



## **PBF Recruitment and environmental variability**

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## INTRODUCTION

For many decades, fisheries oceanography has sought to understand what drives year-to-year variability in the recruitment of commercially harvested species. Recruitment refers to the addition of young individuals to the adult segment of the population that supports a fishery (Turley, 2019). One influential explanation, the critical period hypothesis, proposes that in species with free-swimming larvae that rely initially on a yolk sac, survival may depend heavily on food availability at the moment when that yolk reserve is depleted and external feeding begins (Hjort, 1914). If sufficient prey is not available during this transition, the strength of a year class may be substantially reduced before individuals reach maturity.

Lasker's (1975) research on northern anchovy addressed the paradox that average oceanic plankton concentrations appeared too low to sustain larval fish feeding. By examining prey density at specific depths off southern California, he found that chlorophyll maximum layers could provide sufficiently dense food patches for first-feeding larvae, although prey species composition was also critical. Observations that winter storms disrupted these thin plankton layers led to the development of the stable ocean hypothesis, which proposes that nutrient-mixing events followed by calm conditions create the stratified plankton layers necessary for successful larval survival (Lasker, 1978, 1981).

This hypothesis has guided more than a century of research focused on identifying the environmental and biological processes, particularly during early life stages and juvenile development, that shape recruitment variability in marine species of commercial importance. These stages are considered partially independent of fishing pressure because they occur before individuals become vulnerable to harvest (Hjort, 1914; Houde, 2008). For species management, the level of recruitment is a very important factor in building the biomass of the stock.

## METHODS

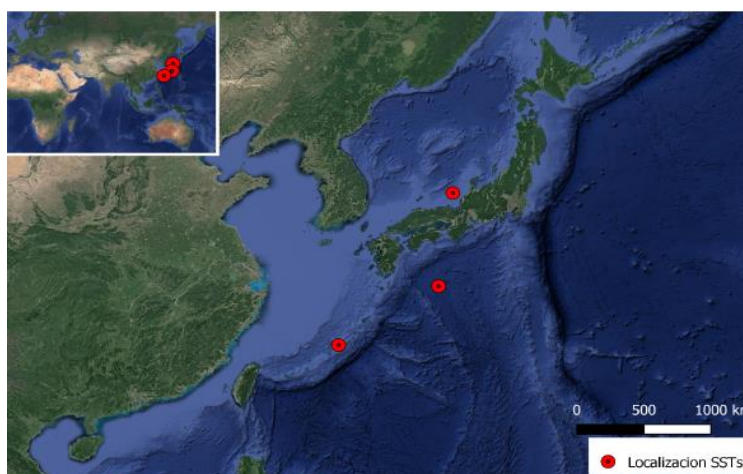
### **Data and response variable**

Pacific bluefin tuna (*Thunnus orientalis*) recruitment was analyzed to evaluate its association with large-scale climate variability and regional oceanographic conditions using two

complementary modeling approaches: Generalized Additive Models (GAMs) and Self-Organizing Maps (SOMs). Recruitment estimates were derived from the 2022 and 2024 stock assessments conducted by the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC).

Climate variability was characterized using three widely recognized indices: Oceanic Niño Index (ONI), Southern Oscillation Index (SOI), and the Pacific Decadal Oscillation (PDO). The study period spanned 1952–2022, corresponding to the temporal coverage of available recruitment estimates and environmental data. Three oceanographic regions associated with Pacific bluefin spawning and early life history were defined for environmental data extraction: a northern area (36.5° N, 135.5° E; Sea of Japan), a central area (30.5° N, 134.5° E; Nagasaki region), and a southern area (26.5° N, 127.5° E; Nansei Islands), where larval and early juvenile development occurs (Fig. 1).

Sea surface temperature (SST) data were obtained from the HadISST (Hadley Centre Sea Ice and Sea Surface Temperature) dataset, which provides global monthly SST fields on a 1° spatial grid from 1870 to the present. Data were accessed through the NOAA CoastWatch ERDDAP server by extracting spatial and temporal subsets via structured URL queries. Monthly SST values were averaged within each region and subsequently aggregated to a quarterly temporal resolution for analysis.



**Figure 1.** Geographic locations of the three regions used for extraction of sea surface temperature data associated with Pacific bluefin tuna recruitment

## Model framework

Generalized Additive Models (GAMs) were used to evaluate potential non-linear relationships between recruitment and environmental covariates. Models were fitted in R using the *mgcv* package, which estimates smooth functions through penalized regression splines and determines the optimal degree of smoothness via restricted maximum likelihood (REML).

To address dimensionality and potential multicollinearity among environmental predictors, spatially aggregated indices were constructed for sea surface temperature (SST) and for the south–north SST gradient (SST and SN). Pairwise correlation analyses indicated strong correlations among SST measurements across spatial subregions and among gradient estimates, suggesting redundancy in the environmental signal.

To minimize variance inflation and improve model interpretability, regional SST values were averaged to generate composite indices representing broad-scale oceanographic conditions during the four trimesters of each year (January–March SSTs and environmental indices, April–June, July–September and October to December). This aggregation strategy preserves dominant environmental variability while reducing the number of effective predictors and stabilizing model estimation. The use of aggregated SST and gradient indices is consistent with the objective of capturing large-scale environmental forcing relevant to recruitment dynamics while maintaining parsimony in the GAM framework.

The final model included smooth terms for all climate covariates:

$$\log(\text{Recruitment}) \sim s(\text{ONI}) + s(\text{PDO}) + s(\text{SOI}) + s(\text{mean\_SST}) + s(\text{grad\_SN})$$

Low-rank smoothers were used for all covariates (basis dimension  $k=3$ ) to ensure model parsimony and numerical stability, particularly given the moderate length of the time series. As mentioned before separate models were constructed for each trimester (Models 1–4), incorporating large-scale climate indices (ONI, PDO, SOI) and regional oceanographic variables corresponding to the same seasonal period. This approach allowed us to assess whether recruitment variability was more strongly associated with environmental conditions

occurring earlier or later within the annual cycle. Model comparison was based on explained deviance, Akaike's Information Criterion (AIC) and diagnostic checks (residual structure and basis dimension adequacy). Among the trimester-specific models, Model 4 (October to December) consistently exhibited the highest explained deviance and the lowest AIC.

### Analysis of the Self-Organizing Map (SOM)

An artificial intelligence technique known as a Self-Organizing Map (SOM) was used to detect patterns. This method is analogous to the brain's learning process, operating through neural connections and mechanisms of excitation and inhibition. The SOM model consists of two layers of neurons. The input layer (composed of  $N$  neurons, one for each input variable) receives external information and transmits it to the output layer. The output layer (composed of  $M$  neurons) processes the information and constructs the feature map. Typically, the neurons in the output layer are arranged in a two-dimensional map, as shown in Figure 2.

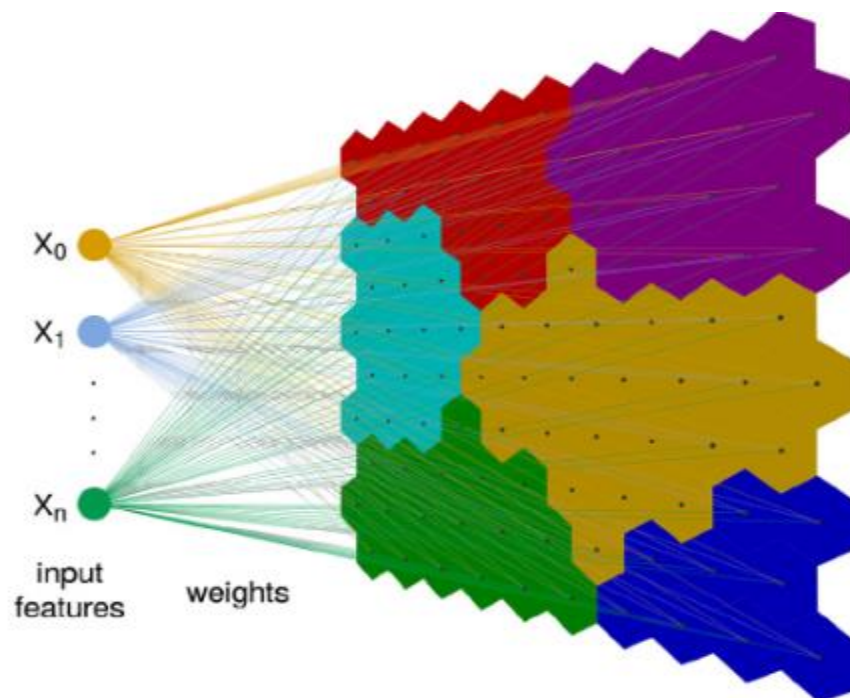


Figure 2. **Note.** From *GUASOM: An adaptive visualization tool for unsupervised clustering in spectrophotometric astronomical surveys*, by Álvarez, M. A., Dafonte, C., Manteiga, M., Garabato, D., & Santoveña, R., 2022, *Neural Computing and Applications*, 34(11), 1993–2006.

## RESULTS

### GAM results

The final model included smooth terms for ONI4, PDO4, SOI4, mean SST in the southern region (mean\_SST4), and the north–south temperature gradient (grad\_SN4).

The model explained 22.7% of the deviance, with an adjusted  $R^2$  of 0.159 ( $n = 71$ ; REML score = 57.85; scale estimate = 0.2385), indicating moderate explanatory power typical for environmentally driven recruitment models.

Approximate F-tests for smooth terms indicated:

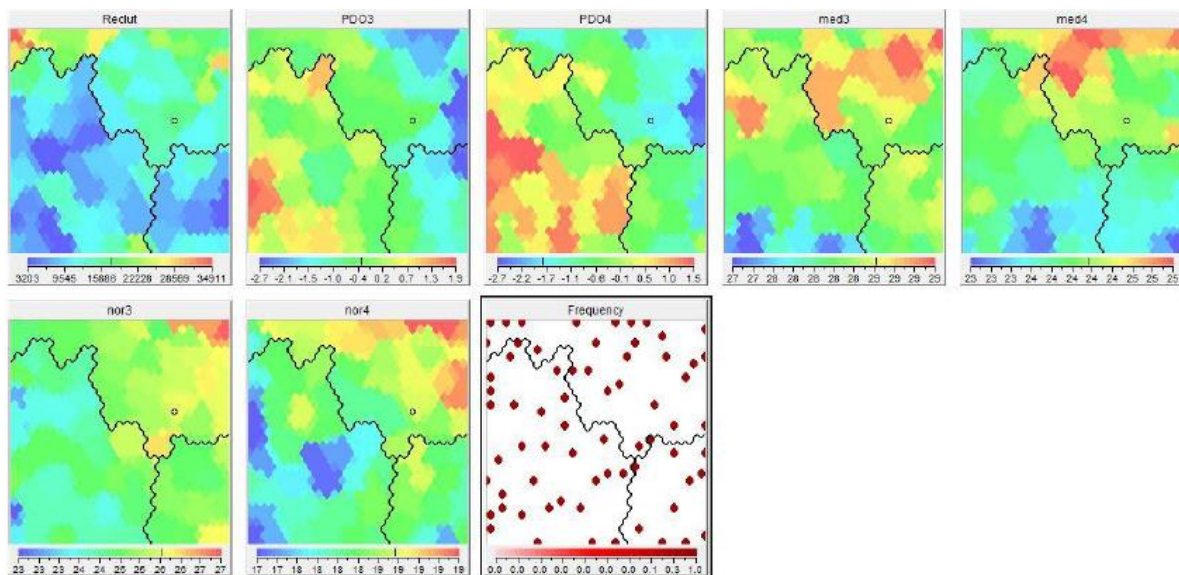
- SOI4: marginal effect ( $F = 3.41$ ,  $p = 0.069$ )
- mean\_SST4: marginal effect ( $F = 3.44$ ,  $p = 0.068$ )
- ONI4, PDO4, and grad\_SN4 were not statistically significant ( $p > 0.19$ )

Although most smooth terms were not individually significant at  $\alpha = 0.05$ , SOI4 and mean\_SST4 showed near-significant effects, suggesting potential climatic influence on recruitment variability. Model diagnostics indicated stable and appropriate model performance. The model converged successfully under REML estimation after 12 iterations. The gradient range was near zero and the Hessian matrix was positive definite (eigenvalue range:  $5.34e-06$  to 32.50), confirming numerical stability and reliable parameter estimation. Basis dimension adequacy was evaluated using the k-index diagnostic from `mgcv`. For all smooth terms k index values were close to 1, which indicates that the selected basis dimension ( $k = 3$ ) was sufficient and that there was no evidence of underfitting due to an overly restrictive smoother basis. Residual inspection showed no major deviations from model assumptions.

### SOM results

Vectors were generated including the dependent variable (recruitment) and all independent variables (environmental indices and temperature from three quadrants) at a quarterly scale. Several SOM model trials were conducted, and variables that showed no relationship with

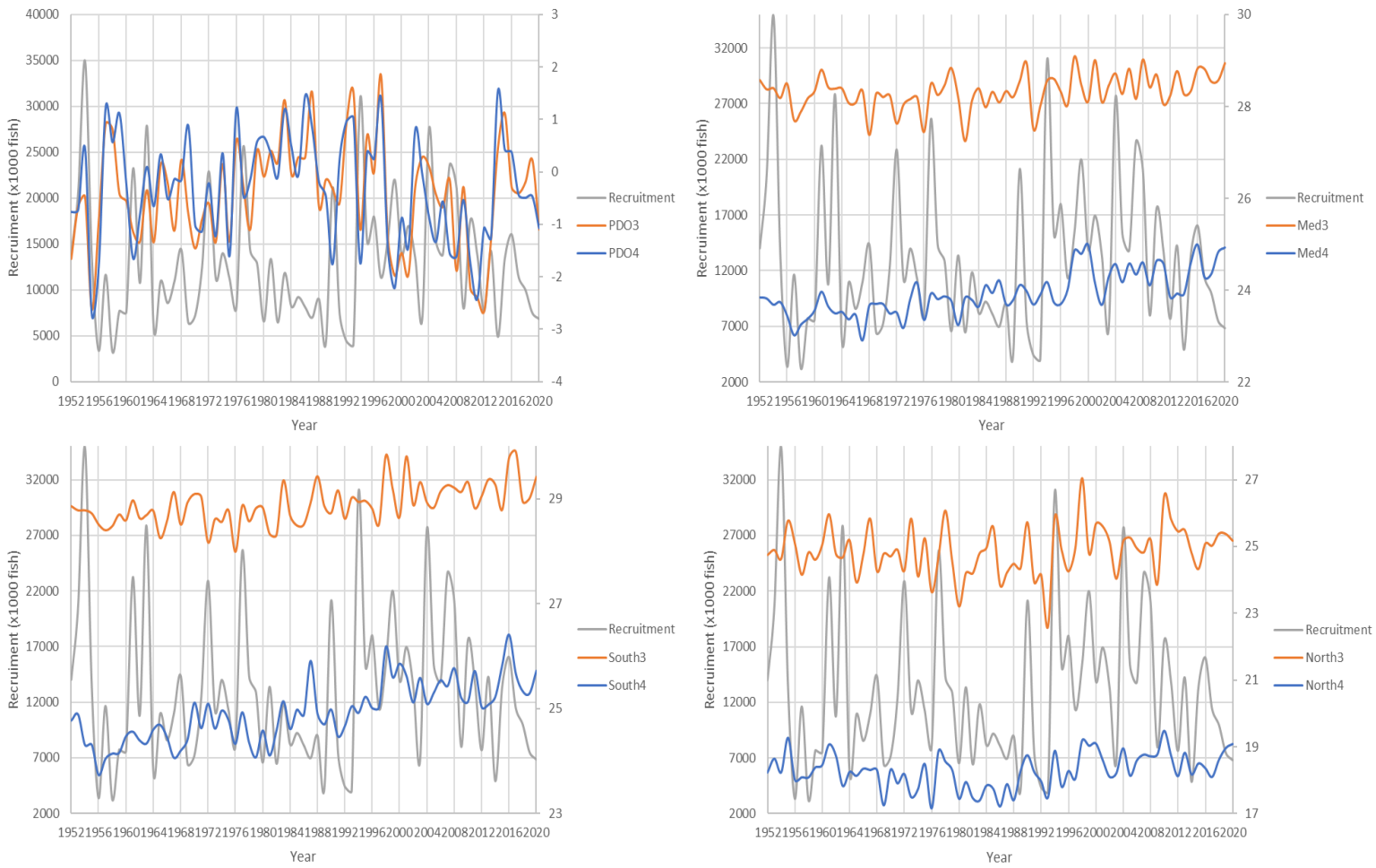
recruitment levels were discarded. The best-performing model is presented in Figure 2, where multiple variables and time periods that showed no association with the dependent variable were excluded. Three clusters can be observed: two characterized by low recruitment levels associated with high PDO index values and lower temperatures, and one cluster characterized by high recruitment levels associated with higher temperatures and low PDO values (considering only the third- and fourth-quarter indices).



**Figure 3.** Self-organizing map of vectors including Recruitment, PDO for the third and fourth quarters, and temperature from the three selected quadrants of the western Pacific during the third and fourth quarters. The frequency table indicates the position on the map of the vectors used.

The data for these variables were standardized to a 0–1 range in order to examine possible correlations (Figures 3 to 6). This simpler analysis shows that temperature in the “northern” quadrant exhibits a stronger correlation (see Table I) with recruitment; however, by itself it explains only 20% of the variability. The SOM model appears to better represent the association among phenomena than this simpler analysis, possibly because the relationships between recruitment and the effects of environmental factors are not linear.

Figure 4. Time series of bluefin tuna recruitment from previous stock assessments (1952–2020), along



with PDO and SST values for each area during the third and fourth quarters of the year.

Table I. Correlations between estimated Pacific bluefin tuna recruitment from the 2022 stock assessment and each of the environmental variables identified as relevant by the SOM.

RvsPDO3	RvsPDO4	RvsSUR3	RvsSUR4	RvsMED3	RvsMED4	RvsNOR3	RvsNOR4
-0.26441162	-0.36326333	0.12292451	0.15542297	0.31071672	0.2672428	0.31140647	0.45460272

## DISCUSSION AND CONCLUSION

The present analysis demonstrates that recruitment variability is partially associated with large-scale climatic forcing during the fourth trimester, although the magnitude of this effect is moderate. The final GAM explained 22.7% of the deviance, indicating that environmental

variability contributes meaningfully to recruitment fluctuations, yet does not fully determine them. The results suggest that ENSO-related atmospheric variability (SOI4) and regional thermal conditions (mean\_SST4) have the strongest influence among the tested predictors. Notably, the effective degrees of freedom for most smooth terms were close to one, indicating predominantly linear relationships within the observed environmental range. This suggests that recruitment responds gradually to interannual climate variability rather than exhibiting nonlinear thresholds or regime shifts.

There were differences between the SOM and the GAM, as well as similarities. Both models agree that the temperature in areas where pre-recruits are found is indicative of recruitment levels. Regarding the indices, the SOM identified PDO as relevant, whereas in the GAM it showed a low level of significance, and SOI was detected as the most important index. The comparatively weaker role of PDO4 relative to SOI4 implies that interannual variability may be more influential than decadal-scale oscillations in shaping early life survival. This finding aligns with ecological theory suggesting that short-term variability in temperature, stratification, and circulation during spawning or larval stages can directly affect survival, growth, and transport processes. Fourth-trimester conditions may therefore correspond to a biologically sensitive window influencing cohort strength. It may be that higher temperatures increase growth rates, thereby reducing the time individuals are exposed to higher predation risk.

Despite the detectable climatic signal, the majority of recruitment variability remains unexplained. This likely reflects the combined influence of density dependence, trophic dynamics, predation, spawning biomass variability, and unmeasured oceanographic processes. Temperature by itself is only a proxy of many phenomena that can be acting at the same time, some of them with opposing effects. Another issue to consider is that actual recruitment is not used; instead, we use the Stock Synthesis-predicted recruitment as reality.

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