

Update of the Japanese longline abundance index for Pacific blue marlin (*Makaira nigricans*) using the habitat model (1994-2024)

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Abstract

An updated standardized catch-per-unit-effort (CPUE) index for Pacific blue marlin (*Makaira nigricans*) was developed for the period 1994-2024 to inform the upcoming stock assessment. The analysis was based on the established habitat model methodology, applied to Japanese longline fishery logbook data. The model incorporated monthly environmental data, including Mixed Layer Depth and subsurface Potential Temperature, from the Copernicus Marine Service. The resulting standardized index shows relatively little divergence from the nominal CPUE trend despite accounting for temporal shifts in fishing strategy and environmental conditions. The time series is characterized by a decline from high levels in the mid-1990s, followed by a multi-decade period of fluctuation with a gentle declining trend, and culminates in a sharp increase in the terminal year. The index, with uncertainty estimated via a non-parametric bootstrap procedure, is presented for consideration as a primary input for the upcoming ISC stock assessment for Pacific blue marlin.

Introduction

Pacific blue marlin (*Makaira nigricans*) is an apex predator distributed throughout the tropical and temperate waters of the Pacific Ocean. It is a highly migratory species that plays a key role in the pelagic ecosystem. Although primarily caught as a bycatch in tuna-directed longline fisheries, its economic value makes it an important component of the catch, and it is also a prized target in recreational fisheries. The sustainable management of this trans-boundary stock requires robust scientific advice, a responsibility principally undertaken by the International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean (ISC). The ISC conducts periodic stock assessments that rely on the best available scientific information, including fishery-dependent indices of abundance, to evaluate stock status and provide management recommendations.

Periodic stock assessments are the cornerstone of the scientific management process. The standardized catch-per-unit-effort (CPUE) index, derived from the Japanese longline fishery, has historically been an important input for such assessments. The habitat model (Hinton and Nakano, 1996), which explicitly accounts for the influence of oceanographic conditions on catch rates, has become the standard methodology for developing the CPUE index in the case of Pacific blue marlin (Ijima, 2020; Kai et al., 2016). The most recent stock assessment thus also utilized a CPUE time series that was an update based on this same methodology (ISC, 2021). With several additional years of fishery and environmental data now available, a timely update to this index is required to provide the most current scientific advice for the upcoming assessment cycle.

The objective of this working paper is to update and extend the standardized abundance index for

Pacific blue marlin. Following the established habitat model methodology (Ijima, 2020; Kai et al., 2016), this study analyzes Japanese longline fishery data for the period 1994-2024. The analysis incorporates state-of-the-art environmental data from the Copernicus Marine Service. The resulting time series is intended to serve as a primary input for the upcoming ISC stock assessment.

Methods

Fishery Data Source and Processing

The fishery data used in this analysis were sourced from the logbooks of the Japanese distant-water and offshore longline fleets operating in the Pacific Ocean from 1994 to 2024. The raw set-level data were processed using a series of filtering criteria to ensure the quality and consistency of the dataset for CPUE standardization. Only data from tuna-directed operations were included, explicitly excluding sets recorded as targeting swordfish or sharks; the reason for this is that blue marlin are predominantly caught bycatch of the tuna longline fishery. The dataset was further refined to include only fishing activity within the Pacific Ocean between 40°N and 40°S, on sets where the sea surface temperature was greater than 20°C. To remove non-standard or erroneous gear configurations, only sets with 3 to 36 hooks between floats (HBF) and a total of more than 200 hooks were retained for the analysis.

Following the filtering process, the cleaned set-level data were aggregated into operational strata to create the final analytical dataset. Each stratum represents a unique combination of year, quarter, spatial location (on a 1x1 degree grid), and key gear configuration parameters. These gear parameters included mainline material, hooks between floats (HBF), branch line length, float line length, and the interval between branch lines. For each of these strata, the total number of hooks deployed and the total number of blue marlin caught were summed. This aggregation process reduces the dataset to a computationally manageable size while preserving the essential spatio-temporal and operational resolution required by the habitat model.

A portion of the raw logbook records ($\approx 36\%$) were missing essential gear configuration parameters (i.e., branch line length, float line length, or branch line interval) necessary for the gear model. To avoid discarding these otherwise valid records, a hierarchical imputation method was employed, consistent with the approach of previous analyses. The dataset was first separated into "complete" records (with gear data) and "incomplete" records (without gear data). A series of lookup tables were then constructed from the "complete" records, containing the average gear parameters for strata defined at progressively broader levels of temporal, spatial, and operational resolution. Each "incomplete" record was then matched against this hierarchy, from most specific to most general, and assigned the corresponding average gear parameters from the first matching stratum. This

process allowed for the robust retention of $\approx 65\%$ of fishing sets that would have otherwise been excluded from the analysis due to missing gear data.

Environmental Data

The environmental data required by the habitat model were sourced from the Copernicus Marine Service global ocean physics reanalysis product (GLOBAL_MULTIYEAR_PHY_001_030). Two variables were extracted for the Pacific Ocean (40°N-40°S, 105°E-70°W) for the period from January 1994 to December 2024: monthly mean Mixed Layer Depth (m_{lotst}), defined by the density criterion, and monthly mean Potential Temperature (θ_{σ}) for all available depth layers down to 500 meters. The native high-resolution data ($\approx 0.083^\circ$) were spatially aggregated by averaging to a 1x1 degree grid to match the resolution of the processed fishery data. This resulted in two final environmental datasets: a 3D data array for MLD (time, latitude, longitude) and a 4D data array for potential temperature (time, depth, latitude, longitude).

Habitat-Based Standardization Model

The CPUE was standardized using a three-step habitat model. This approach standardizes fishing effort by explicitly calculating the overlap between the vertical distribution of the fishing gear and the preferred vertical habitat of Pacific blue marlin.

First, the vertical distribution of hooks in the water column for each operational stratum was estimated using a catenary curve model (Suzuki et al., 1977; Yoshihara, 1951). The depth of each individual hook within a basket of gear was calculated based on the recorded gear parameters: float line length, branch line length, branch line interval, and the HBF number. These individual hook depths were then binned into a standardized vertical grid (5-meter intervals from 0 to 500 meters) to produce a final gear profile representing the proportion of a stratum's fishing effort at each depth.

Second, the vertical habitat suitability for blue marlin was calculated for each stratum. This was based on the species' known preference for specific temperatures relative to the ambient mixed layer temperature, as determined by acoustic telemetry studies (Hinton and Nakano, 1996). For each stratum, the temperature at the mixed layer depth (MLD) was first identified. Using the corresponding subsurface potential temperature profile, the depths of the isotherms representing temperatures from 1°C to 8°C cooler than the MLD temperature were then calculated via linear interpolation. The proportion of the blue marlin population expected to be at each of these temperature-defined depths was then mapped onto the same standardized vertical grid used for the gear model, resulting in a habitat suitability profile for each stratum.

Finally, the standardized CPUE for each stratum was calculated by quantifying the overlap between the gear and habitat profiles. For each stratum, a dimensionless Habitat Overlap Index was computed as the dot product of the gear profile vector (the proportion of hooks at each depth) and the habitat

suitability profile vector (the proportion of fish at each depth). This index, ranging from 0 to 1, represents the fraction of total fishing effort that was deployed in suitable habitat. The nominal fishing effort (total hooks) for the stratum was then multiplied by this index to calculate the "effective effort." The final standardized CPUE for the stratum was then computed as the total catch of blue marlin divided by this effective effort.

Annual Index Calculation and Uncertainty

The final annual relative abundance index was derived from the full set of stratum-specific standardized CPUE values. For each year, a single index value was calculated as the area-weighted mean of the standardized CPUEs from all strata within that year. The weight applied to each stratum was the physical surface area (in km²) of its 1x1 degree latitude band. This weighting procedure is essential to account for the geometric convergence of meridians at higher latitudes, ensuring that strata in larger equatorial grid cells have a proportionally greater influence on the final index than those in smaller, higher-latitude cells.

Uncertainty for the annual index was quantified using a non-parametric bootstrap procedure. A total of 1,000 bootstrap datasets were generated by resampling the complete set of strata with replacement. For each of these datasets, the full area-weighted annual index time series was recalculated. The final 95% confidence intervals for each year were then derived from the resulting distribution of 1,000 annual index estimates by taking the 2.5th and 97.5th percentiles. The coefficient of variation (CV) for each year was also calculated from this distribution.

Results

The final processed dataset used for the analysis consisted of 1,721,727 individual longline sets from the period 1994-2024, after applying all filtering and imputation procedures ($\approx 92\%$ of filtered but unimputed sets). The overall spatial distribution of fishing effort is presented in **Figure 1**. Effort was concentrated across the tropical and subtropical latitudes of the Western and Central Pacific Ocean, with significant activity extending eastward along the equator and into the South Pacific. Temporal trends in total annual fishing effort, effective fishing effort as estimated by the habitat model, and the corresponding catch of blue marlin are shown in **Figure 2**. Nominal fishing effort, measured in total hooks, was highest in the mid-1990s and exhibited a consistent declining trend throughout the time series. Effective effort followed the same general trend, while its magnitude indicated that a few hooks per 1,000 could be found at a depth preferred by blue marlin. Total catch also showed a general decline over the period, albeit with some inter-annual variability.

The standardized and normalized (mean=1.0) annual abundance index for Pacific blue marlin, derived from the habitat model, is presented in **Figure 3** (solid blue line; also see **Table 1**). The index begins

at a high point in the mid-1990s (e.g., 1.94 in 1995) before declining sharply to about 1.00 by 1999. It then fluctuates with a gentle declining trend for nearly two decades. The end of the time series is characterized by high variability, with a low point in 2021 (0.62) followed by a sharp increase to 1.21 in 2024, a value unseen since 1995. The uncertainty, as indicated by the 95% confidence intervals (shaded ribbon), is relatively consistent. The mean annual coefficient of variation (CV) from 1994-2024 is approximately 0.05 with a slight increase in recent years.

Discussion & Conclusions

In this study, an updated standardized abundance index for Pacific blue marlin was successfully developed for the period 1994-2024 using a habitat model applied to Japanese longline fishery data. The analysis produced a robust time series of relative abundance, complete with uncertainty estimates derived from a comprehensive bootstrap analysis. The updated index is broadly consistent with the historical index used in the 2016 stock assessment (Kai et al., 2016), strengthening the confidence in the methodological approach.

The final standardized index presents a dynamic history of the stock's relative abundance. A key feature is the initial rapid decline from the high levels observed in the mid-1990s. For the subsequent two decades, the index appears relatively stable, fluctuating with a gentle declining trend. This period of gentle decline culminates in a sharp increase in the terminal year of the analysis (2024), which represents the highest points in the time series since 1995. This recent data point should be interpreted with caution, however; the uncertainty is slightly higher in the most recent years, and data for the terminal year are often subject to minor revisions as logbooks are finalized.

A distinct methodological component of this analysis was the robust handling of missing operational data. A significant portion of the raw logbook records ($\approx 36\%$) were missing one or more essential gear parameters required by the habitat model. Rather than excluding this substantial fraction of the available data, a hierarchical imputation approach was employed. This approach allowed for the successful retention of approximately 65% of these otherwise incomplete records by inferring their gear characteristics from similar, complete fishing sets. The inclusion of these data maximized the spatial and temporal coverage of the analysis, leading to a final index that is more representative of the full scope of the fishery's operations.

The standardized abundance index presented in this paper is designed to be a scientifically robust measure of relative abundance for Pacific blue marlin. The index incorporates the most recent fishery and environmental data through 2024, accounts for temporal shifts in fishing strategy through the habitat model, and has been evaluated against the historical index used in previous assessments. These features should make the index suitable to serve as one of primary inputs for the upcoming

ISC stock assessment for Pacific blue marlin.

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Tables

Table 1. Time series of nominal and standardized CPUEs, the 95% confidence interval (CI), the coefficient of variation (CV), and the standardized & normalized (mean=1.0) CPUE.

| <i>Year</i> | <i>Nominal CPUE</i> | <i>Standardized CPUE</i> | <i>Lower CI Bound</i> | <i>Upper CI Bound</i> | <i>CV</i> | <i>Standardized & Normalized</i> |
|-------------|-------------------------|------------------------------|---------------------------|---------------------------|-----------|--|
| 1994 | 0.4532 | 1.8752 | 1.7401 | 2.0094 | ▣▣▣▣ | ▣▣▣▣ |
| 1995 | 0.4789 | 2.2207 | 2.0845 | 2.3610 | ▣▣▣▣ | ▣▣▣▣ |
| 1996 | 0.2972 | 1.2952 | 1.2001 | 1.3960 | ▣▣▣▣ | ▣▣▣▣ |
| 1997 | 0.3949 | 1.2178 | 1.1264 | 1.3265 | ▣▣▣▣ | ▣▣▣▣ |
| 1998 | 0.3557 | 1.3359 | 1.2510 | 1.4395 | ▣▣▣▣ | ▣▣▣▣ |
| 1999 | 0.3174 | 1.1597 | 1.0418 | 1.3113 | ▣▣▣▣ | ▣▣▣▣ |
| 2000 | 0.3337 | 1.2080 | 1.1241 | 1.2969 | ▣▣▣▣ | ▣▣▣▣ |
| 2001 | 0.3035 | 1.1088 | 1.0231 | 1.2015 | ▣▣▣▣ | ▣▣▣▣ |
| 2002 | 0.2814 | 1.1436 | 1.0513 | 1.2385 | ▣▣▣▣ | ▣▣▣▣ |
| 2003 | 0.3084 | 1.1052 | 1.0209 | 1.1907 | ▣▣▣▣ | ▣▣▣▣ |
| 2004 | 0.3452 | 1.2287 | 1.1223 | 1.3445 | ▣▣▣▣ | ▣▣▣▣ |
| 2005 | 0.3452 | 1.2467 | 1.1400 | 1.3596 | ▣▣▣▣ | ▣▣▣▣ |
| 2006 | 0.3037 | 1.1014 | 0.9899 | 1.2210 | ▣▣▣▣ | ▣▣▣▣ |
| 2007 | 0.2816 | 1.0691 | 0.9505 | 1.1955 | ▣▣▣▣ | ▣▣▣▣ |
| 2008 | 0.2873 | 0.8802 | 0.7875 | 0.9890 | ▣▣▣▣ | ▣▣▣▣ |
| 2009 | 0.3001 | 0.9539 | 0.8499 | 1.0656 | ▣▣▣▣ | ▣▣▣▣ |
| 2010 | 0.3293 | 1.2474 | 1.1441 | 1.3487 | ▣▣▣▣ | ▣▣▣▣ |
| 2011 | 0.3058 | 1.0202 | 0.9203 | 1.1333 | ▣▣▣▣ | ▣▣▣▣ |
| 2012 | 0.2615 | 0.9296 | 0.8391 | 1.0278 | ▣▣▣▣ | ▣▣▣▣ |
| 2013 | 0.2781 | 1.1314 | 1.0432 | 1.2365 | ▣▣▣▣ | ▣▣▣▣ |
| 2014 | 0.3184 | 1.0963 | 0.9887 | 1.2096 | ▣▣▣▣ | ▣▣▣▣ |
| 2015 | 0.2884 | 1.0399 | 0.9403 | 1.1595 | ▣▣▣▣ | ▣▣▣▣ |
| 2016 | 0.3336 | 1.2811 | 1.1534 | 1.4089 | ▣▣▣▣ | ▣▣▣▣ |
| 2017 | 0.2857 | 1.0638 | 0.9488 | 1.1850 | ▣▣▣▣ | ▣▣▣▣ |
| 2018 | 0.2671 | 0.9682 | 0.8658 | 1.0716 | ▣▣▣▣ | ▣▣▣▣ |
| 2019 | 0.2837 | 0.9975 | 0.8786 | 1.1234 | ▣▣▣▣ | ▣▣▣▣ |
| 2020 | 0.1774 | 0.7484 | 0.6570 | 0.8439 | ▣▣▣▣ | ▣▣▣▣ |
| 2021 | 0.2337 | 0.7152 | 0.6136 | 0.8204 | ▣▣▣▣ | ▣▣▣▣ |
| 2022 | 0.2557 | 0.9393 | 0.8031 | 1.0778 | ▣▣▣▣ | ▣▣▣▣ |
| 2023 | 0.2817 | 0.8395 | 0.7253 | 0.9487 | ▣▣▣▣ | ▣▣▣▣ |
| 2024 | 0.4198 | 1.3934 | 1.2170 | 1.5783 | ▣▣▣▣ | ▣▣▣▣ |

Figures

Figure 1. Spatial distribution of total fishing effort (number of hooks) from the Japanese longline fishery, aggregated on a 1x1 degree grid within the analysis area in the Pacific Ocean for the period 1994-2024. The color scale is logarithmic to visualize both high and low effort areas.

Figure 2. Annual time series of total nominal (total hooks, red line) and effective (as estimated by the habitat model, dark blue line) fishing efforts (both right axis) and total catch of Pacific blue marlin (numbers, light blue bars, left axis) from the processed Japanese longline logbook data, 1994-2024.

Figure 3. Annual abundance indices for Pacific blue marlin from 1994 to 2024. The nominal (unstandardized) CPUE is shown as a green dashed line, while the updated standardized abundance index from this study, derived from the habitat model, is shown as a solid blue line. A historical standardized CPUE is provided for comparison as a gray dotted line. The shaded blue area represents the 95% confidence interval for the updated index, estimated via a non-parametric bootstrap procedure. All time series have been normalized to have a mean of 1.0 over the common period of 1994-2014 for comparative purposes.