM) recommended in 2003 to use simulated data sets with known values of underlying population trends to test the robustness of CPUE standardization methods (Anon. 2004). The recommendation was renewed by the 2015 WGSAM (Anon. 2016). During the 2015 meeting of the WGSAM the topic of the "Incorporation of oceanographic and environmental changes in the stock assessment process" was discussed. It was noted that broadly, the environment can have two types of effects on a population: an effect on the distribution, or an effect on the productivity of the stock. Likely these two effects are not mutually exclusive, but in practice may be difficult to differentiate. Generally, the group expressed interest in a simulation to inform how to best capture environmental effects on a given species with the available data. Basically, to answer this question it would be necessary to simulate an environmental effect on a fish population, sample from the simulated population with an idealized fishing fleet, and then test whether the environmental effect could be standardized via analysis of the data. The Group noted that the background for the simulation study comes from the 2014 WGSAM work plan.

At that same meeting the group further discussed a paper entitle "Proposed study design for best practices when including environmental information into ICCAT indices of abundance". The group agreed on the structure of the study as well as the establishment of an ad hoc simulation working group and a separate analysis group. Work on this investigation has proceeded a bit slower than anticipated, however significant progress has been made. A dedicated position has been created to assist in the investigation. Furthermore, we now have access a long-term time series (1948-2012) of model-base oceanographic variables. This model is called the Community Earth System Model version 1 (CESM 1) developed by the National Center for Atmospheric Research (Gent *et al.*, 2011; Stowe *et al.*, 2009). It is a global climate ocean-sea-ice coupled model that is also coupled to a biogeochemistry model BEC (Biogeochemical Elemental Cycle).

This paper describes preliminary work that is used to demonstrate how the more extensive study will take form. A Habitat Suitability Model (HSM) approach coupled with blue marlin biology, to distribute fish according to suitable preferred temperature and dissolved oxygen. U.S. fisheries longline effort is used to sample the fish throughout the year and to produce simulated catch per unit effort for subsequent analysis. The objective of the current stage of the work is to populate the HMS model with the appropriate environmental data as well as the U.S. longline effort data.

2. Material and methods

Simulation model. A longline CPUE data simulator (LLSIM) was developed to meet the earlier requirement to simulate known data for testing a variety of hypotheses (Goodyear 2006). The core element of the simulation is the catch on a single hook of a longline set. Each hook has a depth probability distribution and attributes of latitude, longitude, year, month, time of day, and position along the longline. Each of these attributes is associated with the individual longline set. T-he catch is a probabilistic event and is simulated for each hook of each set. The simulator has been applied to evaluate several aspects of longline data related to effects of environmental attributes and the implications of shifts in species targeting by the fisheries (Goodyear and Bigelow 2010, Goodyear and Bigelow 2012, Schirripa and Goodyear 2010). The original LLSIM code was written in Compaq Fortran V6 which is no longer supported. To meet the more recent working group requirements. The longline simulator was rewritten to the public domain GNU Fortran specification using the Simply Fortran 2 IDE available at http://approximatrix.com/. The new code, designated LLSIM (V2) and available from the second author, is now undergoing validation analysis. The X-Y spatial structure of the simulator is from 35S to 55N latitude and 95W to 20E longitude, exclusive of major land masses. This area is broken down into 7067 cells; each cell is 1 degree of latitude by 1 degree of longitude. All spatial distributions of input and output variables reference an array of cell identities. Each longitude-latitude cell is also divided into depth strata. The number and depth of the depth strata are arbitrary. The initial number of depth layers was set at 50, but it can be easily modified as needed. The depths of each layer can be readily adjusted and will be selected based on the layer structure of the best available oceanographic data. The model requires input specifications of the three-dimensional distributions of species and gear by month and year.

Environmental Data. Application of the HSM approach to predict the spatial distribution of a species requires quantitative data about the physical environmental variables that are important determinants of its habitat. Temperature and dissolved oxygen concentrations are major factors shaping the pelagic marine environment. Temperature is perhaps the major feature of the pelagic ocean and is the environmental variable most frequently employed in habitat standardizations. Dissolved oxygen is an important variable to include because at low levels it becomes a critical factor limiting habitat suitability. We have already arranged cooperation with Dr. Sang-Ki Lee to provide the best available modeled environmental data from which to populate this part of the longline simulator. This model is the Community Earth System Model (CESM1). It is a global ocean-sea-ice coupled model coupled to a biogeochemistry model as known BEC (Biogeochemical Elemental Cycle). We will be using the newly publically released CESM version 1, which is an extension of the Community Climate System Model, version 4 (CCSM4) .The global covers the global ocean with a latitudinal and longitudinal resolution of 1.0° and 60 vertical layers with the bottom level at 5500 m.

The biogeochemical component (BEC) is based on the classic food wed model of nutrient-phytoplankton-zooplankton-detritus. The modeled ecosystem is represented by three explicit phytoplankton groups (diatoms, pico-nano phytoplankton and diazotrophic), that measure primary productivity and one zooplankton group with phytoplankton grazing rates. The phytoplankton groups' growth is determined by temperature, nutrient limitation and light availability (Long *et al.*, 2013). The small group dominates under nutrient limitation; this size class resists sinking. Large phytoplankton represents diatoms and other phytoplankton that bloom and sink quickly. Finally, diazotrophs fix nitrogen gas directly from the atmosphere. Phytoplankton growth rates are modeled. We will have this data available to us for 1948-present. The output will be monthly for the global ocean including the entire Atlantic. The best method of incorporating these variables into the prediction of swordfish distributions is part of the research objective of this study.

Species distribution. Data describing the physical environment within the model region will be used to predict fish abundances using habitat suitability modeling (HSM). This approach is in common use for predicting habitat quality from habitat suitability indices (HSI) based on ecological niche theory (Hirzel and Lay 2008). Applications to billfish species include the identification of potential new fishing grounds (Chang *et al*., 2012, 2013), and forecasts of the effects of climate change (Robinson *et al.*, 2015). We will adapt the HSM formulation presented in Goodyear (2016) to make the species distribution estimates for the longline simulations in support of the 2014 WG requirements. The method predicts the relative concentration of fish by latitude, longitude, depth and month that can be expanded to absolute densities in the same parameter space for known or hypothetical total populations. The approach estimates weighted habitat volume to quantify the amount and distribution of usable habitat in three dimensions using the oceanographic features at each point in time. An example prediction of the distribution of the blue marlin habitat using World Ocean Atlas 2013 August mean oceanographic climatology (Boyer and Mishonov, 2013) using the model conventions in Goodyear (2016) is presented in **Figure 1**.

Species data required for simulations are defined in two steps. The first defines the average population number alive during the year and month by species (and sex-age grouping if considered). The second step defines the relative densities of the population by latitude, longitude, year, month and depth (these densities are computed so that the sum of the products of the relative density x volume for each latitude, longitude, and depth = 1.0). The products of the two vectors give the actual densities relative to each hook for the simulation. We propose that this study use several possible vectors for population abundances. One of these should replicate the best case result from the most recent assessment. Others should include arbitrary upward, downward, constant, and fluctuating population trends.

The simulation program is designed to simulate longline catch of 1 to 6 species/stocks at a time. Species subgroupings needed to reflect dissimilar distributions and behaviors of different life history assemblages of the species populations can be accommodated as separate species. Where appropriate, one or more of the "species" could also be an aggregate of "other species" to account for competition for hooks. The program can be easily modified to add more species as needed.

Longline sets. The longline effort for each simulation is defined by the gear specifications in two files. The first defines each gear in terms of the number of hooks between floats and the proportion of time fished in each depth layer below the surface. The second file specifies the number and locations of sets of each gear in each longitude-latitude cell for each month and year of the simulation. The catch on a hook is based on the local species densities and their relative catchabilities which must be calibrated to match observed catch rates for each gear in the simulation. The gears fished and their distribution in time and space are externally derived and consequently may be specified randomly or from some design consideration. We propose that this study use a suite of gears that best represent the data sets used to construct the abundance indices used in the stock assessment model fits. However, this may require random assignments of sets from larger spatial resolutions to the 1° x 1° resolution of the simulator.

3. Results

The HSM computes a 3-D spatial distribution of the habitat as a function of oceanographic conditions. The result is expressed as a matrix of the population relative density, Y_{ijkt}, for the latitude, longitude, depth, and time of day. The two-dimensional relative abundance in the latitude-longitude plane (the areal distribution) is a useful way to view the result. Day-night movements only affect the vertical position in the water column. Hence the examination of the predicted areal distribution neglects this feature and is based on the predicted relative abundance, N_{ij}. The results are presented in **Figure 1** for the monthly averages of the oceanographic variables evaluated here. The concentration gradient in the figure depicts the ratio of the N_{ij} to the maximum observed during the month. The area of suitable habitat is clearly a subset of the Atlantic that excludes broad regions of the northern and southern ocean. Maximum abundance is on the western side of the ocean, centered about the tropics but with seasonal shifts that follow summertime conditions in the northern and southern hemispheres. There is also a clear East to West shift in abundance in areas just offshore the Central West African coast from a peak around the March equinox to a minimum around the equinox the following September (**Figure 1**). The broad equatorial region from the African coast westward toward South America exhibits moderate abundance for most months. However high surface densities in this area are moderated downward because the densities diminish quickly from the surface to uninhabitable environs just below, where a steep thermocline marks the beginning of an unsuitable hypoxic environment.

The 1956-2012 aggregate catch of blue marlin in 5° by 5° bins summarized in the CATDIST data files maintained by ICCAT are significantly correlated with annual average of the predicted areal abundances summed to this level of resolution (Figure 3). The exclusion of a single outlier off the African Coast just south of Ghana (**Figure 2**) increased the correlation from $r=0.35$ ($n=237$) to $r=0.62$ ($n=236$) but $p<0.0001$ regardless.

Figure 3 is an example of the daytime HSM prediction for the average May climatology from the World Ocean Atlas. The view is looking downward toward the ocean surface and westward from Africa. The influence of the tropical Oxygen Minimum Zone (OMZ) on the distribution of acceptable habitat is clear, rising slowly from the south and west to a broad shallow band that extends northwest from the Central African Coast nearly all the way across the Atlantic. This OMZ shelf drops sharply to the north at about 25 degrees latitude.

Most recent work has utilized the annual environmental data described above. There is a discernable difference in the distribution of blue marlin when the abundance is examined over the entire water column (**Figure 4, top**) and when compared to the density of fish in only the top layer (**Figure 4, bottom**). Overall, the greatest habitat occurs in the western Atlantic, however the densities of fish are greatest in the area of the OMZ in the Gulf of Guinea.

Changes in the expected night time density of blue marlin over the past decades demonstrates how the habitat is in a non-equilibrium state (**Figure 5**). As this habitat changes, as well as the geographic distribution of the fishing gear over time, so does the expected CPUE, even if the stock size where to remain constant (which presumably it hasn't). It is this phenomena that this work will attempt to capture so that proper techniques can be discovered to standardize for the effects.

4. Future work

The next steps that are currently underway involve including annual environmental data and the habitat preference functions associated with them. This will entail examination of PSAT tagging data where the time-at-depth of the fish can be calculated as well as temperature or other environmental factor preferences can be discerned. This approach is much more preferable than using fishery dependent CPUE information as it takes an approach based on first principals rather than depending on where and when the fish was captured.

Where this work will require the assistance of other ICCAT CPC's will be in the detailed description of the longline gear used over time and space. It will not be necessary to know if sets were are successful or not, so any confidentiality in the catch should not be an issue. However, in situations where the required information is lacking, techniques in interpolation may have to be used.

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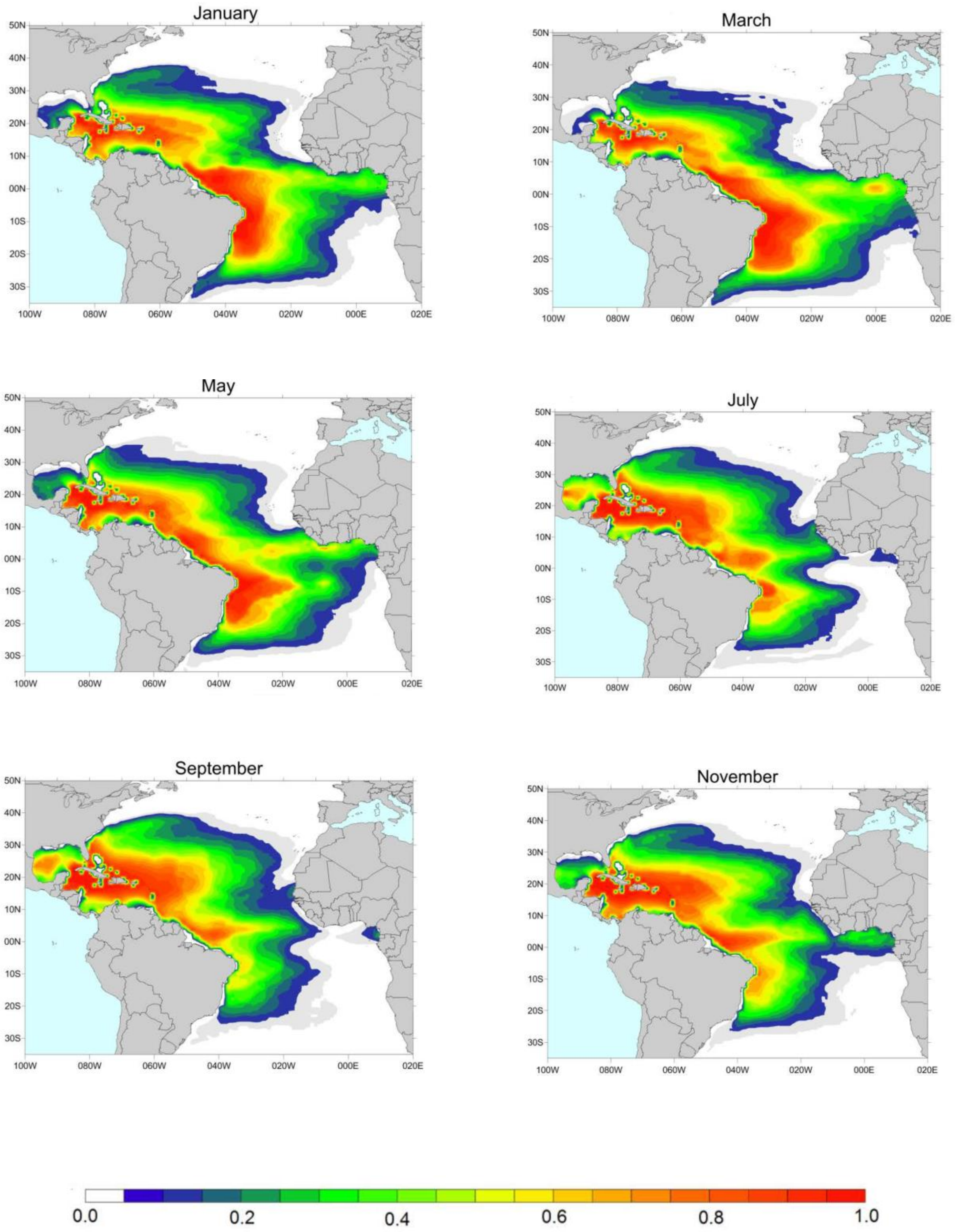


Figure 1. HSM predicted areal distribution of blue marlin habitat by month. The scale depicts the ratio of the abundance summed over depth at the geographic position to the maximum abundance for the month.

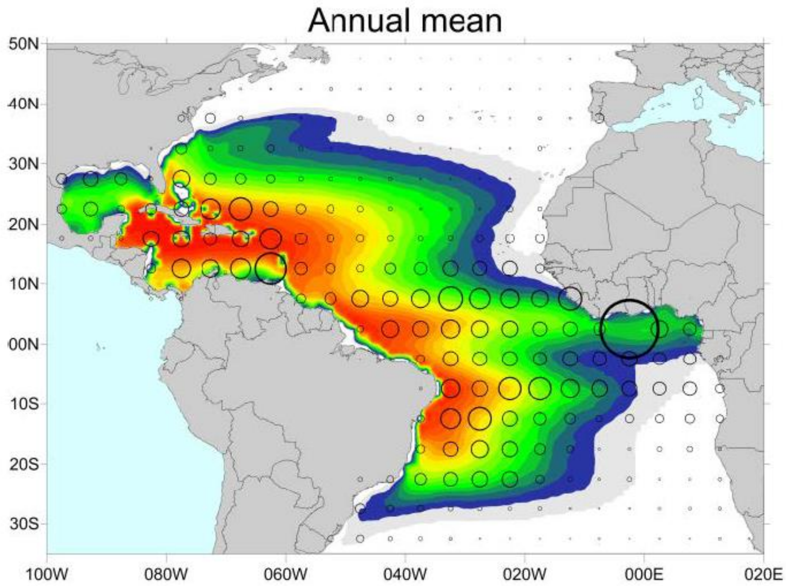


Figure 2. Isopleths of HSM-predicted areal distribution of blue marlin habitat averaged over all months and the 1956-2012 total blue marlin catch on longlines by 5° by 5° latitude-longitude bins (circles). The contour scale depicts the ratio of the abundance summed over depth at the geographic position to the average maximum abundance. The area of each circle is proportional to the catch in that bin. The catch data are from the CATDIST data files maintained by ICCAT.

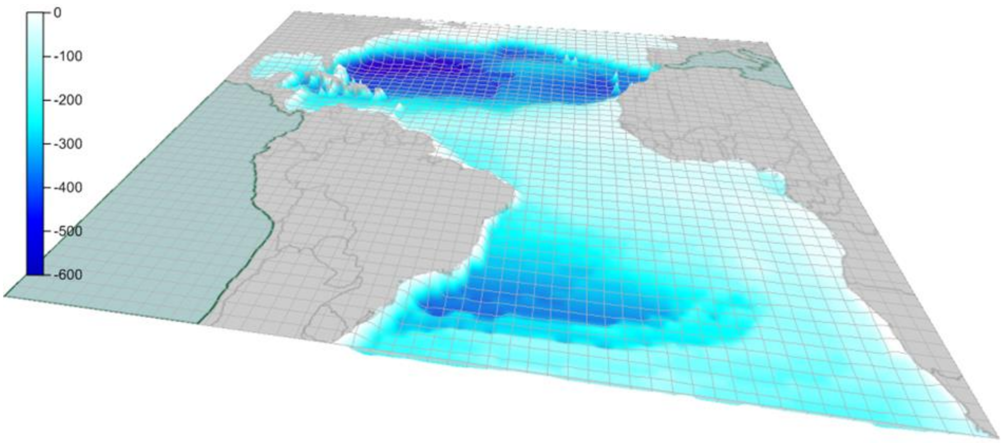
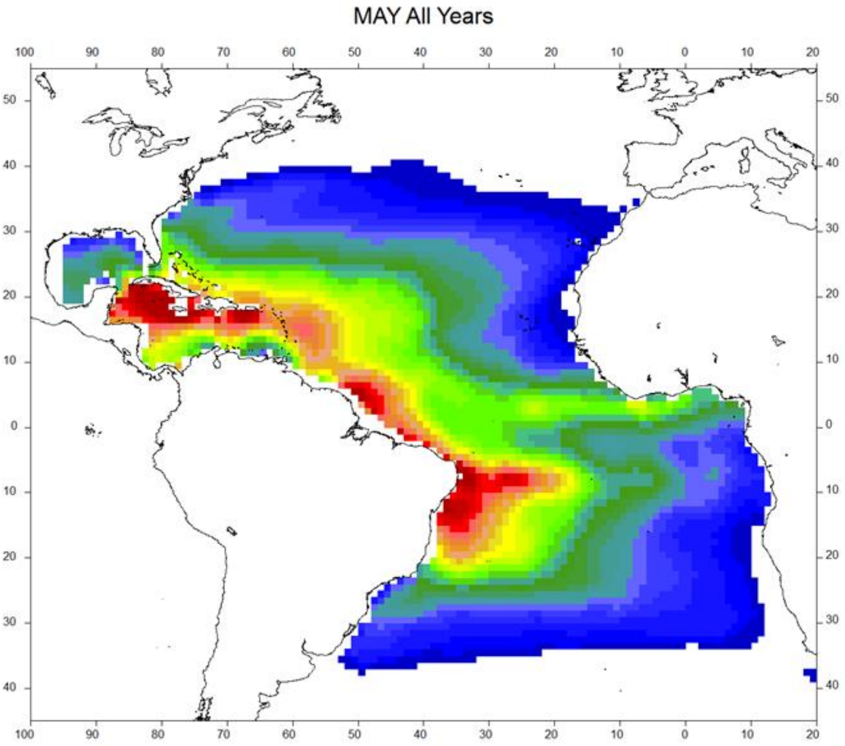


Figure 3. Daytime profile of the depths of the shallowest layer of Atlantic blue marlin habitat that includes 99% of the population based on WOA 2013 monthly average oceanography for May. The perspective is looking downward toward the ocean surface and in a westerly direction from the African continent.



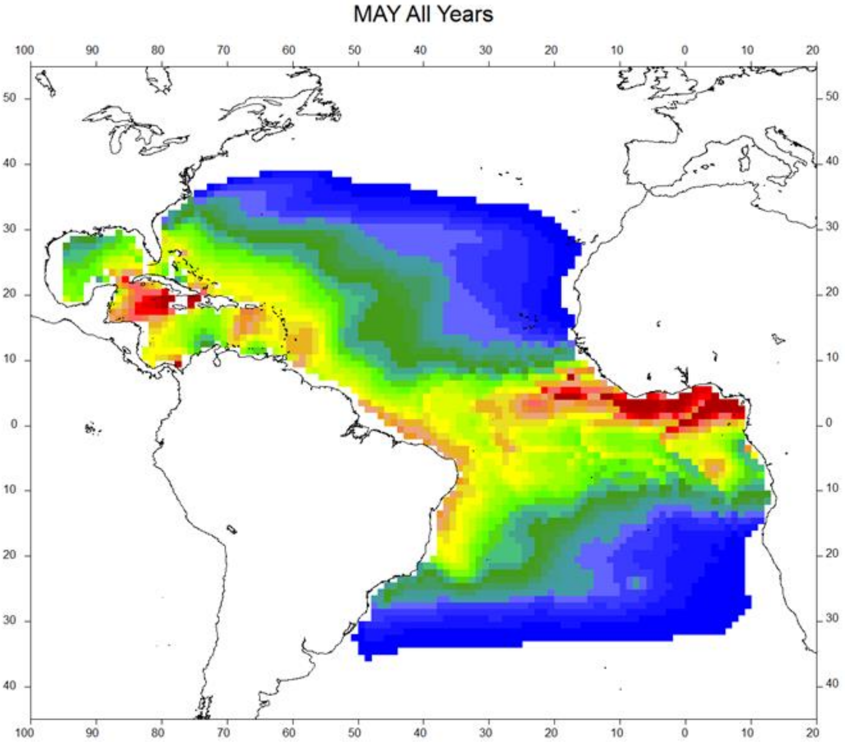


Figure 4. Sum of abundance of blue marlin over vertical water column (top), and night time density of blue marlin in the top layer (bottom) for the month of May over all years.

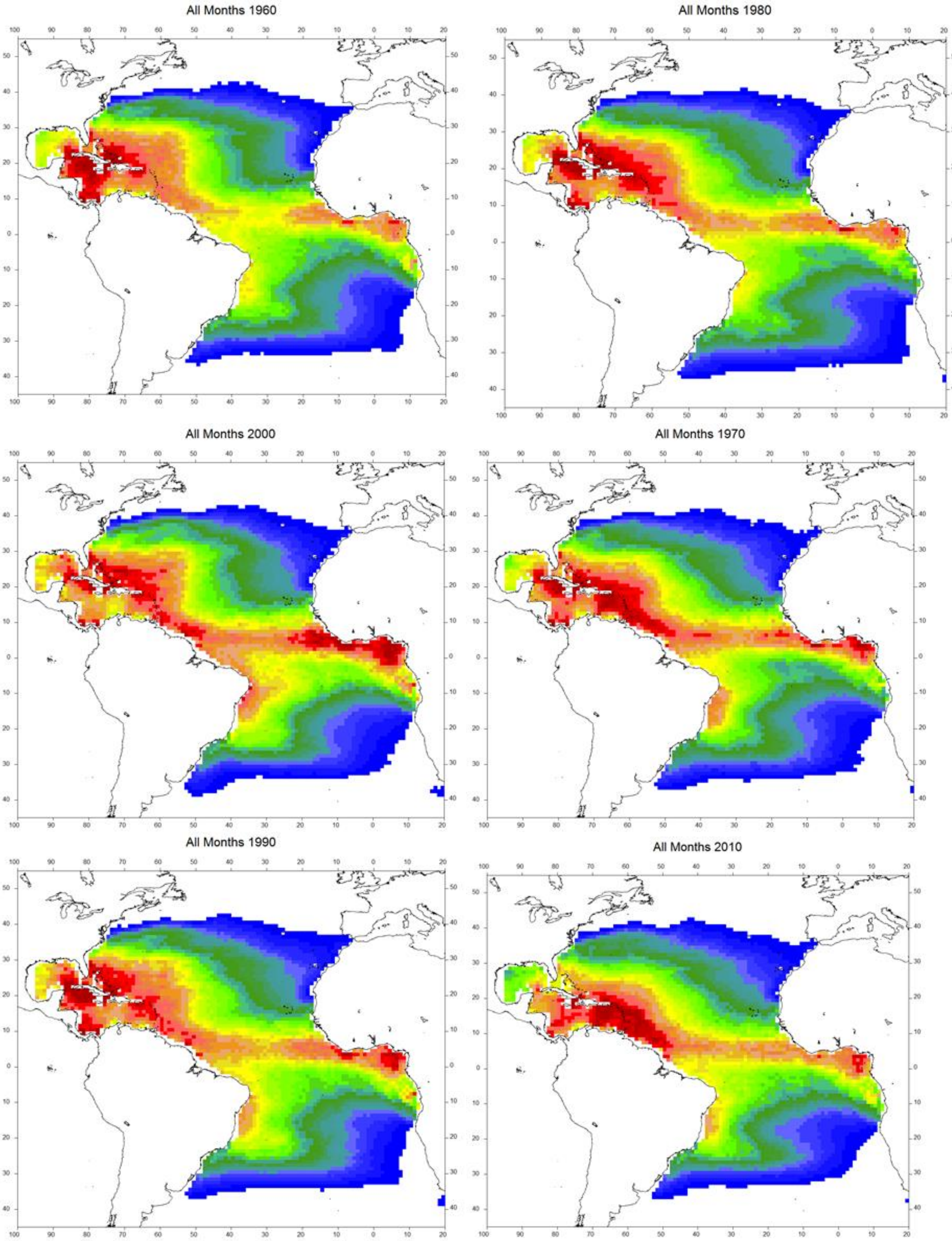


Figure 5. Night time density of blue marlin in the top layer for the month of May by decade.