EVALUATION OF VARIABILITY IN SABLEFISH, *ANOPLOPOMA FIMBRIA*, ABUNDANCE INDICES IN THE GULF OF ALASKA USING THE BOOTSTRAP METHOD

MICHAEL F. SIGLER AND JEFFREY T. FUJIOKA[1]

ABSTRACT

Relative population numbers (RPN's) and length compositions were computed for sablefish, *Anoplopoma fimbria*, in the Gulf of Alaska from the results of the Japan-United States cooperative longline survey from 1979 to 1986. A statistical evaluation of annual changes in the RPN's using the bootstrap method is demonstrated and showed that sablefish abundance increased significantly from 1979 to 1986, an increase likely due to recruitment of two strong year classes. The effect of missing data on the bootstrap calculations was examined and found to be negligible.

Early in this century, United States and Canadian fishermen began harvesting sablefish, *Anoplopoma fimbria*, in nearshore waters from California north to southeastern Alaska, but sablefish were not heavily exploited until Japanese longline vessels began fishing in the Bering Sea in 1958. Japanese catches off both the U.S. and Canadian coasts rose dramatically in the following two decades. After passage of the Fishery Conservation and Management Act, foreign catches were reduced and the domestic allocation was increased. The domestic catch eventually increased nearly fivefold, thereby replacing the foreign fishery, and in 1985, sablefish in the Gulf of Alaska were harvested entirely by domestic fishermen.

Before the reduction of the foreign fishery, information on sablefish abundance consisted of statistics on catch per unit effort from the Japanese longline fishery. In 1978, the Fisheries Agency of Japan and the U.S. National Marine Fisheries Service (NMFS) began a cooperative longline survey along the continental slope of Alaska to assess the abundance of sablefish and Pacific cod, *Gadus macrocephalus*. The survey, conducted annually, has provided eight consecutive years (1979–86) of data for the Gulf of Alaska, seven years (1980–86) of data for the Aleutian region, and five years (1982–86) of data for the eastern Bering Sea. The first year of the survey, 1978, was experimental.

Relative population numbers (RPN's) and length compositions from the longline survey results from 1979 to 1985 have been estimated previously by Sasaki (1986). In this study, the observed increase in the RPN's for sablefish in the Gulf of Alaska is evaluated statistically and an explanation of the probable source of the increase is discussed.

Statistical analysis of the survey results is based on the bootstrap method (Efron 1982; Efron and Gong 1983). This method is a relatively new statistical procedure that has been little used in fisheries analysis. Thus, this paper also demonstrates an application of the bootstrap method to statistical evaluation of fishery survey data.

SURVEY METHODS

The Gulf of Alaska portion of the Japan-U.S. cooperative longline survey, conducted annually each summer from 1979 to 1986, covered five International North Pacific Fisheries Commission (INPFC) statistical areas: Shumagin, Chirikof, Kodiak, Yakutat, and Southeastern (Fig. 1). One of a total of 47 stations each ranging in depth from about 100 to 1,000 m was sampled daily by longline. The longline was 16 km long and consisted of 160 hachis (the Japanese word for "skate" or length of longline); each hachi was 100 m long and consisted of 45 hooks baited with squid. Soak time, the time between setting and retrieval, varied from 3 hours at the beginning of the longline gear to 7 or 8 hours at its end. The depth at which the fish were caught was estimated by measuring the depth of water under the vessel with an echo sounder every fifth hachi. The fish caught were tallied by species and hachi as the longline was brought aboard, then they were weighed and their length was measured. Most

[1]Northwest and Alaska Fisheries Center Auke Bay Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 210155, Auke Bay, AK 99821.

Manuscript accepted May 1988.
FISHERY BULLETIN: VOL. 86, NO. 3, 1988.

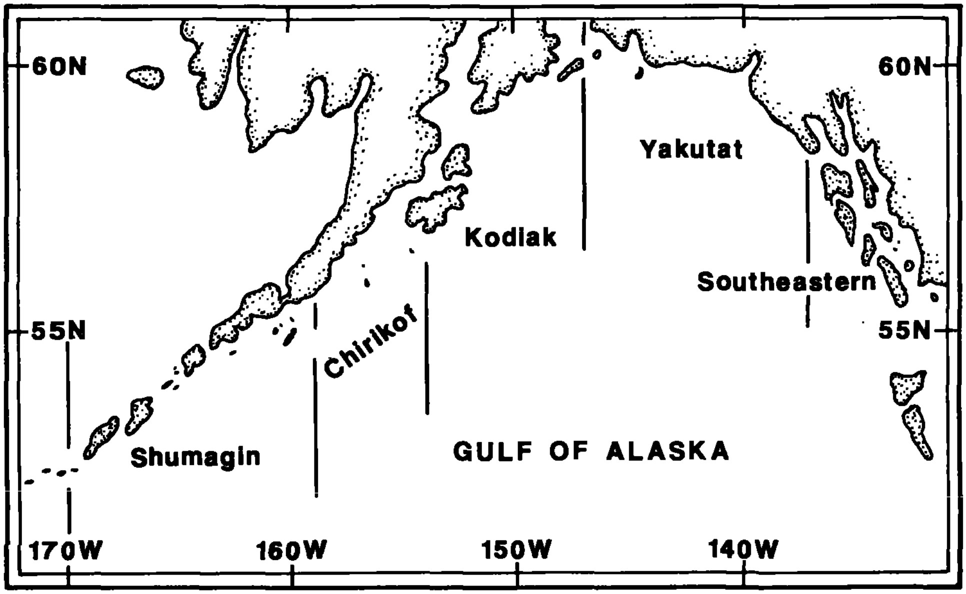

FIGURE 1.—International North Pacific Fisheries Commission statistical areas sampled during the Gulf of Alaska portion of the Japan-U.S. cooperative longline survey, 1979–86.

sablefish were sexed, some were tagged and released, and others were sampled for otoliths and scales. Detailed survey methods are described in Sasaki et al. (1983).

STATISTICAL METHODS

The catch data were stratified because of differences in the catch rate by depth. Assignment of the

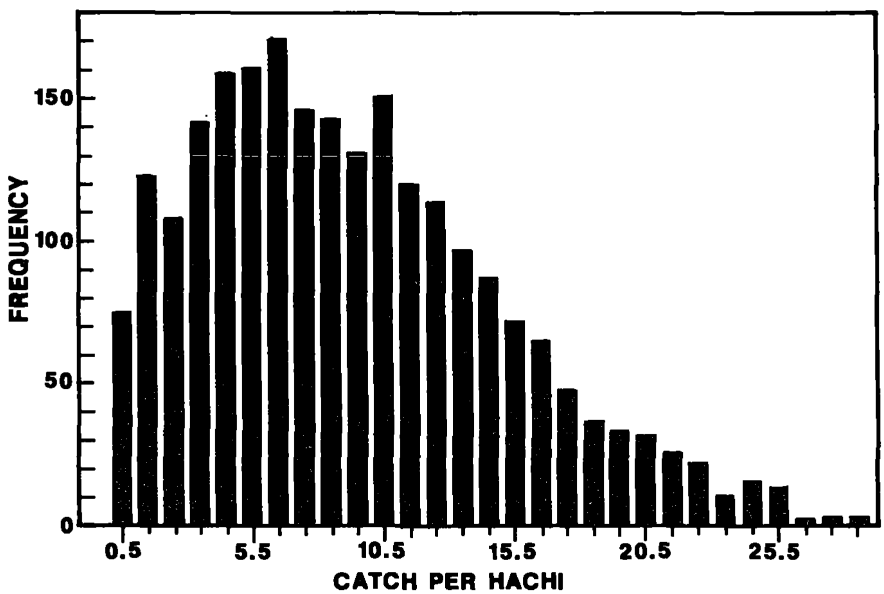

FIGURE 2.—Frequency distribution of sablefish catch per hachi (numbers) by year, station, and strata, 1979–86.

catch data to a stratum was based on the recorded depth of every fifth hachi or the interpolated depth of each of the intervening four hachis. The number of strata totaled nine, with the first stratum representing 101–200 m, the second representing 201–300 m, and so on. A catch per hachi value was calculated for each stratum of a station (Fig. 2), and the resultant values within each statistical area were averaged.

Not all strata were sampled at each station and as a result, sometimes no stations were sampled within certain strata (Table 1). Although not sampled one year, these strata generally were sampled the previous year, because of slight annual differences in the depths sampled at each station. Catch per hachi values $\mathrm{CPUE}_{i,j}$ were estimated for stations within the unsampled strata from the catch per hachi values for sampled stations from the previous year and the annual change in the catch per hachi values in the adjacent stratum. For each station:

$$\mathrm{CPUE}_{i,j} = \mathrm{CPUE}_{i-1,j} * \mathrm{CPUE}_{i,j'}/\mathrm{CPUE}_{i-1,j'}$$

where i = year, j = stratum, and j' = the adjacent stratum. Catch per hachi values were estimated only for stations within unsampled strata. If one or more stations within a stratum were sampled, then no catch per hachi values were estimated for the unsampled stations. The effect of these missing values on the survey results will be discussed later.

Relative population numbers were calculated from the catch per hachi values to index annual changes in sablefish abundance. As in Sasaki (1985), the average catch per hachi was multiplied by the areal size of each stratum and statistical area to calculate an RPN for each stratum and statistical area. The areal sizes used to calculate the RPN's are for the continental slope only (Table 2), which corresponds to the area covered by the survey. The resultant RPN's were summed across strata to calculate an RPN for each statistical area, and these RPN's were summed

TABLE 1.—Number of stations sampled by year, INPFC area, and depth during the Japan-U.S. cooperative longline survey, 1979–86.

		INPFC statistical area							INPFC statistical area				
Year	Depth (m)	Shumagin	Chirikof	Kodiak	Yakutat	Southeast	Year	Depth (m)	Shumagin	Chirikof	Kodiak	Yakutat	Southeast
1979	101–200	7	4	6	6	2	1983	101–200	9	5	7	8	3
	201–300	7	5	7	10	5		201–300	10	6	9	11	9
	301–400	7	5	8	11	6		301–400	10	5	9	11	8
	401–500	7	5	9	11	6		401–500	10	6	9	11	8
	501–600	6	4	9	11	6		501–600	10	5	9	11	8
	601–700	6	4	8	11	5		601–700	9	5	9	11	7
	701–800	6	4	7	11	5		701–800	8	4	8	11	7
	801–900	5	1	4	9	4		801–900	5	4	4	10	7
	901–1,000	4	1	2	4	1		901–1,000	2	0	1	5	2
1980	101–200	9	5	8	7	4	1984	101–200	10	7	7	8	2
	201–300	10	6	8	10	6		201–300	10	7	9	11	9
	301–400	10	6	8	10	8		301–400	10	6	9	11	8
	401–500	10	6	9	10	8		401–500	10	6	9	11	8
	501–600	10	5	9	10	7		501–600	10	5	9	11	8
	601–700	9	5	9	9	7		601–700	8	5	8	11	8
	701–800	6	4	8	9	7		701–800	7	5	6	10	8
	801–900	6	2	3	7	4		801–900	3	0	3	7	5
	901–1,000	5	1	2	6	1		901–1,000	0	0	0	6	1
1981	101–200	9	6	7	8	1	1985	101–200	9	6	6	7	1
	201–300	10	6	9	11	9		201–300	10	7	8	11	9
	301–400	10	6	9	11	9		301–400	10	6	9	11	8
	401–500	10	6	9	11	9		401–500	10	6	9	11	7
	501–600	10	6	9	11	9		501–600	10	6	9	11	8
	601–700	9	4	9	11	9		601–700	9	5	9	11	8
	701–800	7	2	7	11	9		701–800	7	4	9	10	8
	801–900	6	1	5	7	7		801–900	4	4	4	11	6
	901–1,000	2	0	1	2	1		901–1,000	0	0	0	5	2
1982	101–200	9	5	7	10	4	1986	101–200	9	5	7	7	2
	201–300	9	6	9	11	9		201–300	10	6	9	11	9
	301–400	10	5	9	11	8		301–400	10	6	9	11	8
	401–500	10	6	9	11	8		401–500	10	6	9	11	8
	501–600	10	5	9	11	8		501–600	10	6	9	11	8
	601–700	10	5	9	11	8		601–700	10	4	9	11	8
	701–800	9	4	8	11	7		701–800	10	3	8	11	8
	801–900	7	4	6	9	6		801–900	5	2	7	11	8
	901–1,000	3	3	5	8	3		901–1,000	1	1	3	5	1

TABLE 2.—Slope area sizes (km²).

Depth (m)	Slope area (km²)[1]				
	Shumagin	Chirikof	Kodiak	Yakutat	Southeast
201–400	4,001	2,350	3,106	2,988	1,781
401–600	2,269	1,766	2,255	1,666	822
601–800	1,629	1,955	1,923	1,470	1,006
801–1,000	1,248	2,012	2,296	1,489	1,165
201–1,000	9,147	8,083	9,580	7,613	4,774

[1]Shumagin, Chirikof, and Kodiak areas and Yakutat area from long. 147–144°W; data from E. Brown (NWAFC Seattle Laboratory, NMFS, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115, pers. commun. December 1985). Yakutat area from long. 144–137°W. and Southeastern area; data from R. Haight (NWAFC Auke Bay Laboratory, NMFS, NOAA, P.O. Box 210155, Auke Bay, AK 99821, pers. commun. 1986).

across statistical areas to calculate an RPN for the Gulf of Alaska. The bootstrap method (Efron 1982; Efron and Gong 1983) then was applied to the resultant RPN's to test the statistical significance of annual changes in the RPN's.

The bootstrap method is a nonparametric statistical procedure based on Monte Carlo methods (see Shreider [1966] for a description of Monte Carlo methods). The bootstrap method is a new technique not common in the fisheries and ecology literature, but examples of its application to survey design and biomass estimation can be found in Kimura and Balsiger (1985) and Haslett and Wear (1985), respectively. In addition, Rao and Wu (1984) proved the applicability of the bootstrap method to stratified sampling, which is the sampling method used in the longline survey. The bootstrap method is useful when parametric assumptions are difficult to justify; no parametric estimate is readily available for the accuracy of a statistic, e.g., a sample median; or the procedure to compute the statistic of interest is complicated. Simply described, the bootstrap method works as follows: Given the observed data set $\langle X_1, X_2, \ldots, X_n \rangle$, the sample $\langle X_1^*, X_2^*, \ldots, X_n^* \rangle$ is drawn by independent random sampling with replacement from the observed data set and the desired statistic (e.g., a median) is computed from the sample. The resultant statistic is termed the bootstrap replicate. In the next step, the sample is drawn and the bootstrap replicate is computed some large number B times. The resultant B bootstrap replicates form the bootstrap distribution. An estimate of the accuracy of the median, a standard error, then can be calculated from the bootstrap distribution by standard methods.

In this study, we used the bootstrap method to test the null hypothesis that the difference $\mathrm{RPN}_{i',k} - \mathrm{RPN}_{i,k} = 0$, for any $\mathrm{RPN}_{i,k'}$, where i = year (1979–86), i' = any subsequent year, and k = statistical area (Shumagin, Chirikof, Kodiak, Yakutat, and Southeastern). The bootstrap method was used because parametric assumptions are difficult to justify for the longline survey data and the procedure to compute the statistic of interest, the variance of the RPN, is tedious and error prone. In our application of the bootstrap method, stations were randomly sampled with replacement within each area. A value denoted $\mathrm{RPN}_{i,k}^*$ was computed from the catch per hachi values of the sampled stations by the method of RPN calculation described previously. Stations then were sampled with replacement from year i' within each area, a second value denoted $\mathrm{RPN}_{i',k}^*$ was computed, and the difference $\mathrm{RPN}_{i',k}^* - \mathrm{RPN}_{i,k}^*$ was found. Sampling with replacement from the 2 years and the computation of the difference were repeated 1,000 times producing a bootstrap distribution of 1,000 differences.

Efron and Tibshirani (1986) outlined three methods for setting an approximate confidence interval from a bootstrap distribution for a statistic of interest, here the difference $\mathrm{RPN}_{i',k} - \mathrm{RPN}_{i,k}$. Use of the simplest method, the percentile method, is considered correct if the bootstrap distribution of the statistic of interest is described by a normal distribution (Efron and Tibshirani 1986). The normality of the bootstrap distribution for the difference was tested using the D'Agostino D Test (D'Agostino and Stephens 1986) and found to be normal, thus justifying the use of the percentile method. The statistical significance of the difference $\mathrm{RPN}_{i',k} - \mathrm{RPN}_{i,k}$ then was evaluated by the following criteria. If the 95% confidence interval for the difference did not include zero, then the null hypothesis was rejected, the annual change in the RPN was considered statistically significant, and the change in sablefish abundance was considered real. Conversely, if the 95% confidence interval for the difference included zero, the null hypothesis was accepted and the change in sablefish abundance was not considered significant.

RESULTS

The RPN for the Gulf of Alaska increased 111% from 1979 to 1986 (Fig. 3). The 95% confidence interval for this increase did not include zero and therefore was judged statistically significant (alpha = 0.05; Table 3), showing that the difference was not due to random error in the survey and that sablefish abundance in the Gulf of Alaska has increased markedly since 1979. The difference consists of significant increases from 1980 to 1981, 1981

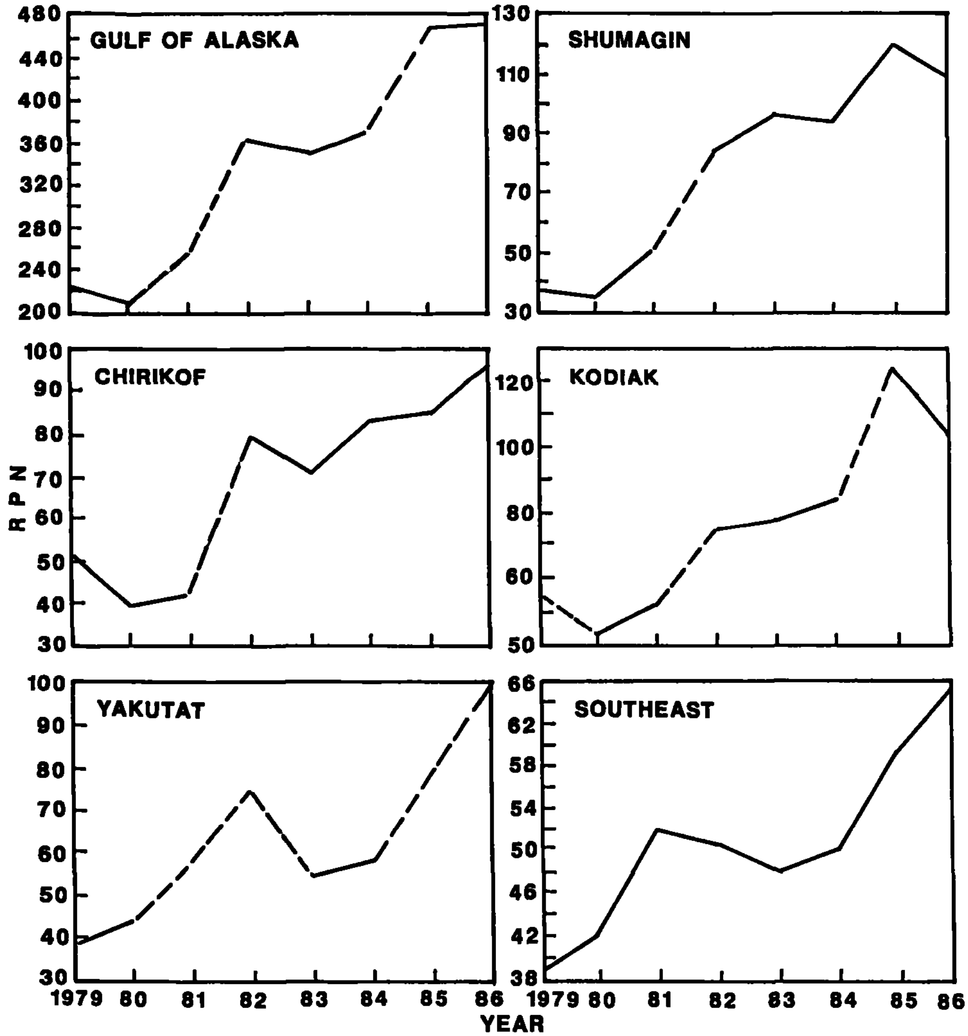

FIGURE 3.—Relative population number (RPN) for the Gulf of Alaska and the Shumagin, Chirikof, Kodiak, Yakutat, and Southeastern areas, 1979–86. Dashed lines (----) signify that the annual change was statistically significant.

to 1982, and 1984 to 1985 (Fig. 3). Differences between other years were not significant.

The RPN for each of the statistical areas of the Gulf of Alaska generally increased from 1979 to 1986 (Fig. 3); the differences between 1979 and 1986 were statistically significant for all areas (Table 3), showing that sablefish abundance has increased throughout the Gulf of Alaska. The sharp jump in the RPN for the Gulf of Alaska from 1980 to 1982 was caused by significant increases in four areas, Shumagin, Chirikof, Kodiak, and Yakutat. The sharp jump from 1984 to 1985 was caused by significant increases in two areas, Kodiak and Yakutat.

DISCUSSION

As noted earlier, sometimes not all strata were sampled at a station (Table 1). This shortcoming was a consequence of the length of the sampling gear and the topography at a station. At stations where the bottom gradient was slight for all or part of the station, the 16 km of longline gear sometimes was not long enough to sample all strata. As a result, sometimes no stations were sampled within certain strata. For these strata, catch per hachi values were estimated using combined data from the current and previous year's data. The resultant values are esti-

TABLE 3.—Statistical significance of annual changes in relative population number of sablefish, Gulf of Alaska, Japan-U.S. cooperative longline survey, 1979–86. The symbols used are defined as follows: + signifies a significant increase in RPN; – signifies a significant decrease in RPN; O signifies no significant change.

Area	Year	80	81	82	83	84	85	86
Gulf of Alaska	1979	O	+	+	+	+	+	+
	1980		+	+	+	+	+	+
	1981			+	+	+	+	+
	1982				O	O	+	+
	1983					O	+	+
	1984						+	+
	1985							O
Shumagin	1979	O	O	+	+	+	+	+
	1980		O	+	+	+	+	+
	1981			+	+	+	+	+
	1982				O	O	+	+
	1983					O	O	O
	1984						O	O
	1985							O
Chirikof	1979	O	O	+	+	+	+	+
	1980		O	+	+	+	+	+
	1981			+	+	+	+	+
	1982				O	O	O	+
	1983					O	O	+
	1984						O	O
	1985							O
Kodiak	1979	–	O	+	+	+	+	+
	1980		O	+	+	+	+	+
	1981			+	+	+	+	+
	1982				O	O	+	+
	1983					O	+	+
	1984						+	O
	1985							O
Yakutat	1979	O	+	+	+	+	+	+
	1980		+	+	O	+	+	+
	1981			+	O	O	+	+
	1982				–	–	O	+
	1983					O	+	+
	1984						+	+
	1985							+
Southeastern	1979	O	+	+	O	+	+	+
	1980		O	O	O	O	+	+
	1981			O	O	O	O	+
	1982				O	O	O	+
	1983					O	O	+
	1984						O	+
	1985							O

mates of catch per hachi as if the strata had been sampled. Because the estimated values mimic the observed data, the probability of rejecting the null hypothesis is somewhat higher than the nominal value. In general an inaccurate estimate should have a small total effect because catch per hachi values were missing for only 9 of the 320 strata available during the survey (8 years × 5 areas × 9 strata). The only comparison where the estimated catch per hachi values might have caused an incorrect conclusion is the 1984–85 comparison where 7 strata were unsampled. This comparison was retested using only the observed catch per hachi values. The annual change, like the comparison using the estimated catch per hachi values, was found to be statistically significant.

Another potential effect of incomplete sampling at a station is bias in the bootstrap calculation. Each bootstrap replicate $RPN_{i,k}^*$ was computed from a bootstrap sample selected by sampling with replacement from the stations within an area. If one or more stations were missing an observation for a strata, then it was possible for the bootstrap sample to have all missing values for the strata. In this case, no catch per hachi values were available to calculate a value for the strata and the value for the strata was treated as zero. This treatment may negatively bias the resultant $RPN_{i,k}^*$. The extent of the negative bias was tested by comparing the RPN to a bootstrap estimate of the RPN, denoted RPN_b, where RPN_b is the mean of the 1,000 $RPN_{i,k}^*$ from an area and year. If RPN_b generally was smaller than RPN, then the bootstrap replicates were negatively biased. The percentage difference between the resultant RPN_b's compared to the RPN's ranged from −0.7 to +0.5 and averaged only +0.03, showing that the negative bias had little effect on the $RPN_{i,k}^*$.

Other fishery and survey data substantiate the significance of the overall increase in the RPN and also the marked increases from 1981 to 1982 and from 1984 to 1985. The CPUE in the Japanese longline fishery showed a similar pattern to the RPN's for the years the data overlapped, from 1979 to 1983; the fishery CPUE increased from the late 1970's, with the largest increase from 1981 to 1982, and decreased from 1982 to 1983 (Fig. 4).

Examination of length compositions for depths 101–200 m indicate that the strong 1977 year class (Sasaki 1982; McFarlane and Beamish 1983; Funk and Bracken 1984) was responsible for the RPN increase from 1980 to 1982 and that the RPN increase from 1984 to 1985 was due to a strong 1980 year class. Sablefish recruiting to the survey area first appear at depths 101–200 m, and strong year classes are more distinguishable in the length compositions at these depths. The length compositions for depths 101–200 m show the initial appearance and subsequent increase in length of fish of the strong 1977 year class (Fig. 5). The mode at 47 cm FL in 1979 indicates the first year that the 1977 year class was available to the survey gear. The rightward movement of the mode in succeeding years illustrates the increase in fish length for the 1977 year class. The movement of the mode slowed in 1982 which we interpret to be due mainly to the movement of larger

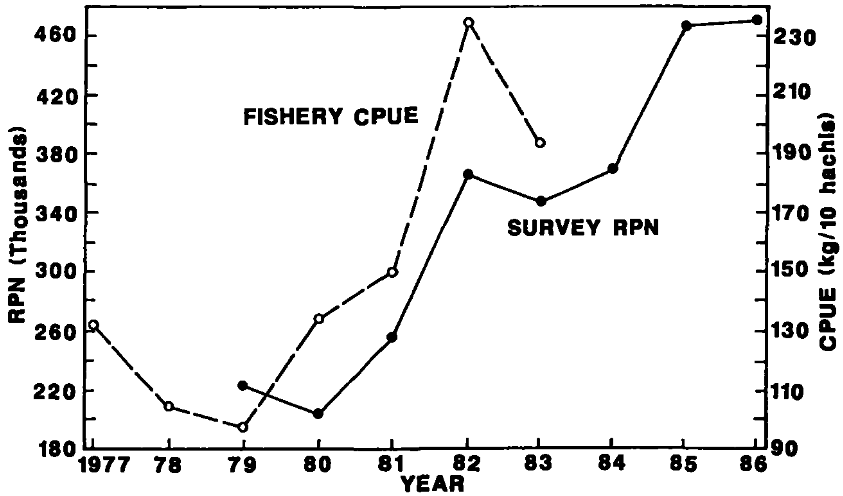

FIGURE 4.—Sablefish catch per hachi (kg/10 hachis) for the Japanese longline fishery, 1977–83 (Fujioka 1986) and relative population number (RPN), 1979–86.

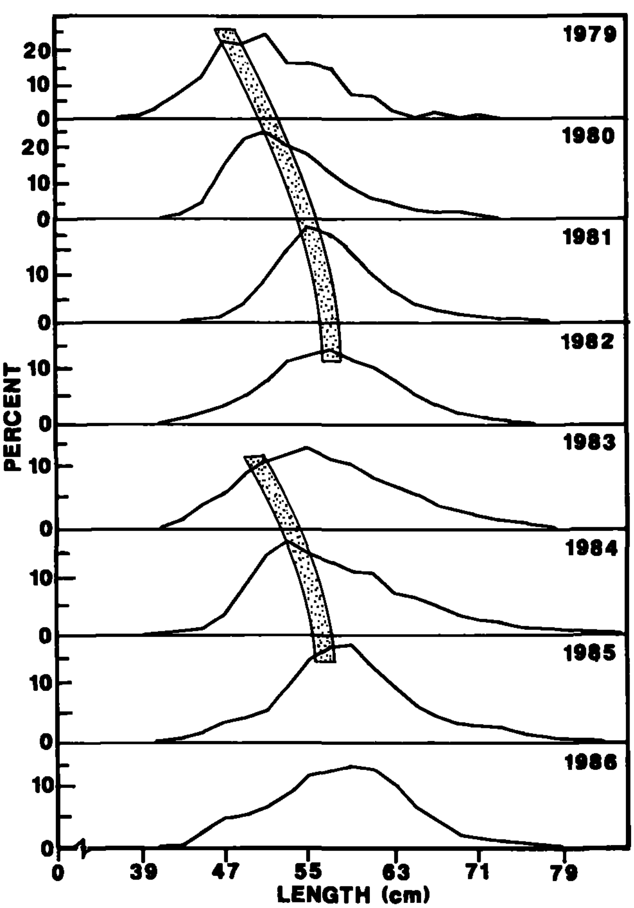

FIGURE 5.—Length-frequency distributions of sablefish in the Gulf of Alaska for depths 101–200 m, 1979–86. The shaded bands illustrate the progression of the modes of two strong year classes, 1977 and 1980.

fish to depths >200 m. The timing of this movement corresponds to the year that the RPN significantly increased.

The pattern of length compositions from 1983 to 1985 parallels those due to the strong 1977 year class and suggests that the 1980 year class is also strong (Fig. 5). The shoulder at 49–51 cm FL in 1983, not present in 1982, indicates the first year that the 1980 year class was available to the survey gear. This shoulder is due to distinct modes at 47–51 cm FL in the Chirikof, Yakutat, and Southeastern areas. The rightward movement of the mode in succeeding years illustrates the increase in fish length for the 1980 year class. The mode at 53 cm FL in 1984 is similar to the modes at 50–57 cm FL found in the Gulf of Alaska for depths 101–200 m during a trawl survey conducted in 1984 by the Northwest and Alaska Fisheries Center (Brown 1986) and is further evidence for a strong 1980 year class. The rightward movement of the mode slowed in 1985, presumably due to movement of larger fish to depths >200 m, and again corresponds to the year of a significant increase in RPN.

ACKNOWLEDGMENTS

Thanks to Evan Haynes and Leslie Williams for thoroughly editing the manuscript, Jerry Pella for statistical advice, and Takashi Sasaki for courteously providing cooperative survey data.

LITERATURE CITED

BROWN, E.
1986. Preliminary results of the 1984 U.S.-Japan cooperative bottom trawl survey of the central and western Gulf of Alaska. *In* R. L. Major (editor), Condition of groundfish resources of the Gulf of Alaska region as assessed in 1984, p. 259–296. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-106.

D'AGOSTINO, R. B., AND M. A. STEPHENS.
1986. Goodness-of-fit techniques. Marcel Dekker, N.Y.

EFRON, B.
1982. The jackknife, the bootstrap and other resampling plans. Appl. Math. 38, 92 p. Soc. Ind. Appl. Math., Phila.

EFRON, B., AND G. GONG.
1983. A leisurely look at the bootstrap, the jackknife, and cross-validation. Am. Stat. 37:36–48.

EFRON, B., AND R. TIBSHIRANI.
1986. Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. Stat. Sci. 1:54–77.

FUJIOKA, J.
1986. Sablefish. *In* R. L. Major (editor), Condition of groundfish resources of the Gulf of Alaska region as assessed in 1985, p. 79–108. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/NWC-106.

FUNK, F., AND B. E. BRACKEN.
1984. Status of the Gulf of Alaska sablefish (*Anoplopoma fimbria*) resource in 1983. Alaska Dep. Fish Game, Info. Leafl. 235, 55 p.

HASLETT, S. J., AND R. G. WEAR.
1985. Biomass estimation of Artemia at Lake Grassmere, Marlborough, New Zealand. Aust. J. Mar. Freshwater Res. 36:537–557.

KIMURA, D. K., AND J. W. BALSIGER.
1985. Bootstrap methods for evaluating sablefish pot index surveys. N. Am. J. Fish. Manage. 5:47–56.

MCFARLANE, G. A., AND R. J. BEAMISH.
1983. Overview of the fishery and management strategy for sablefish (*Anoplopoma fimbria*) off the west coast of Canada. *In* Proceedings of the International Sablefish Symposium, p. 13–35. Alaska Sea Grant Rep. 83-8, Univ. Alaska, Fairbanks.

RAO, J. N. K., AND C. F. J. WU.
1984. Bootstrap inference for sample surveys. *In* J. E. Gentle (editor), Proceedings of the section on survey research methods, p. 106–112. Am. Stat. Assoc.

SASAKI, T.
1982. Condition of sablefish stocks in the North Pacific. Far Seas Fish. Lab. Fish. Agency Jpn., Shimizu, 17 p. (Document submitted to the International North Pacific Fisheries Commission.)
1985. Studies on the sablefish resources in the North Pacific Ocean. Far Seas Fish. Res. Lab., Bull. 22, 107 p. Fisheries Agency of Japan, Shimizu.
1986. Stock assessment of sablefish in the eastern Bering Sea, Aleutian Islands region, and the Gulf of Alaska. Far Seas Fish. Res. Lab., Fish. Agency Jpn., Shimizu, 33 p.

SASAKI, T., D. RODMAN, AND K. FUNATO.
1983. Preliminary report on Japan-U.S. joint longline survey by *Ryusho maru No.* 15 in the eastern Bering Sea, Aleutian region and Gulf of Alaska, 1982. Far Seas Fish. Res. Lab., Fish. Agency Jpn., Shimizu, 116 p.

SHREIDER, Y. A.
1966. The Monte Carlo method. Pergammon Press, N.Y.