Variations in Growth and Mortality of Bigeye Tuna (*Thunnus obesus*) in the Equatorial Western Pacific Ocean

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Abstract

Monthly weight frequency distributions of bigeye tuna (*Thunnus obesus*) landed by Japanese coastal longliners in the Guam fresh tuna transshipment fishery were used in a mode progression analysis. Recruitment was highly defined and occurred during the first quarter of the year. Seven year classes (1989-95) were tracked over a span of 4 or 5 years. The growth coefficient, k, for each year class ranged from a low of 0.201 to a high of 0.465 per year. Except for 1990 and 1993 year classes, high growth (> 0.3 per year) was associated with El Niño conditions and conversely low growth (< 0.3) with La Niña event. $L_{¥}$ extended from 157.9 to 204.9 cm fl. The values of t_0 for each year class ranged from -0.0061 to -0.0034. Age at the recruitment size of 80 cm fl ranged from 1.52 to 2.5 yr and averaged 1.8 yr. Cohort-related total mortality (Z) extended from 0.324 to 0.901 and averaged 0.612 per year. Variations in mortality were attributed to changes in the catchability coefficient, q.

Introduction

The three elements of a population that describes the history of a cohort or year class as it passes through the fishery from the time the individual fish first become big enough to be caught until the last survivor dies or is caught are the pattern of entry of the young fish into the fishery (recruitment and selection), the decrease in numbers once they have entered the fishery, and the growth of individual fish. Assessment of the events during the life of a cohort of fish is largely a matter of balance between decreasing numbers of individuals and increasing individual weight (Gulland 1983).

The analytical approach to fish growth included the enumeration of recognizable marks on hard body parts; i.e., otoliths, scales, or hard rays. By counting these the age of individual fish can be determined and from age and size observations of individual fish a table of average size at each age created. These tables are subsequently used in fitting growth curves. The most direct of the methods is tag and recapture studies that rely on a set of tag returns to determine the change in size over time. Another method for fish with distinct spawning season is the Petersen method. In the size frequency distributions there will be modes corresponding to sizes of fish produced at the peak of each spawning season, and growing at the average rate.

Studies on the growth of bigeye tuna (*Thunnus obesus*) in the Pacific through mode progression analysis have been widespread. Iverson (1955) compared growth lines from several year classes of bigeye tuna caught around the Hawaiian Islands and other locations in the North Pacific. In 1967, Suda and Kume tracked seven different year classes of bigeye tuna and estimated a comprehensive growth rate (k) of 0.207 per year and natural mortality (M) at 0.361. Modes in the monthly weight frequency distributions of bigeye tuna caught around the Hawaiian Islands from March 1960 to April 1961 were used in a comparative growth study between males and females (Shomura and Keala 1967). Each year class was tracked and serialized between the 2 years with the assumption of no differences in growth between the year classes. Growth rate in males (k = 0.114 per year) was lower than in females (k = 0.167 per year). Similarly, Kume and Joseph (1966) studied bigeye length frequencies from longline catches in the eastern Pacific and reported a k of 0.38 and a M of 0.477.

In the western Pacific Ocean, small bigeye tuna are taken on the surface by artisanal fishermen, commercial pole-and-line fishermen, and purse seine fishermen, whereas, the longline fishery takes the larger, deeper water, and more valuable fish for the sashimi market. Since 1986, the island of Guam has become a major port for the Japanese coastal and Taiwanese offshore longliners that fish in the equatorial western Pacific (2-5°N latitude and 140-160°E longitude) (Fig. 1) and transship fresh fish to Japan. In 1990, 7,006 metric tons (t) and 5,016 t of fresh bigeye and yellowfin (*Thunnus albacares*), respectively were transshipped, of which the Japanese longliners accounted for 74% of the landings. Annually, bigeye landings peaked in 1990 at 5,760 t but fell to a low of 1,214 t in 1996 (slope = -458.6, p = 0.002) and as such, the number of bigeye tuna landed also declined from a high of 165,896 in 1990 to a low of 32,419 pieces in 1996 (slope = -22,720.2, $p < 0.001$) (Kikkawa et. al. in prep). In this study size frequency distributions of bigeye tuna from Japanese longliners from 1989 to 1998 were examined. Seven year classes or cohorts were identified and tracked from time of recruitment to near asymptotic size. Growth and time of hatching were determined through the mode progression analysis and a modified von Bertalanffy growth model. Total mortality for each year classes were determined with the exponential method.

Materials and Methods

The Guam Department of Commerce (GDOC) in the late 1988 established a distant-water fishery data collection system to monitor and study the quantities of tuna being offloaded and transshipped from Guam. The data gathered also included individual fish weights. Monthly proportional weight frequency distributions were computed on the bigeye tuna landings by the Japanese longline vessels from 1989 to 1998. A technique developed by MacDonald and Pitcher (1979) on the distribution mixture model separated the size frequency distributions into modes which were defined by the means, standard deviations, and relative probabilities; each mode was also assumed to be normal distribution. And like most mode progression analysis, this study also assumed discrete seasonal spawning as evident by the annual pulses of recruits to the fishery. Seven year classes were tracked for 4 or 5 years from the time of first entry into the fishery.

Unlike length-based mode progression analysis, the growth in weight allowed for a extended tracking period for each age group before the modes coalesced and became indistinguishable around the asymptotic size. Monthly weights-at-age were then converted to FL’s-at-age by Kume and Shiohama’s (1964) equation of bigeye caught in the area south of 28°N latitude and west of 170°E longitude. Because mode progression analysis was based on relative age, the von Bertalanffy (VB) growth model was modified by including an adjustment factor, “*r*”, to convert relative to real age. The modified model, VB’, was as follows:

$$L_t = L_\infty (1 - e^{-k((t+r)-t_0)}); \qquad (1)$$

where L_t = length at age t,
$L_{¥}$ = asymptotic size,
k = growth constant,
t = relative age,
t_0 = age at length zero, and
r = adjustment factor .

Initially, with all of the parameters unrestricted, the model failed to converge on reasonable estimates of r and t_0. In a numerical experiment where r was constrained in a range between 0.5 and 3 years, which were reasonable estimates of recruitment age, the VB’ model converged on k and $l_{¥}$. Consequently, t_0 was determined algebraically (Lopez Veiga, 1979) from known hatching size of 2.5 mm (Yasutake et. al., 1973) with the unmodified VB model. The data were again refitted to the VB’ with a known t_0 to predict $l_{¥}$, k, and r parameters.

Instantaneous total mortality (Z), as the change of abundance (N) over time, was determined through the exponential decay method. Monthly estimates of relative abundance were calculated by the product of monthly mean catch rate and the probability of the year class. Mean catch rate as the number of bigeye tuna landed per fishing day was calculated with the following equation:

$$CPUE_i = \frac{\sum C_i}{\sum d_i}, \qquad (2)$$

where $CPUE_i$ is the catch rate in month i, C_i is the bigeye landings in month i, and d_i is the fishing days in month i. In the absence of detailed fishery information, effort was determined by adjusting the number of sea days by the number of transit days or nonfishing days (Kikkawa et. al., in prep). The catch rate as the number of bigeye landed per day varied between 3.8 to 19 and averaged 7.9.

Results

Annual recruitment of bigeye tuna to the fishery centered on the first quarter and at about 80 cm FL. There were 5 or 6 highly identifiable modes or year classes in each of the monthly size frequency distributions. From time of entry each year class was tracked for about 4-5 years as the modes advanced in size. With the advancement of the modes both growth rate and relative probability decreased because of mortality and the inclusion of new recruits, thus, tracking the age groups became more difficult as the modes approached the asymptotic size (Fig. 2).

Of the seven age groups, the 1989 year class recorded the highest growth rate (k) at 0.465 per year and correspondingly, the lowest asymptotic size (L_{∞}) of 157.9 cm FL. By contrast, the lowest growths per year occurred for the 1991 and 1992 year classes at 0.224 and 0.201, respectively. Asymptotic sizes were similar at 204.9 and 204.1 cm FL. The t_0 or age at zero length ranged from a low of -0.0061 to a high of -0.0034 for the seven year classes. At the recruitment size of 80 cm fl the age of bigeye ranged from 1.52 to 2.47 yr and averaged 1.83 yr (Table 1). Total mortality, Z, was the lowest for the 1990 year class at 0.316 and highest at 0.980 for the 1994 class (Table 1); the overall average was 0.615 (SE = 0.0814) per year.

Discussion

Estimates of growth for the individual year classes agreed well with previous bigeye studies in the Pacific Ocean. At the low end of the growth range Suda and Kume (1967) reported growth rate of 0.201 per year that matched the 1992 year class of similar value. Growths of 0.367 and 0.38 per year from a composite of several age groups of the bigeye caught around the Hawaiian Islands and in the eastern Pacific (Shomura and Keala, 1963; Kume and Joseph, 1966) were very close to overall study mean of 0.308 per year. Although well above previous mode progression analysis estimates, the 1989 cohort k value of 0.465 per year was still comparable to results from the tagging study in the western Pacific Ocean by Hampton (1998) with an estimated growth rate of

0.427 per year. Of the few studies that investigated individual age groups, Iverson (1955) compared growth lines from several year classes of bigeye tuna caught around the Hawaiian Islands and other locations in the North Pacific but detected no interannual differences; although a two-year cycle was evident . Suda and Kume (1967) tracked seven different year classes of bigeye tuna caught in the Pacific Ocean; however, individual year class estimates were not provided.

Growth rates of the individual year classes could be partitioned into either relatively high ($k >$ 0.3 per year) and low ($k <$ 0.3 per year) growth periods. With the available fishery data it was not possible to fully explaining factors affecting bigeye growth; however, the low growth rates of the 1991 and 1992 year classes, hatching could be associated with a prominent La Niña event that peaked in 1989 (Fig 3). Under these conditions waters in the western Pacific would be characterized by a deeper thermocline depth, thus reducing the mixing of the deeper and colder nutrient rich waters with the upper euphotic layer. Consequently, there would be a decline in primary production and available food for larval growth and survival. Gerking (1966) suggested that many of the variations in growth rates can be attributed to the growing season at the early age where rate of temperature change, light regime, and food may combine to influence secretion of growth hormone. For year classes of relatively high growth the opposite was true. The 1989 year class had the highest growth and hatching occurred at the peak of a very strong El Niño event in 1987 (Fig. 3). With the exception of 1990 and 1993, year classes of high growth were associated with prevailing El Niño conditions (Fig 3).

Total mortality estimates for each of the year classes were well within the range of Suda and Kume (1967) study of Japanese longline catches in the Pacific Ocean from 1957 to 1964 with Z ranging from 0.6 to 1.4 per year. Hampton (2000) addressed size specific mortalities for bigeye caught in the western Pacific Ocean; although no numbers were available; the graph presented that the total mortality of bigeye tuna at 80 cm fl would extend from 0.3 to >1.0 per year.

For the coastal longline fishery in the equatorial western Pacific interannual variations of total mortality, Z, appeared to be caused changes in the catchability coefficient, q. Previous studies by Kume and Joseph (1966) and Hampton (1998) have shown the range of natural mortality of bigeye tuna to be very narrow. The earlier study on bigeye length frequencies from longline catches in the eastern Pacific natural mortality was estimated at 0.477 per year and from the tagging study in the western Pacific mortality ranged from 0.46 to 0.51 per year. Therefore, it can be concluded that much of the variations in total mortality must be attributed to the changes in F. Albeit, because the combined effort of Japanese and Taiwanese longliners in the Guam transshipment fishery remained relatively stable during the same period (Kikkawa et.al. In prep.) it can be further deduced that variations in F were principally caused by changes in the catchability coefficient (q). Such variations in q can be the result of biological and physical factors such as competition, population density, predation, and water temperature (Hilborn and Walters, 1992).

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Table 1. Bigeye tuna (*Thunnus obesus*) population parameters of estimated age before recruitment at 80 cm FL, conversion factor *r*, von Bertalanffy growth parameters of L_4 , *k*, and t_0, r^2 values and instantaneous total mortality rate (*Z*) with standard error in parenthesis landed by the Japanese coastal longline vessels in the Guam fresh tuna transshipment fishery from 1989-98.

Year Class	Age (yr) at recruit-ment size of 80 cm fl	r	$L4$ (cm)	*k*	t_0 (yr)	r^2	*Z*
1989	1.52	1.077 (0.0497)	157.9 (1.038)	0.465 (0.0158)	-0.0034	99.3	0.687 (0.0427)
1990	1.67	1.521 (0.1016)	165.7 (2.566)	0.395 (0.0261)	-0.0038	99.1	0.324 (0.0246)
1991	2.22	2.160 (0.1751)	204.9 (9.891)	0.224 (0.0283)	-0.0055	98.8	0.783 (0.0706)
1992	2.47	2.492 (0.1928)	204.1 (8.987)	0.201 (0.0238)	-0.0061	98.9	0.437 (0.0470)
1993	1.87	1.634 (0.0761)	177.6 (2.376)	0.319 (0.0156)	-0.0044	99.6	0.564 (0.0452)
1994	2.22	2.176 (0.1809)	189.8 (6.542)	0.246 (0.0265)	-0.0054	98.5	0.901 (0.0811)
1995	1.89	1.704 (0.1221)	181.2 (5.513)	0.307 (0.0286)	-0.0045	99.1	0.590 (0.1059)

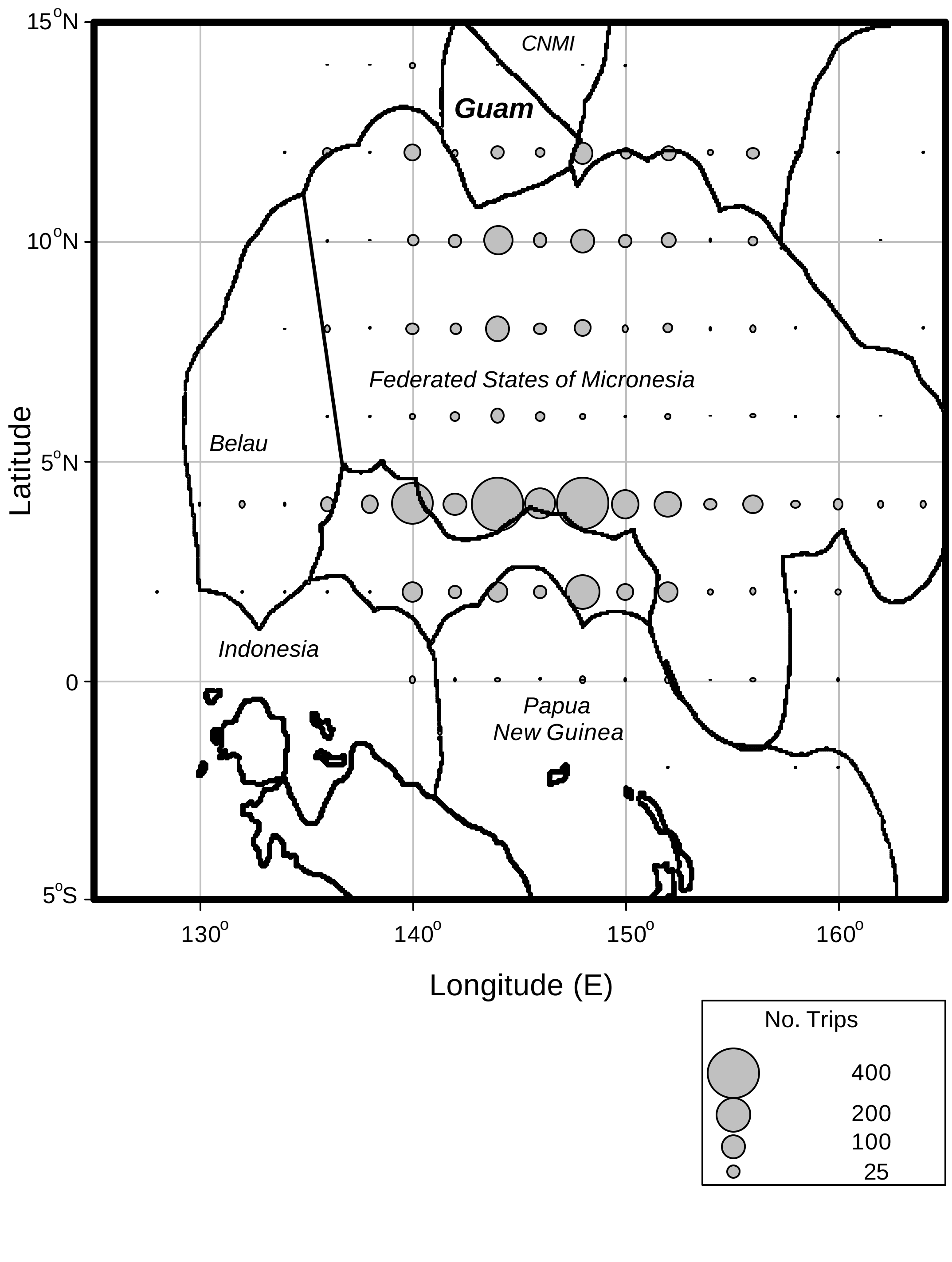

Figure 1. Reported fishing areas and estimated effort of the Japanese longliners in the Guam fresh tuna transshipment fishery in 1989-98.

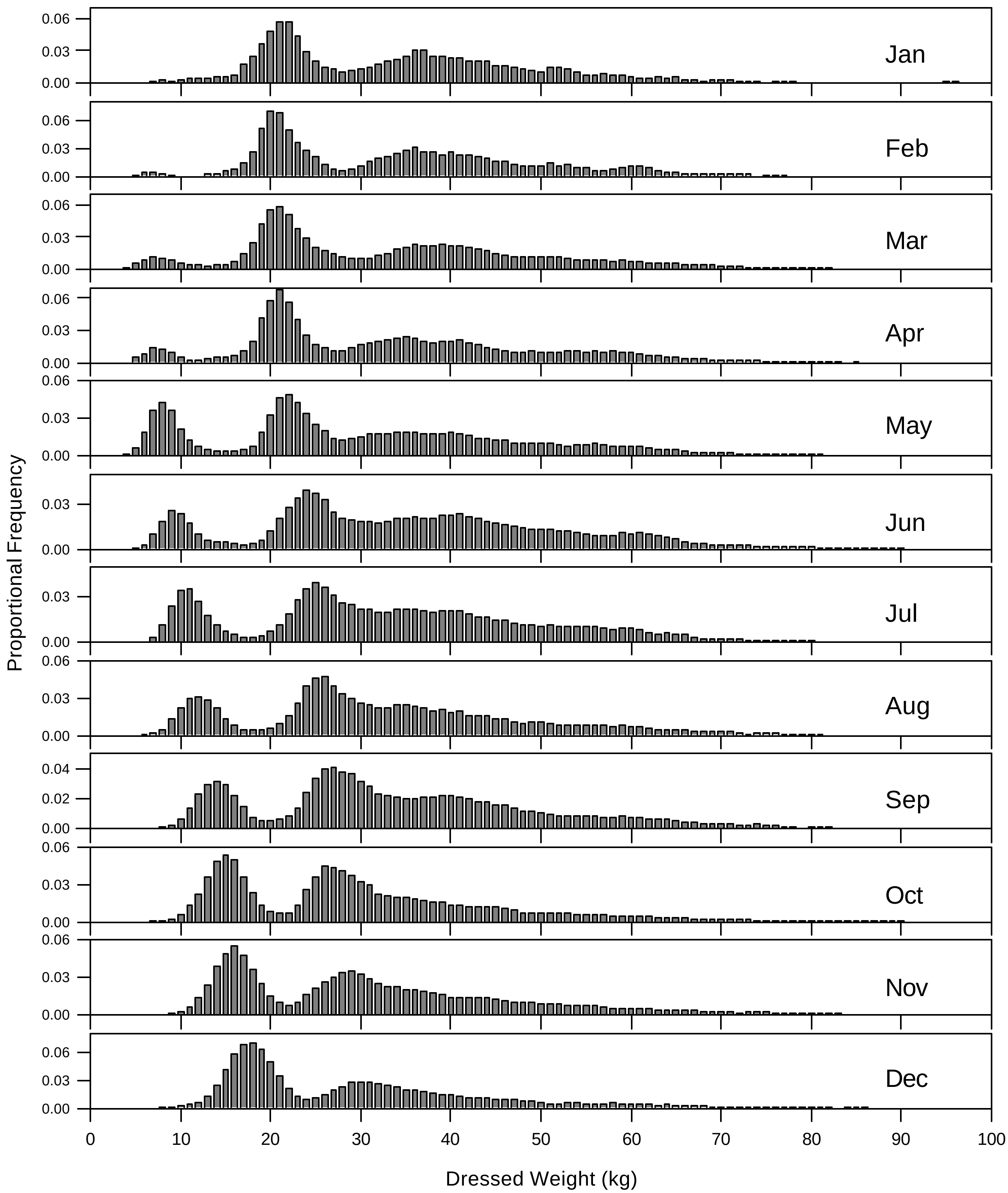

Figure 2. Proportional monthly dressed weight frequency distribution of bigeye tuna (*Thunnus obesus)* caught in the equatorial western Pacific Ocean by Japanese longline vessels in the Guam fresh tuna transshipment fishery in 1989.

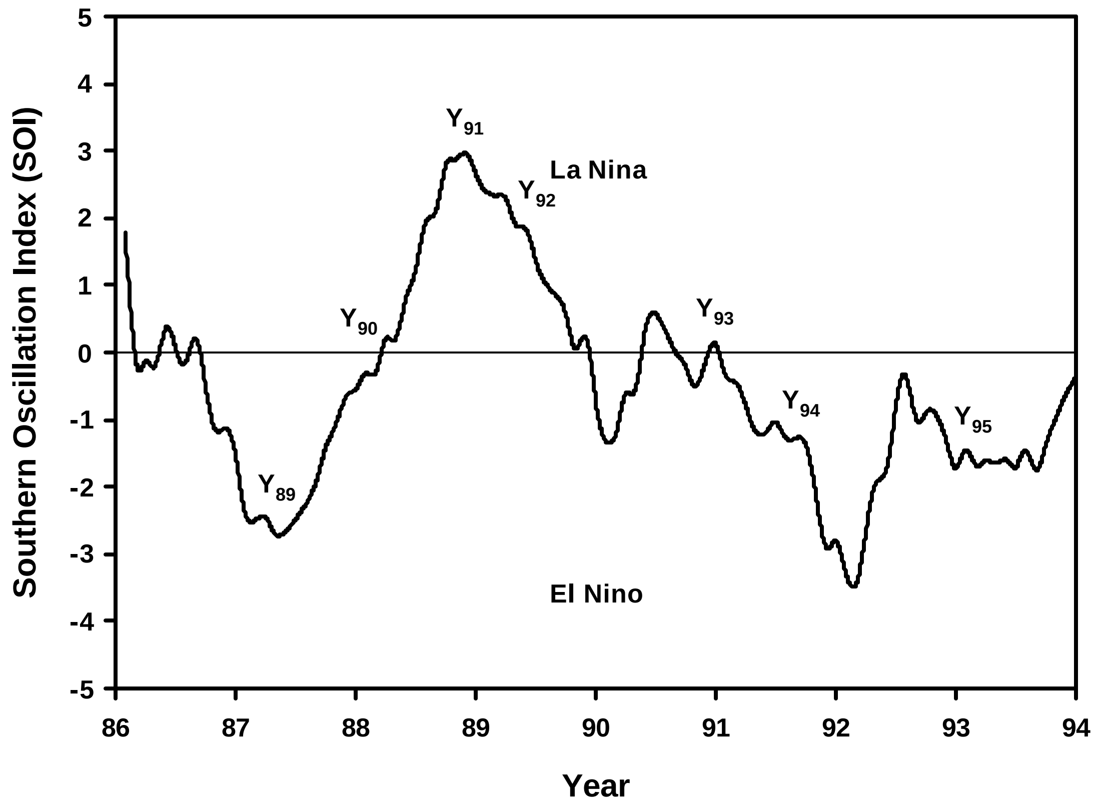

Figure 3. Time of hatching for the seven year classes (Y_{89}, Y_{90}, Y_{91}, Y_{92}, Y_{93}, Y_{94}, and Y_{95}) and in relationship to the Southern Oscillation Index (SOI).