

Using SEAPODYM to better understand the influence of El Niño Southern Oscillation on Pacific tuna fisheries

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Introduction

In 2015–2016, El Niño was a strong event, among the three strongest since 1950 (together with 1982–1983 and 1997–1998). In the Pacific Ocean, El Niño Southern Oscillation (ENSO) influences the dynamics of the world's largest tuna fisheries (Lehodey et al. 2011) and ecosystem structure, leading to regime shifts in ocean productivity (Barber et al. 1996; Chavez et al. 1999). The different phases of ENSO move the longitudinal location of the convergence zone of the equatorial Pacific's two distinct and abutting ecosystems: the “western Pacific warm pool”, which is characterised by low primary production and high sea surface temperatures, compared with the “eastern Pacific cold tongue” (characterised by cold up-welled nutrient-enriched waters and low sea surface temperature). During the El Niño phase of ENSO, when the tradewinds weaken, the westward flowing currents that drive the westward extent of the cold-tongue weaken, and the warm pool stretches from its origin in the western equatorial Pacific to the eastern Pacific. Conversely, during ENSO's La Niña phase, these currents strengthen under enhanced tradewinds and the westward extent of the cold tongue strengthens and the warm pool is pushed to the far western equatorial Pacific (Picaut et al. 1996). The shifting geographic distribution of these two ecosystems has potentially important implications for understanding the movement of biota, such as tuna, across the Pacific Ocean. The convergence zone between the warm pool and cold tongue is hypothesised to be an ecotone that provides abundant tuna forage, resulting in the core of the skipjack tuna (*Katsuwonus pelamis*) distribution being centered on it (Lehodey et al. 1997). In contrast, bigeye tuna (*Thunnus obesus*), although widely distributed across the equatorial Pacific is hypothesised to be in higher densities in the cold tongue. A relevant question arising from these hypotheses of tuna distribution is whether these two tuna species track the movement of their preferred ecosystems across the Pacific as ENSO shifts the longitudinal boundary

of the convergence zone. Moreover, the distribution of skipjack and bigeye is largely inferred from fisheries catch data. It may be that both species are distributed more or less homogeneously across these two ecosystems and the variation in the catch data reflects different vulnerabilities to capture in the two ecosystems.

Analyses have shown that purse-seine fishing vessels with licensing capabilities to fish across the equatorial Pacific Ocean follow the eastward movement of the warm pool with the onset of El Niño (Lehodey et al. 1997, 2011; Williams and Terawasi 2014). The notion that this fleet behaviour is in response to tuna movement is supported by the high catches of tuna that have been reported from the exclusive economic zone of Kiribati during El Niño phases and from Papua New Guinea during La Niña (Lu et al. 2001; Williams and Terawasi 2011, 2012; Zainuddin 2004). However, the strength of this relationship weakens with the duration of El Niño, with some vessels returning to the western Pacific before the westward migration of the warm pool at the cessation of El Niño (Lehodey 2001). Similarly, during El Niño phases, although the tuna catches in Papua New Guinea are lower than those during La Niña, they remain regionally high (Williams and Terawasi 2011). This suggests that tuna movement may be more complex than simply following the position of the convergence zone or the cold tongue.

We use the spatial ecosystem and population dynamics model (SEAPODYM) to synthesise the population dynamics of skipjack and bigeye tunas in the Pacific Ocean, and investigate the response of these tuna species to El Niño, La Niña and neutral phases of ENSO. SEAPODYM is an age-structured, spatio-temporal model that integrates both environmental data and fisheries-dependent and independent data. We summarised the outputs of SEAPODYM using wavelet analyses to assess the impact of ENSO on the abundance and distribution of adult and juvenile tuna age classes.

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Material and method

SEAPODYM is an ecosystem model developed for exploring spatial tuna population dynamics under the large-scale influence of fishing and environment effects. Skipjack and bigeye biomass of both adult and young (immature) fish were analysed over the period 1980–2001 (terminating in 2001 as it was the last year for which the large-scale environmental data were available, Uppala et al. 2005). The resolution of the model was two degrees and one month. The Pacific Ocean was divided into nine regions (Fig. 1 – middle panel); spatial boundaries of these regions were the Longhurst

biogeochemical provinces and a division of the eastern equatorial Pacific into two units using the boundary of the Western and Central Pacific Fisheries Commission.

We used the Oceanic Niño Index (ONI) (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) to represent ENSO. ONI is a continuous three-months mean of sea surface temperature anomalies for the Niño 3.4 region and is a reliable index of ENSO at the Pacific scale. In our study, we chose ONI values > 0.9 to qualify an event as El Niño, and values < -0.9 for La Niña. These limits were the standard deviation of ONI time series and are used by

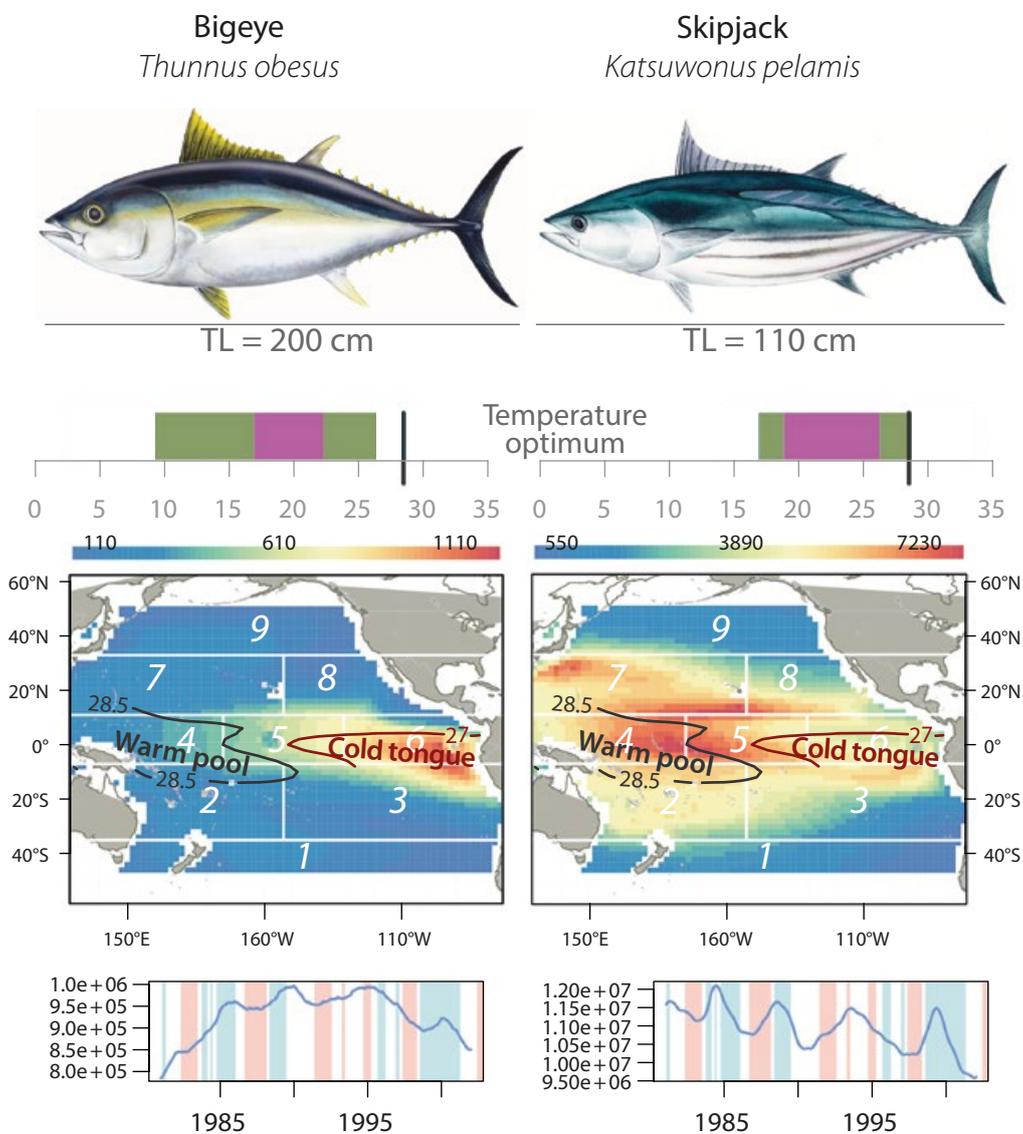


Figure 1. Optimum temperature (shown below fish illustrations) with tolerance and preference, respectively, in green and purple (Boyce et al. 2008). The vertical black line refers to the lowest surface temperature of the warm pool (28.5°C). The maps show the mean adult biomass distribution predicted by SEAPODYM over the entire period (1980–2002) for each species, with high biomass shown in red and low biomass in blue. The biomass values indicated above the maps are expressed in tonnes per 2° square. The white lines are region delimitations. The two bottom graphs show the total biomass evolution through time predicted by SEAPODYM, with El Niño events and La Niña events shown as pink and blue rectangles, respectively.

the US National Oceanic and Atmospheric Administration to classify ENSO events.

A wavelet analysis was used to study how biomass was related to ENSO through time. It allowed us to test whether tuna abundances fluctuated in response to the four to seven years dominant frequencies of ENSO, and to quantify the temporal lag between the two times series on this frequency range. To visualise changes in abundance for each tuna species and maturity class in each zone with ENSO, we correlated each biomass (adjusted for the lagged response) with the ONI index.

Results and discussion

Skipjack and bigeye tunas have different ecologies. Bigeye has a lower turnover rate⁵, occupies habitats between the ocean's surface and thermocline, and undergoes a daily vertical migration as part of its foraging strategy (Fig. 1 – top left). Given the estimates of current harvest rates and biomass status for bigeye, the stock is considered to be currently fished at an unsustainable rate (Harley et al. 2015). Skipjack has a high turnover rate, lives in the surface layer, and generally inhabits warmer

waters (Fig. 1 – top right). Given the estimates of current harvest rates and biomass status, the stock is considered to be fished at a sustainable rate (Harley et al. 2015). SEAPODYM estimated that the skipjack biomass was mostly concentrated in the equatorial western and central Pacific (regions 4 and 5) whereas the estimated bigeye biomass (or vulnerability) was concentrated mostly in the eastern Pacific (region 5 and 6) (Fig. 1 – middle). In general, SEAPODYM predicted skipjack density to be higher in the warm pool and bigeye density to be higher in the cold tongue. For both species, the biomass is concentrated in the equatorial region. SEAPODYM predicted a decreasing biomass for skipjack over the simulation period (Fig. 1 – bottom). A decrease in biomass is also predicted for bigeye in the latter third of the simulation (Fig. 1 – bottom). For both species, there are regular biomass fluctuations over the time series.

Our results highlight that the impact of ENSO on biomass depends on species, maturity (adult or juvenile), and the species' location in the Pacific. Adult and juvenile bigeye increased in abundance in the eastern Pacific (region 6) during El Niño (positive ONI value), and decreased during La Niña (negative ONI value) (Fig. 2). Changes in

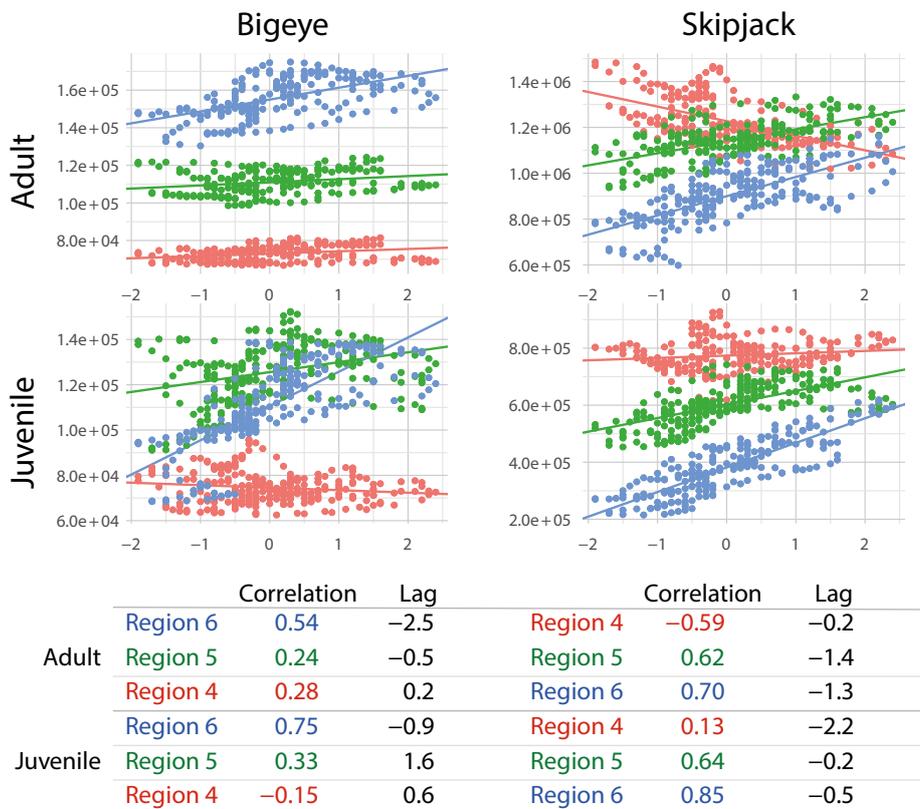


Figure 2. Modelled biomass from SEAPODYM function of ONI for bigeye tuna (left) and skipjack tuna (right) and for adult tuna (top) and juvenile tuna (bottom) coloured by Pacific region (region 4 in red, 5 in green and 6 in blue – see Fig. 1 for region delimitations). The bottom table presents both the correlation (with the lag) and the corresponding lag (in years) between each quantity and ONI time series.

⁵ The turnover rate of a fish stock is the percentage of the stock replaced every year. A high turnover means a quick replacement.

abundance in the western and central Pacific (regions 4 and 5) were within the variances observed during neutral years for both El Niño and La Niña. A shift in the western boundary by approximately 30° of longitude to the west was observed (Fig. 3). Little movement in the gravity centre⁶ was observed (Fig. 3). Skipjack abundance (adult and juvenile) increased in the central and eastern Pacific (regions 5 and 6) during El Niño events (Fig. 2). A decrease in the western Pacific (region 4) during El Niño was observed for adults but not for juveniles (Fig. 2). An eastward shift of up to 70° of longitude was observed for the eastern boundary of the skipjack population (Fig. 3). This effect was evident in both juvenile and adult skipjack tuna but more pronounced in juveniles. Little movement in the gravity centre was observed (Fig. 3).

Purse-seine fishing effort is higher in the central Pacific during El Niño (Evans et al. 2015; Williams and Terawasi 2015). Minimising purse-seine catches of bigeye is currently a conservation focus for the Western and Central Pacific Fisheries Commission to improve the conservation status of bigeye (FFA 2015). The predicted changes in bigeye abundance by SEAPODYM suggest that it is unlikely that purse-seine fishing, which principally catches juvenile bigeye tuna, would be fishing a significantly higher biomass of bigeye in the central Pacific during El Niño than during neutral phases. It is plausible that the increased purse-seine effort during El Niño in the central Pacific results in greater localised depletion of bigeye, which in turn may be relevant for managing the rebuilding of the bigeye stock. Monitoring catch per unit effort (CPUE) rates of bigeye in the central Pacific could provide an indicator for this effect. If CPUE rates increase or remain constant this may trigger the need to evaluate whether additional conservation measures for the central Pacific region may be warranted during such events. Similarly, monitoring the CPUE of longline catches of bigeye in the central Pacific may be warranted given the predicted increase in adult biomass during El Niño and the potential for higher depletion rates if CPUE increases.

Previous studies have hypothesised that changes in the location of purse-seine fishing effort reflect the potential tracking of the warm pool-cold tongue convergence zone

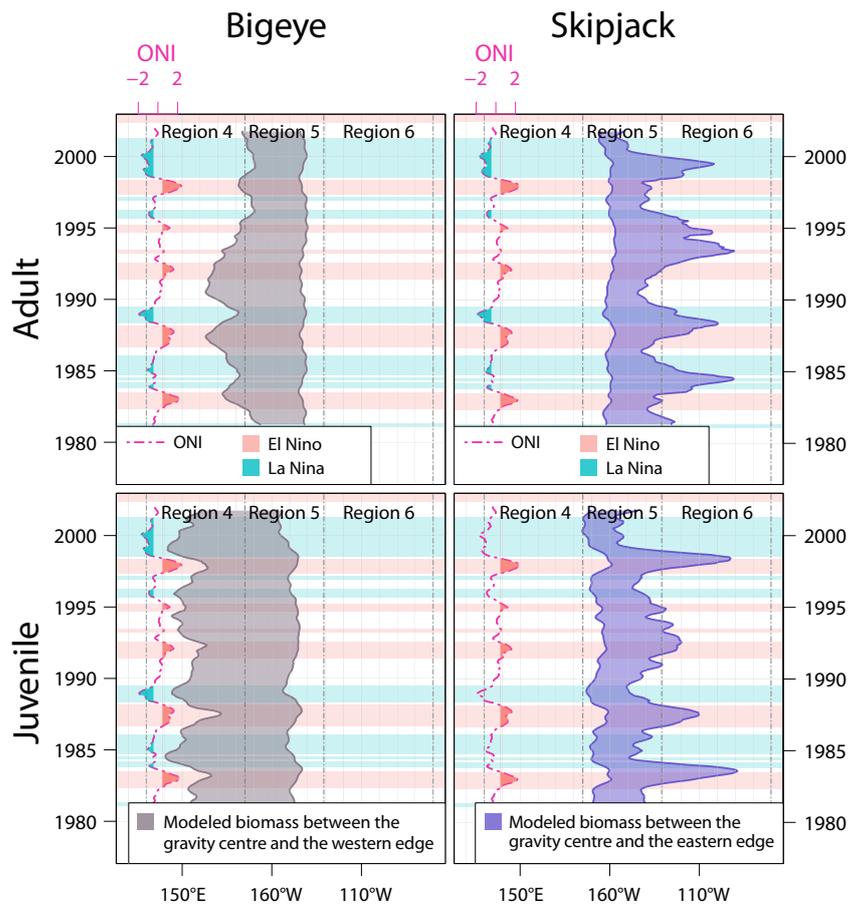


Figure 3. Space-time graphic for adult tuna (top) and juvenile tuna (bottom) representing bigeye biomass (left) and skipjack biomass (right), with ONI time series (pink dot and dash line) and with El Niño events (pink rectangles) and La Niña events (blue rectangles) for each plot.

by skipjack tuna (Lehodey et al. 1997; Suarez-Sanchez et al. 2004). The results from the SEAPODYM simulations estimated only relatively small changes in the gravity centres of adult and juvenile skipjack during El Niño and La Niña (Fig. 3). Notwithstanding that these small changes are important, they suggest that the movement in general is only a small proportion of the populations that are resident in each region. This may help explain why catches of skipjack similar to those of neutral years are maintained in the western Pacific during El Niño. Similarly, Lehodey and colleagues (1997) noted that purse-seine effort shifts westwards before El Niño conditions terminate, and proposed that this may be due to skipjack moving back towards the western Pacific due to foraging conditions (upwellings) becoming more preferable. The SEAPODYM results suggest that this pattern may not be due to skipjack movement but rather that purse-seine fishing conditions become more favourable in the period just before El Niño terminates. The

⁶ The gravity centre is the modelled mean longitude of the population biomass, and is used as a proxy for the mean position of the population biomass.

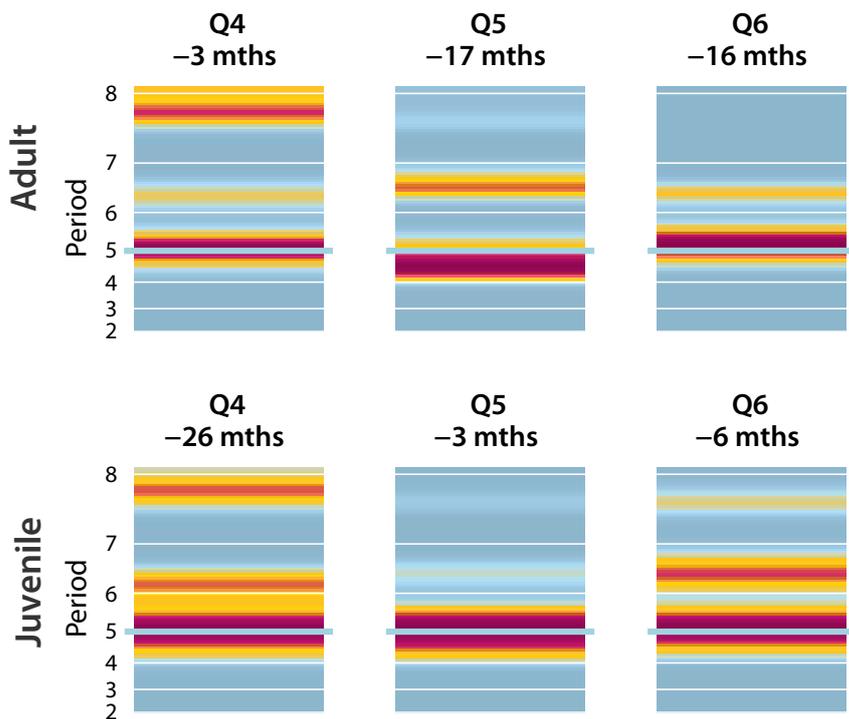


Figure 4. Average coherency over time between ONI and skipjack tuna abundances in the western Pacific (first column), central Pacific (second column) and eastern Pacific (third column), both for adult (top) and juvenile (bottom) fish. The five-year band is the average fluctuation period of ENSO.

two-degree resolution of the forcing used in this optimisation of SEAPODYM may not be sufficiently fine enough for the movement dynamics to be fully captured, and this may dampen the temporal variability of the biomass within the large regions of this study.

Our SEAPODYM simulation predicted a lack of synchrony between changes in skipjack abundance and the eastward and westward shifts in the convergence zone during the onset and cessation of El Niño, indicating that skipjack movement may not be as responsive as previously hypothesised. We detected closer synchrony between adult skipjack and the onset of El Niño with decreased abundance in the western Pacific occurring three months after the peak in El Niño. Peaks in juvenile abundance in the central Pacific were observed three months after the peak in El Niño (Fig. 4 top). Peaks in adult abundance in the central Pacific, however, were evident 17 months after the peak in El Niño (Fig. 4 bottom). Skipjack reach maturity at approximately 10 months. The observation of maximum abundance at 17 months is interpreted as adult and juvenile skipjack moving eastwards with El Niño, enhanced spawning in the central Pacific due to the favourable habitat El Niño generates, and this recruited biomass remaining in the central Pacific for a period of time after El Niño rather than shifting westward with the convergence zone at the cessation of El Niño. Recent studies examining mixing

rates (Kolody and Hoyle 2015; Schaefer et al. 2015) and stock structure (Grewe et al. 2015) support hypotheses of large horizontal movements as the exception rather than the rule for equatorial tuna in the Pacific Ocean (Schaefer et al. 2015).

Our approach for this study was based on the assumption that SEAPODYM provides a realistic description of tuna population dynamics. An important next step is the validation of the generality of these results with additional analyses of catch and effort data (independent of SEAPODYM) from ENSO events that were not included in the optimisation of SEAPODYM (e.g. the 2015–2016 El Niño). Understanding how skipjack and bigeye respond to the Modoki Niño is also warranted. The Modoki Niño (Ashok and Yamagata 2009) is an El Niño with main sea surface temperature anomalies in the central Pacific rather than in the eastern Pacific in the classical (“canonical”) El Niño (Kug et al. 2009). In our time series the results were less conclusive for the period between 1992 and 1996, which coincides with Modoki Niño events. Modoki Niño was common during 2000–2013. The ERA-interim optimisation of SEAPODYM includes this period and could be used to investigate this phenomenon in more detail.

The analyses presented here improve our global understanding of the drivers of movement for mobile species under climatic variability, an aspect highlighted by Evans et al. (2015) as a research priority to ensure the sustainable management of tuna fisheries in the western and central Pacific Ocean. Understanding when and why tuna move is required to adapt fisheries management policies. These results from SEAPODYM contribute to the broader debate concerning the use of tuna for improving food security and public health in Pacific Island countries and territories (Bell et al. 2015).

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