INTER-AMERICAN TROPICAL TUNA COMMISSION
COMISION INTERAMERICANA DEL ATUN TROPICAL

INTERNAL REPORT--INFORME INTERNO

No. 12

INFORMATION PERTINENT TO STOCK ASSESSMENT OF NORTHERN BLUEFIN TUNA, *THUNNUS THYNNUS*, IN THE PACIFIC OCEAN

by

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La Jolla, California

1979

P R E F A C E

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INTRODUCTION

This report was originally prepared for a meeting on stock assessment of tunas, held at Shimizu, Japan, on June 13-22, 1979. Subsequent to that meeting it was revised, and it is now presented as an Internal Report for the convenience of persons working on stock assessment of this species.

FISHERY

Surface fishery in the eastern Pacific Ocean

Sport fishing for northern bluefin began in California in 1898 (Bell, 1970). Prior to World War I, before the advent of the commercial fishery, many large fish were taken, particularly by vessels based at Catalina Island. The largest of these weighed 251 pounds (114 kg). Since then the average size of the sport-caught fish has been roughly 25 pounds (11 kg). Most of these are caught by fishermen who are directing their efforts primarily toward albacore.

Northern bluefin are caught commercially in the eastern Pacific Ocean almost entirely by purse seiners. The fishery began in 1918 (Whitehead, 1931). From that time until about 1959 or 1960 most of the vessels were relatively small, with capacities less than about 200 short tons (181 metric tons). None of them fished exclusively for northern bluefin. The smaller ones fished chiefly for sardines, mackerel, and other pelagic fish other than tunas, and the larger ones fished mostly for yellowfin and skipjack. During 1959 and 1960 most of the larger tuna baitboats were converted to purse seiners, and during the ensuing years many new purse seiners were built. During the 1960's and 1970's many of the smaller, older vessels sank or dropped out of the fishery, and the new vessels which replaced them tended to increase in size during this period. As a result there are now more larger purse seiners and fewer smaller ones than had been the case during the early 1960's. Northern bluefin are now taken by vessels of all sizes, but the smaller ones account for a proportionally larger share of the catch. The portion of the catch made by vessels which fish primarily for pelagic fish other than tunas is less now than it was in the earlier years of the fishery, as the center of abundance of northern bluefin has shifted southward beyond the area where these vessels normally fish.

Purse-seine fishing occurs in hours of both daylight and darkness. "If bluefin are in "dirty" water they cannot readily see the net and are not frightened into sounding when encircled; thus good fishing occurs during daylight hours. If they are in clear water, however, they can see the net during the daytime and so night fishing, especially during the dark of the moon, is more successful" (Clemens, no date).

Surface fishery in the western Pacific Ocean

The information in this subsection is principally from Yamanaka et al. (1963) and Hisada, Shingu, and Yonemori (1979). In the western Pacific northern bluefin are caught at the surface by gill nets, purse seines, traps (set nets), trolling gear, baitboat gear, harpoons, and sport fishing gear. They are caught by gill nets southeast of Hokkaido and east of northern Honshu. These fish range up to more than 200 kg in weight (gilled and gutted). Since the early 1950's at least, northern bluefin have been caught by purse seiners southeast of Hokkaido and east of northern Honshu from about May to October. The purse seines have been employed with either one or two boats, but during the 1970's the former have largely replaced the latter. Most of these have capacities of about 100 to 500 metric tons. The fish caught by purse seiners range up to more than 200 kg in weight, with the average weight being about 50 kg. Small, medium, and large northern bluefin are caught in traps on both the Pacific and Sea of Japan coasts of Honshu and Hokkaido from about April to October. The troll fishery is pursued principally west of Kyushu during October to January, south of Kyushu from December to April, and southeast of Kyushu, Shikoku, and Honshu during April to September. Most of these vessels have capacities of less than 5 metric tons. The fish caught south of Kyushu weigh about 2 kg (round weight) each, while those caught southeast of Kyushu, Shikoku, and Honshu weigh less than 1 kg each.

Longline fishery

The longline fishery is pursued by vessels of Japan, the Republic of China, and the Republic of Korea. These vessels fish not only for bluefin, but also for other species of Thunnus and for billfishes. The fishery takes place in all months of the year and in nearly all areas in which tunas and billfishes occur. Japanese vessels of about 20 to 50 gross tons operate near Japan (Yamanaka et al., 1963), whereas those which fish in more distant waters are larger.

DISTRIBUTION OF THE CATCHES

Surface fishery in the eastern Pacific Ocean

Northern bluefin are rarely encountered south of Cabo San Lucas, Baja California, or north of Point Conception, California. Within this area a considerable change has taken place during the 20th century (Bell, 1970). Prior to 1930 fishing was conducted only off California. During that year northern bluefin were discovered off Guadalupe Island, Baja California, and about 40 percent of the catch in 1930 was made in that area (Whitehead, 1931). From 1930 through 1947 fishing was conducted off both California and Baja California, but in most years the majority of the catch came from off California. From 1948 to the present, however, most of the catch has been made off Baja California. The average annual catches made west of California during the 1960's and 1970's have been considerably less than the average annual catches made in the same area during the 1918-1929 period. It is believed that the principal reason for this is that during more recent years the larger vessels fishing off Baja California have tended to intercept the fish before they reach the waters off California.

The information discussed in the remainder of this subsection has been obtained from the logbook records of tuna purse seiners. The vessel masters or navigators typically record the catch of each purse-seine set in short tons, the location of each set to the nearest degree and minute of latitude and longitude, and the date. At the end of each trip an abstract of the vessel logbook is prepared. These records are processed by computer, and tables summarizing the northern bluefin catch by month and 1-degree area of latitude and longitude are printed. During the 1969-1978 period the annual logged catches ranged from 72 to 98 percent of the corresponding weighed-out catches.

Northern bluefin have been caught in all months of the year, but nearly all of the catch is made during the period starting in May or June and ending in September or October.

In Figure 1 the distributions of the catches for the 1969-1978 period are shown by 1-degree area and month. During January through April there are typically only light and sporadic catches. Most of these are made off the coast of Baja California between 24°N and 26°N and in the vicinity of Guadalupe Island, located approximately at 29°N-118°N. In May and June the volume of the catch increases, and most of it is made between 24°N and 27°N. In July the fishing area spreads to the north and is at its widest extent of the year; most of the catch is made between 25°N and 33°N. In August there are usually only light catches at the southern end of the fishing area, most of the catch being made between 28°N and 33°N. In September most of the catch is made in the same area as in August, but the amount of catch is usually considerably less. In October the volume of catch continues to decline, and most of it is made in the north. In November and December, as in the first months of the year, the catches are light and scattered.

Northern bluefin are caught in the vicinity of Guadalupe island during all months of the year (but not during every month of every year).

Longline fishery

The Far Seas Fisheries Research Laboratory (FSFRL) of Japan collects data on the catches of northern bluefin, in numbers of fish and by area and date, for a substantial portion of the trips made by Japanese longline vessels. The data were used to estimate the distribution of the total catches of Japanese vessels during 1972-1976 (Anonymous, 1974, 1975, 1976, 1977a, and 1978). The latter data have been used by the Tuna Commission, in conjunction with weight distribution data furnished by the FSFRL, to calculate estimates of the distribution of the catches by weight; these appear in Figure 2.

The catches occur mostly in a band extending from about 30°N-130°W to Japan, east of the Philippine Islands, northeast of Papua New Guinea, and southeast of Australia. The greatest catches have been made between 30° and 35° north latitude and 170° and 175° east longitude (except in 1974, when they were displaced 5 degrees to the north and 5 degrees to the west), south and southeast of Japan, and in the vicinity of New Zealand. In 1975 and 1976 relatively good catches were made off northern Japan.

CATCH AND EFFORT STATISTICS

Annual catches

The total annual surface catches of northern bluefin by commercial and sport vessels in the eastern Pacific Ocean during 1918 through 1978 are shown in Table 1 and Figure 3. The catches prior to 1918 were negligible. The data were obtained from Whitehead (1931), Bell (1963a and 1971), Frey (1971), Oliphant (1973), Pinkas (1974 and 1977), McAllister (1975 and 1976), and unpublished records of the Inter-American Tropical Tuna Commission. The data for 1918 through 1960 include only the catches landed in California, but it is believed that the catches landed elsewhere prior to 1961 were inconsequential. The eastern Pacific subsurface catches for all years are omitted, but these are also believed to be inconsequential.

The catches have tended to be higher during the 1960's and 1970's than during the previous period. This is probably due to the fact that during 1959 and 1960 most of the tuna baitboats were converted to purse seiners, and many new purse seiners were built. During the earlier period the catch was made by small purse seiners, most of which fished part time for tunas and part time for other pelagic fish, whereas during the later period most of the catch has been made by larger purse seiners which fish full time for tunas (but not exclusively for northern bluefin, of course).

Yamanaka et al. (1963) and Anonymous (1971-1978) give catch statistics for the western Pacific for 1951-1959 and 1964-1977, respectively. Yamanaka et al.'s data are for "around Japan" only, but the catches made elsewhere in the western Pacific are probably minor. Their 1951 and 1952 data include southern bluefin, but the catches of this species in the vicinity of Japan are probably inconsequential. Yamanaka et al. also state that fish were scarcer during the 1940's than during the 1930's and 1950's.

Monthly catches

The monthly logged catches of northern bluefin in metric tons in the eastern Pacific Ocean surface fishery are shown in Table 2 for two time periods, 1959-1968 and 1969-1978. The data for 1959-1968 are from Bell (1970), and those for 1969-1978 were compiled from Tuna Commission logbook records. The last column of the table shows the 10-year averages for each month expressed as percentages of the total annual catches for the 10-year periods.

It is apparent that, on the average, the catch of bluefin is concentrated in the months of June through September. In the 1959-1968 period these months averaged 94.8 percent of the annual catch, and in the 1969-1978 period they averaged 85.8 percent of the annual catch. The average monthly percentages are similar in the two decades, but there are some minor differences. In the 1959-1968 period the average percentage catches for May and October were 0.8 and 1.7, respectively, while in the 1969-1978 decade these percentages were higher; 6.8 and 5.5, respectively.

Fishing effort and catch per day's fishing

In order to calculate an estimate of northern bluefin catch per day's fishing in the eastern Pacific it is necessary to define bluefin effort. This raises some difficulties, as almost all of the vessels which catch bluefin also catch yellowfin, skipjack, and bonito. Since virtually all of the bluefin catch is made north of 23° north latitude, only purse-seine effort north of that division need be considered. Also, since the bluefin season extends, at most, from May through October, fishing effort in the other months can be ignored. However, in some years there are few or no bluefin caught during May, and the season may end in September or, rarely, in August.

Therefore, as a first step, it was decided to count all purse-seine effort north of 23° north latitude in the first month of the May-October period in which 100 or more short tons of bluefin were caught and continue on to the last month of the period in which 100 more tons of bluefin were caught. Thus all purse-seine effort north of 23° north latitude during the bluefin season (defined above) is counted as bluefin effort. It is acknowledged, however, that a substantial part of this effort is directed at yellowfin, skipjack, and bonito, all of which are present in this area-time stratum. The estimates of effort thus obtained and the months in which effort was counted are shown in Table 3 for 1966 through 1978. Also shown in the table are the logged catches of bluefin in metric tons corresponding to the effort and the resulting catches per day's fishing.

During the 1966-1978 period the estimates of bluefin fishing effort ranged from a high of 3,694 days in 1972 to a low of 2,203 days in 1974. The average for the period was 2,775 days. The catch per day's fishing ranged from 5.06 to 1.42 metric tons. The high point occurred in 1966 and the low point in 1967. The average was 2.41 tons per day's fishing.

SIZE DISTRIBUTION

Surface fishery in the eastern Pacific Ocean

The California Department of Fish and Game (CDFG) has collected length-frequency data for northern bluefin landed in California during 1951 through 1975. The Inter-American Tropical Tuna Commission has collected similar data for fish landed in California and Mexico during 1973 through the present. Yearly summaries of the CDFG data for

1952-1968 and 1963-1969 and of the Tuna Commission data for 1973-1978 are given by Bell (1970), Schultze and Collins (1977), and Anonymous (1979), respectvely. These summaries are shown in Figures 4 and 5. Most of the samples consisted of 50 fish. The lengths in Figure 5 are grouped by 2-cm intervals and smoothed by moving averages of three, with the center frequency given double weight. No adjustments have been made for unequal sampling of the various area, time, or gear-type strata.

It appears that it would be difficult to assign the fish to age groups from the length-frequency data alone. For example, the smallest mode occurs between 60 and 70 cm in 19 of the years, but between 70 and 80 cm in 5 others. The 60- to 70-cm fish are probably 1+ years of age, as Schultze and Collins (1977) have estimated from scale examination that the fish are about 53 and 80 cm long on their first and second birthday anniversaries, respectively (see below). It is difficult or impossible to interpret the modes of the fish larger than about 60 to 70 cm, as these vary in number, position, and distinctness. It is not surprising that such is the case, as the length-at-age data of Schultze and Collins (1977) indicate that there is considerable overlap in the lengths of the fish of different ages.

The difficulties in interpreting the modes in Figure 4 and 5 could be partially the result of the sampling taking place mostly near the beginning of the season during some years and mostly near the end of the season during others, coupled with growth of the fish during the season. Accordingly, it is appropriate to examine monthly length-frequency data, which are available only for the measurements taken by the Tuna Commission (Figure 6). The positions of the predominant smallest mode are as follows:

	June	July	August	September	October
1973	58	64	64	-	-
1974	70	76	76	78	-
1975	68	70	72	76	80
1976	58	62	64	66	66
1977	68	72	76	74	-
1978	60	62	62	-	-

The lengths vary considerably from year to year, the fish having been relatively small in 1973, 1976, and 1978, and relatively large in 1974, 1975, and 1977.

The fish caught at Guadalupe Island tend to be larger, including some weighing more than 100 pounds (45 kg) (Clemens, no date; Bell, 1963a). Larger fish are also caught elsewhere, however, as none of those in the samples for 1973-1978 were from Guadalupe Island.

Surface and subsurface fisheries in the western Pacific Ocean

Tatsuki, Uto, and Kitamura (1963) show length-frequency data for fish caught by baitboats and trollers in the western Pacific during January-April 1952-1954 and 1957-1959. The fish ranged from 44 to 77 cm in length, with modes at 50 to 58 cm. Yukinawa and Yabuta (1967) show data for January-December 1953-1963 (Figure 7). Weight-frequency data for fish caught by purse seines, traps, and longlines in various years are given by Yamanaka (1958), Yamanaka et al. (1963), Nakamura (1969), and Shingu, Warashina, and Matsuzaki (1974). These fish are considerably larger, most of them weighing more than 80 kg (dressed weight).

AGE AND GROWTH

Bell (1963b), Koski (1967), and Schultze and Collins (1977) give data on the age and growth of northern bluefin in the eastern Pacific Ocean as estimated from their scales. Koski verified that distinctive marks are formed once each year, with the midpoint in April, and thus that the use of scales to estimate the ages of the fish is valid. Bell gives mean lengths of fish of age groups 0 through V, and Schultze and Collins give mean lengths of fish of age groups 1_1 through 1_6 calculated from a von Bertalanffy growth equation derived from length-at-age data. These data are shown in Table 4. Bell's age-group 0 is assumed to be equivalent to Schultze and Collins' age group 1_1, which corresponds to 1 year of age.

The tagging date of Bell (1970) have been used to estimate the rate of growth of this species. Considerable numbers of tagged fish were released in 1962, 1963, 1964, 1966, and 1968, but they were measured only in 1963 and 1964, and then only to the nearest 5 cm. The data include 105 fish for which the length at release, length at recapture, and dates of release and recapture are given.

The first step was to determine whether or not the measurements of the fish at release were accurate. For this purpose it was assumed that the changes in length during the final 20 days after release due to growth or to shrinking or stretching between recapture and measurement were negligible. There were 30 fish at liberty less than 21 days; for 1 of these the length at recapture exceeded the length at release, for 2 of them these lengths were the same, and for the remaining 27 the lengths at recapture were less than the lengths at release. It is apparent from these data that there was a tendency to overestimate the lengths when the fish were released.

The next step was to adjust the lengths at release. Of the 30 fish at liberty less than 21 days 28 were small (58.5 to 75 cm at release) and 2 were medium (85 cm at release). The relationships of the lengths at release to the lengths at recapture for these two groups were calculated to be

$$L_2 = 320 + 0.452L_1 \qquad \text{(small fish) and}$$

$$L_2 = 0.991L_1 \qquad \text{(medium fish),}$$

where L_1 = length at release and L_2 = length at recapture. Accordingly, the lengths at release of the 93 small (58.5 to 75 cm) fish were adjusted by the first equation and those of the 12 medium (80 to 95 cm) fish were adjusted by the second equation.

Finally the data were used to estimate the parameters of the von Bertalanffy growth equation, resulting in estimates of 41,079 cm for l_{∞} and 0.0005 for K on an annual basis. The method used does not involve age estimates of the fish, so it was arbitrarily decided to make the fish of age 1 55.05 cm long, this being midway between the age-1 values of Bell (1963b) and of Schultze and Collins (1977). The calculated values for ages 1 through 6 are shown in Table 4 and Figure 8. It is apparent that the three sets of length-at-age values are quite close. The estimates of l_{∞} and K differ considerably, however, the present study giving the highest $\underline{l_{\infty}}$ estimate and the lowest $\underline{K}$ estimate, Schultze and Collins' data giving the lowest $\underline{l_{\infty}}$ estimate and the highest $\underline{K}$ estimate, and Bell's data giving intermediate estimates of both parameters. It should be noted, however, that Schultze and Collins' estimates are closest to the $\underline{l_{\infty}}$ and $\underline{K}$ estimates of 320.5 and 0.1035, respectively, calculated by Yukinawa and Yabuta (1967) for northern bluefin in the western Pacific Ocean. The points in Figure 8 for the present study are close to those for the study of Schultze and Collins, so it seems that if a few of the lengths at release of the tagged fish had been somewhat different the $\underline{l_{\infty}}$ and $\underline{K}$ estimates would have been much closer to those of Schultze and Collins. In fact, if the data for the seventh fish in Table 1 of Clemens and Flittner (1969), for which the length was estimated from its weight, are included in the calculation $\underline{l_{\infty}}$ and $\underline{K}$ become 512 cm and 0.0500, respectively. Obviously, then, not much significance should be attached to the estimates derived from the tagging data. Better results might have been obtained if there had been less bias in measuring the fish when they were released. Accordingly, if northern bluefin are tagged in the future it is recommended that they be measured to the nearest 1 cm, and with sufficient care to minimize the bias.

LENGTH-WEIGHT RELATIONSHIP

The relationships of weight to length for northern bluefin given by Bell (1970) are shown in Table 5.

MIGRATION

A summary of the northern bluefin tagging activities carried out by the California Department of Fish and Game, the Inter-American Tropical

Tuna Commission, the Mission Bay Research Foundation, and the U.S. Bureau of Commercial Fisheries during 1953-1976 is given in Table 6. Information on the results of these experiments is given by Chatwin and Orange (1960), Orange and Fink (1963), Flittner (1966), Clemens and Flittner (1969), and Bell (1970).

The locations and months of recapture of the tagged fish in the eastern Pacific Ocean are shown in Figure 9. The tagged fish tended to migrate northward along the coast of Baja California and California from June to September. This pattern appears to be the same as that indicated by the data for the distribution of the catches (Figure 1).

Nine returns of tagged fish which migrated from North America to Japan and two returns of tagged fish which migrated from Japan to North America have been received. These are listed in Table 7. The fish which crossed the ocean from west to east were presumably in their first year of life when they were tagged, and were recaptured in the eastern Pacific Ocean only 1 year later. Those which crossed the ocean from east to west were probably in their second or third years of life when tagged, and were recaptured in the western Pacific Ocean 2 to 5 years later.

MORTALITY

Schultze and Collins (1977 : Table 11) show data for the estimated numbers of northern bluefin of each age in the California catches of 1963 through 1969. If it is assumed that the recruitment is constant from year to year and that the fish of the various age groups are equally vulnerable to the fishery the numbers of fish of each age group caught in a single year can be used to estimate the total rate of attrition, which includes fishing and natural mortality and emigration. If it is assumed that the fishing effort is constant from year to year and that the fish of the various age groups are equally vulnerable to the fishery the numbers of fish of the same year class in the catches of different years can be used to estimate the total rate of attrition. The latter assumption is considered more likely to be satisfied than the former, so only the second method was used in this report.

The data are shown in Table 8. The methods of Robson and Chapman (1961) were used to make the estimates. For the 1962, 1963, and 1965 year classes age-group 0 was omitted from the calculations, and for the 1964 year class age-groups 0 and 1 were omitted. The data for the 1965 year class were considered to be truncated on the right, so the method given by Robson and Chapman on their pages 186-188 was used for this year class. The following estimates of the annual instantaneous total rate of attrition were obtained:

Year class	Instantaneous total rate of attrition
1962	1.81
1963	1.62
1964	3.10
1965	1.32

The estimates for the 1962, 1963, and 1965 year classes are fairly close to one another, but that for the 1964 year class is considerably higher. There was evidently some factor present which resulted in too low a catch of these fish as age-1+ fish in 1965 and/or too high a catch of them as age-2+ fish in 1966.

The total rate of attrition was also estimated from data of Bell (1970) on fish tagged in the eastern Pacific Ocean during 1962, 1963, 1965, and 1966. In this case the total rate of attrition includes tag shedding, as well as fishing and natural mortality and emigration. Again it is assumed that the fishing effort was constant from year to year.

The numbers of returns in the eastern Pacific Ocean during each year from the releases in 1962, 1963, 1964, and 1966 are shown in Table 9. The first-year returns are less than they would have been if the fish had been tagged just prior to the start of the fishing season. Accordingly, they were adjusted upward to what it is estimated they would have been if the fish had been tagged at that time. The method by which this was accomplished is best shown by an example. In 1962 a total of 960 fish were tagged during 6 days in August. These tagged fish were available for recapture only during the days after they were tagged. For example, the 75 fish tagged on August 13 were available for recapture only from August 14 through the end of the year, so their availability was 0.000 during January through July 0.581 (18/31) during August, and 1.000 during September through December. Thus these 75 fish were only as available during August as 0.581 x 75 = 43.6 fish tagged on July 31. The sum of this and the corresponding values for the other 5 days during which fish were tagged is 419.6, so the availability of the tagged fish was only 419.6/960 = 0.437 during August. This value was multiplied by the logged catch during August, 5,360 tons, to produce an adjusted value of 2,343 tons. Tags placed on fish in 1962 could have been expected to have been found on none of the fish caught during January-July, 2,343 tons of those caught during August, and all of those caught during September-December. The catches for the last two periods combined and for the year are 2,729 and 12,361 tons, respectively. The former divided by the latter gives 0.220775. This number divided into the number of 1962 returns gives an estimate of 394.1 for the number of tags which would have been returned if the fish had been tagged just prior to the start of the fishing season. The adjusted first-year returns are also shown in Table 9. The above method contains the implicit assumption that the catches of fish were equal on each day of the month or months during which fish were tagged.

The method of Paulik (1962) was used to estimate the annual instantaneous rate of total attrition, using the adjusted first-year tag returns and unadjusted second-and third-year returns. The results were as follows:

Year of release	Instantaneous rate of total attrition
1962	1.90
1963	1.63
1964	1.69
1966	3.55

The estimates for the first three years are reasonably close to one another, and to the estimates obtained by the first method for the 1962, 1963, and 1965 year classes. (The estimates derived from tagging data include two additional sources of attrition, mortality due to carrying the tags and losses due to shedding of the tags, but these were probably negligible, or nearly so, relative to fishing and natural morality and emigration.) The estimate for the last year indicates a higher rate of attrition. This might be due to chance, as the number of fish tagged in 1966 was less than the number tagged in other years, or it might be due to lesser availability or vulnerability of the tagged fish to capture in 1967. Bell (1970) stated that the tagged fish released in 1966 were 15 to 25 pounds (7 to 11 kg) in weight, which means that they were members of the 1964 and 1965 year classes. It is worthy of note that the estimates calculated previously from age composition data indicated a high rate of total attrition for the 1964 year class. Perhaps at the end of the 1966 fishing season a much higher than usual portion of the age-2+ fish emigrated out of the eastern Pacific Ocean.

Studies of attrition should be based upon catches per unit of fishing effort or tag returns per unit of fishing effort, rather than upon catches or tag returns, so further studies of this type should probably be held in abeyance until better estimates of the fishing effort directed toward northern bluefin are available.

A MODEL FOR NORTHERN BLUEFIN MIGRATION IN THE PACIFIC OCEAN

It is useful to formulate models to describe the migration of highly migratory fishes even when relatively little is known of their biology, as such models make it possible to plan future research more effectively. Accordingly, a preliminary model for northern bluefin has been formulated. This model is based to a considerable extent upon the ideas of Flittner (1966), Nakamura (1969), and Bell (1970). However, any errors which appear in this section are the responsibility of the persons who prepared this report. It is anticipated that, as additional data accumulate, or as different interpretations are made of the data presently available, the model will be amplified, modified, or discarded in favor of one that appears to provide a better explanation of what has been observed.

Figure 10 is a diagram of the model. The migrations shown by dashed lines are more speculative than those shown by solid lines. The diagram is intended to show the general areas where the migrations are believed to begin and end, but not the precise routes, as space limitations would make this impractical even if the routes were known. For example, it appears that the route of migration of the juveniles bound for the eastern Pacific is south of the route of migration of the maturing fish bound in the opposite direction, but such is not necessarily the case.

The spawning of northern bluefin occurs between Japan and the Philippine Islands and southeast of Japan during April through July (Yabe, Ueyanagi, and Watanabe, 1966; Nishikama, Kikawa, Honma, and Ueyanagi, 1978). The larvae, postlarvae, and juveniles are carried northward by the Kuroshio Current toward Japan. Fish of age 0+ about 20 to 60 cm in length are caught in the vicinity of Japan during the summer and fall of the same year (Yabe, Ueyanagi, and Watanabe, 1966; Yukinawa and Yabuta, 1967). Some of these remain in the western Pacific Ocean during the winter and others migrate to eastern Pacific (Clemens and Flittner, 1969). It is possible that others migrate from the western to the eastern Pacific during their second, third or even later winters, but there is no evidence of this from tagging. For the 1964 year class there was a shortage of age-1+ fish in the eastern Pacific in 1965, but not a shortage of age-2+ fish in 1966 (Table 8). This may be due to the fish of that year class migrating from Japan mostly during their second winter (1965-1966), instead of during their first winter (1965-1965). The fish which migrate from the western to the eastern Pacific form the basis for the fishery in the eastern Pacific, which takes place principally during May through October. It is believed that during the rest of the year the fish remain in the eastern Pacific Ocean, but become less vulnerable and/or available to the fishery at this time. A portion of them apparently spend the winter in the vicinity of Guadalupe Island, as northern bluefin, especially large ones, are caught there during all months of the year. Some of the fish re-enter the eastern Pacific fishery in the following spring, while others return to the western Pacific eventually to spawn. Those which re-enter the eastern Pacific fishery are destined eventually to return to the western Pacific, however. The return journey to the western Pacific may take nearly 2 years, as 674 days is the minimum time recorded between release and recapture of a tagged fish making this migration (Table 7). This fish was 1+ years old when released and 3+ years old when recaptured. Other tagged fish released at age 1+ in the eastern Pacific were recaptured at age 3+ in the same area 2 years later (Table 9), and fish even older than 3+ years occur in that area (Table 8), so it is obvious that the length of the sojourn of the fish in the eastern Pacific is not uniform.

In Figure 10 it appears that the fish in the eastern Pacific occur further and further offshore and have an increasingly restricted north-south distribution as they grow older. It was necessary for the sake of clarity to make the diagram this way, but actually such is not necessarily the case.

The fish caught by longline vessels between North America and Japan (Figure 2) are probably en route from the eastern to the western Pacific. Upon arriving in the western Pacific they presumably proceed to the area between Japan and the Philippine Islands and southeast of Japan to spawn, either immediately or eventually.

Northern bluefin are also caught by longline vessels east of the Philippine Islands, northeast of Papua New Guinea, and southeast of Australia, especially in the vicinity of New Zealand (Figure 2). The question arises as to whether these fish come from larvae, postlarvae, and juveniles which went south from the spawning area, from young fish which migrated south from Japan after a brief sojourn there, or from older fish which migrated south from the spawning area after spawning. If either the first or second possibility is the case there should be small northern bluefin south of 20° north latitude. The distribution of baitboat-caught northern bluefin south of 20° north latitude during 1972-1976 (Anonymous, 1977b-f) is shown in Figure 11, so it appears that at least some of the northern bluefin caught south of the spawning grounds by longline vessels are the result of movement of larvae, postlarvae, and juveniles from the spawning area or the result of migration of young fish south from Japan. However, this does not mean that none of them are the result of migration of adult fish south from the spawning area after spawning.

Larvae or postlarvae of northern bluefin have not been found in the Australia-New Zealand area, so it is not likely that the fish which are caught there by longlines would have spawned there. Rather, they would have to migrate back to the spawning area or not spawn at all.

After spawning the fish probably disperse from the spawning area to other areas of the western Pacific. Some may even migrate to the eastern Pacific, though this seems unlikely. The following year they presumably return to the spawning area to spawn again.

There might be several subpopulations of northern bluefin in the Pacific Ocean, for example, one which originates in the spawning area, migrates to Japan, and then returns to the spawning area to spawn, one which originates in the spawning area, migrates to Japan, then migrates to North America, and finally returns to the spawning area to spawn, and one which originates in the spawning area, migrates to the area south of

20° north latitude, either directly or by way of Japan, and then returns to the spawning area to spawn. On the other hand, there may be only one subpopulation in the Pacific Ocean, in which case the portions of this which migrate to the eastern Pacific Ocean and the area south of 20°north latitude are presumably determined by oceanographic conditions. It would be useful for stock assessment studies to know which is the case. Genetic studies might be valuable in this regard.

NEEDS FOR FURTHER RESEARCH

It is of fundamental importance for the assessment of any fishery to have adequate statistics of catch and fishing effort. The catch statistics for the surface fishery for northern bluefin in the eastern Pacific Ocean are adequate, but those for the surface fishery in the western Pacific are not, as several species are combined in the statistics for that area. The solution for this is to sample the mixed-species catches to determine the proportions of northern bluefin in those catches and to use the sampling data to estimate the catch of northern bluefin alone. The total longline catches of northern bluefin are estimated from logbook data for a portion of the trips. The portion of the trips for which logbook data are available is reasonably high for the Japanese vessels, but not so for those of the Republic of China or the Republic of Korea. Accordingly, the portions for the latter two nations should be increased.

Adequate fishing effort data are available for the surface fishery of the eastern Pacific Ocean, and for the Japanese longline fishery. Such data are not available for the Chinese and Korean longline fisheries, however, and probably not for the surface fishery of the western Pacific Ocean either.

Even when adequate effort data are available there is still the question of how to interpret them. For example, vessels may be in an area-time stratum in which northern bluefin and other species occur, but some may be directing their effort toward northern bluefin and some toward other species. The problem, then, is to find objective criteria with which to determine which vessels should be assumed to have been fishing for northern bluefin and which should not.

It has been shown that the ages of northern bluefin can be estimated from their scales, and age and catch statistics data have been used to estimate the catches of fish of each age group made by vessels which unloaded in California during 1963 through 1969. This should be done each year for the surface fisheries of both the eastern and western Pacific, and for the former area data for vessels which unload in locations other than California should be included. All the fish from which scales are taken should be measured, of course. Also, since it is easier to measure fish than it is to collect and process scales, additional fish from which scales are not collected should be measured. The age composition and length-frequency data should be studied to attempt to learn more about the life history of the fish and to determine if it is possible to predict the catch in a given year from the age composition of the fish caught in the previous year.

Studies of the sexual development and maturity of the surface- and longline-caught fish should be made, as the results would probably contribute to a greater understanding of the life history of the fish. For example, the fish caught by longliners in the band between 30°N-130°W and Japan might be a mixture of immature and maturing fish, and the maturing ones might gradually disappear each year, first from the eastern area, then from the central area, and finally from the western area. If so, this would probably indicate that the maturing fish were migrating toward the spawning area, and would show at what rate this migration was made. The same applies to the fish which presumably migrate from New Zealand to the spawning area to spawn. If by some chance there is a spawning area for northern bluefin in the southern hemisphere which has not been found the analysis of maturity data might lead to its discovery. The gonads of surface-caught fish from both the eastern and western Pacific should be examined to determine if any are maturing. If so, maturity samples taken on a regular basis might make it possible to predict the proportion of the fish currently vulnerable to the surface fishery which would become invulnerable to it in the near future.

Surface-caught fish should be tagged in both the eastern and western Pacific, particularly the latter. The results would provide additional information on transoceanic migration and total rates of attrition. Fish of ages 1+ and 2+, as well as age 0+, should be tagged in the western Pacific, so it can be determined if any of these migrate to the eastern Pacific. At first some fish could be single tagged and some double tagged to determine which method results in greater return rates. If the early results indicate that the return rates are equal, or higher for the double-tagged fish, all subsequent fish should be double tagged, as this would increase the rate of return for the fish at liberty for long periods of time. Also, these data are necessary for estimation of the rate of shedding of the tags, and such estimates are in turn necessary if the rate of attrition of the fish is to be estimated. The tagged fish should be measured to the nearest centimeter, and with as much care as feasible.

Genetic studies might reveal whether there is one subpopulation or more than one subpopulation of northern bluefin in the Pacific Ocean. Samples from fish older than 0+ caught in the surface fishery off Japan, fish of all ages caught off North America, and large fish caught in the vicinity of New Zealand might reveal the existence of three subpopulations. Furthermore, samples of age-0+ fish caught off Japan might reveal a mixture of fish of the three populations. Such findings would contribute considerably to the resolution of the tentative model which has been formulated for the migration of northern bluefin. If no genetic differences were found, however, it would not necessarily indicate that there was only one subpopulation, as the negative results could be caused by the lack of suitable techniques to resolve the differences.

Oceanographic studies could provide some beneficial results. For example, it would be of interest to understand better why spawning apparently occurs only in the area between Japan and the Philippine Islands and southeast of Japan. Most of the larvae and postlarvae are probably carried northward by the Kuroshio Current, but it would be useful to know more about how this works, and if the fish caught south of 20° north latitude come from larvae which for some reason were not carried northward by that current. Also, further study of oceanography might provide an understanding of the mechanism which induces some of the age-0+ fish (and possibly the older ones as well) off Japan to migrate to North America and others to remain in the western Pacific, provided this is not genetically determined. Finally, it would be of interest to know why the longline catches are greater in the area between 30° and 35° north latitude and 170° and 175° east longitude than in any other offshore area.

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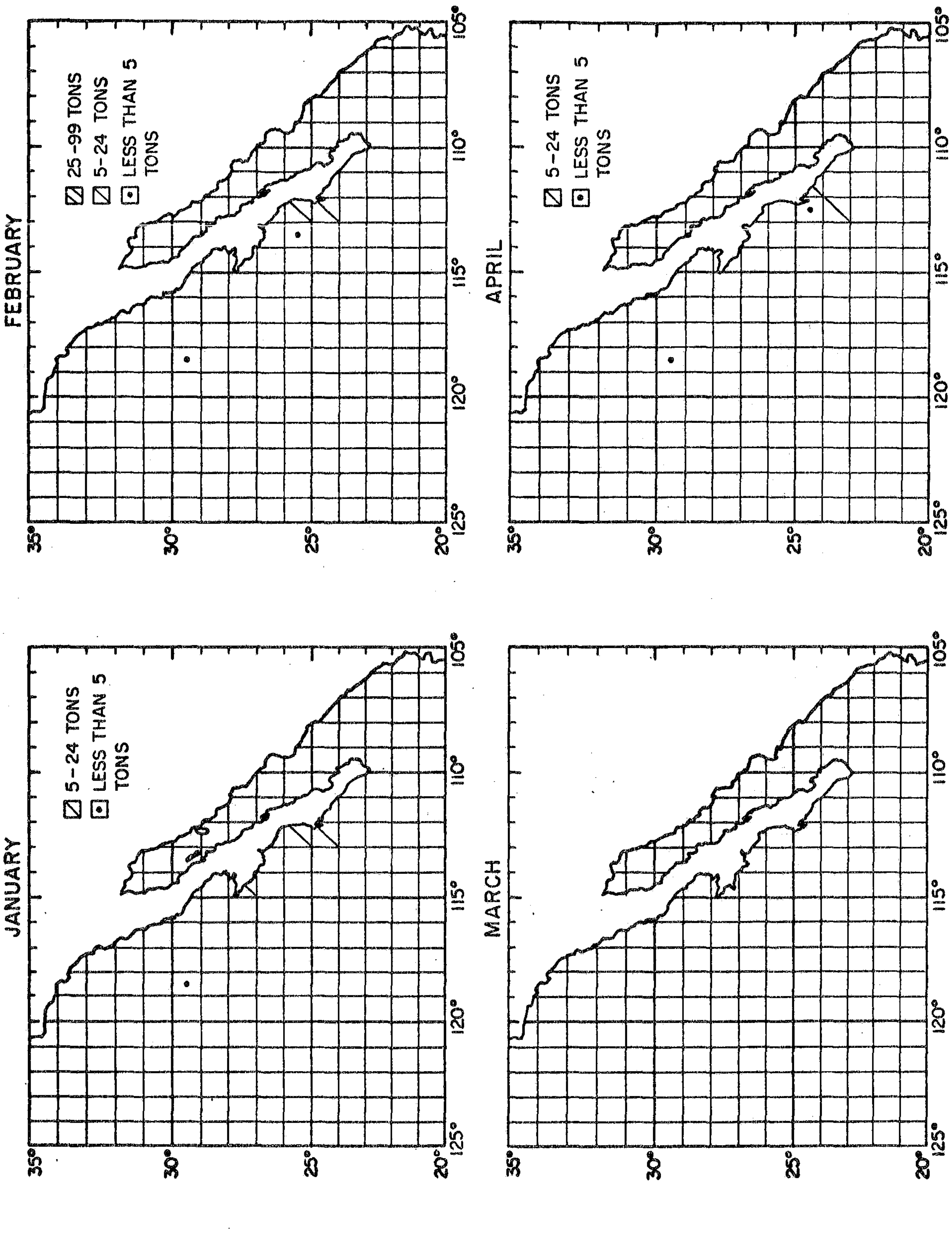
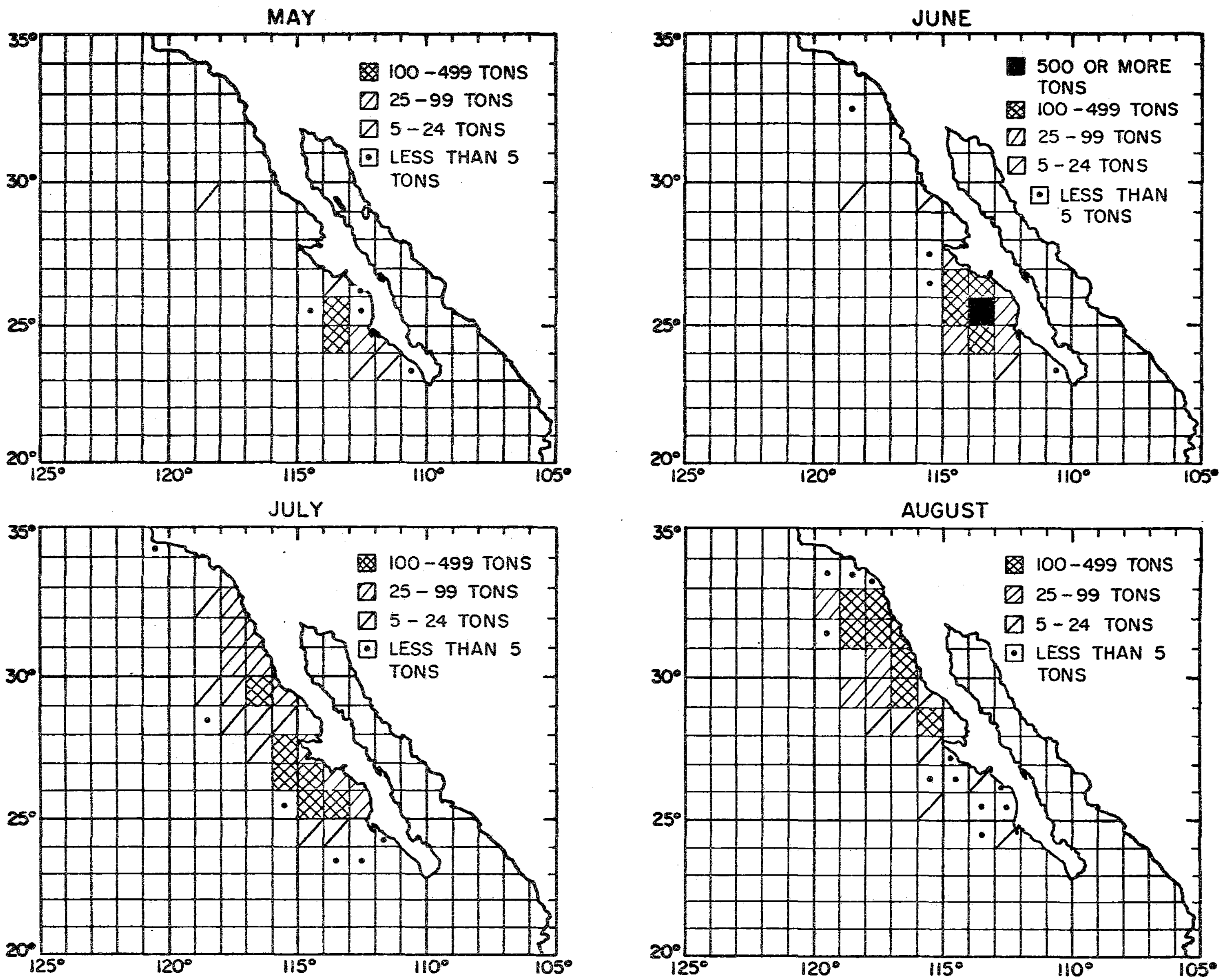


FIGURE 1. Monthly distributions of northern bluefin caught by surface gear in the eastern Pacific Ocean during 1969-1978.



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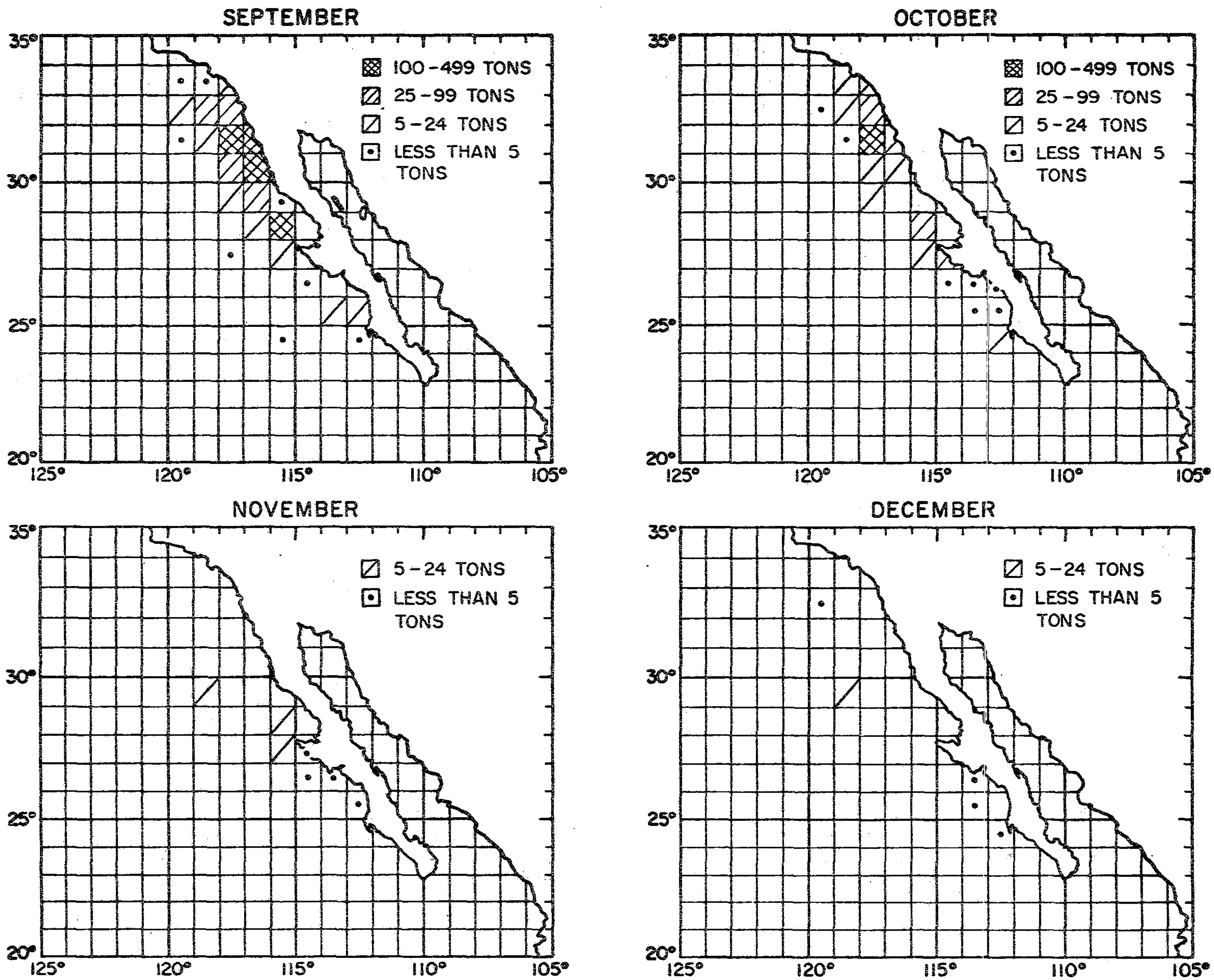

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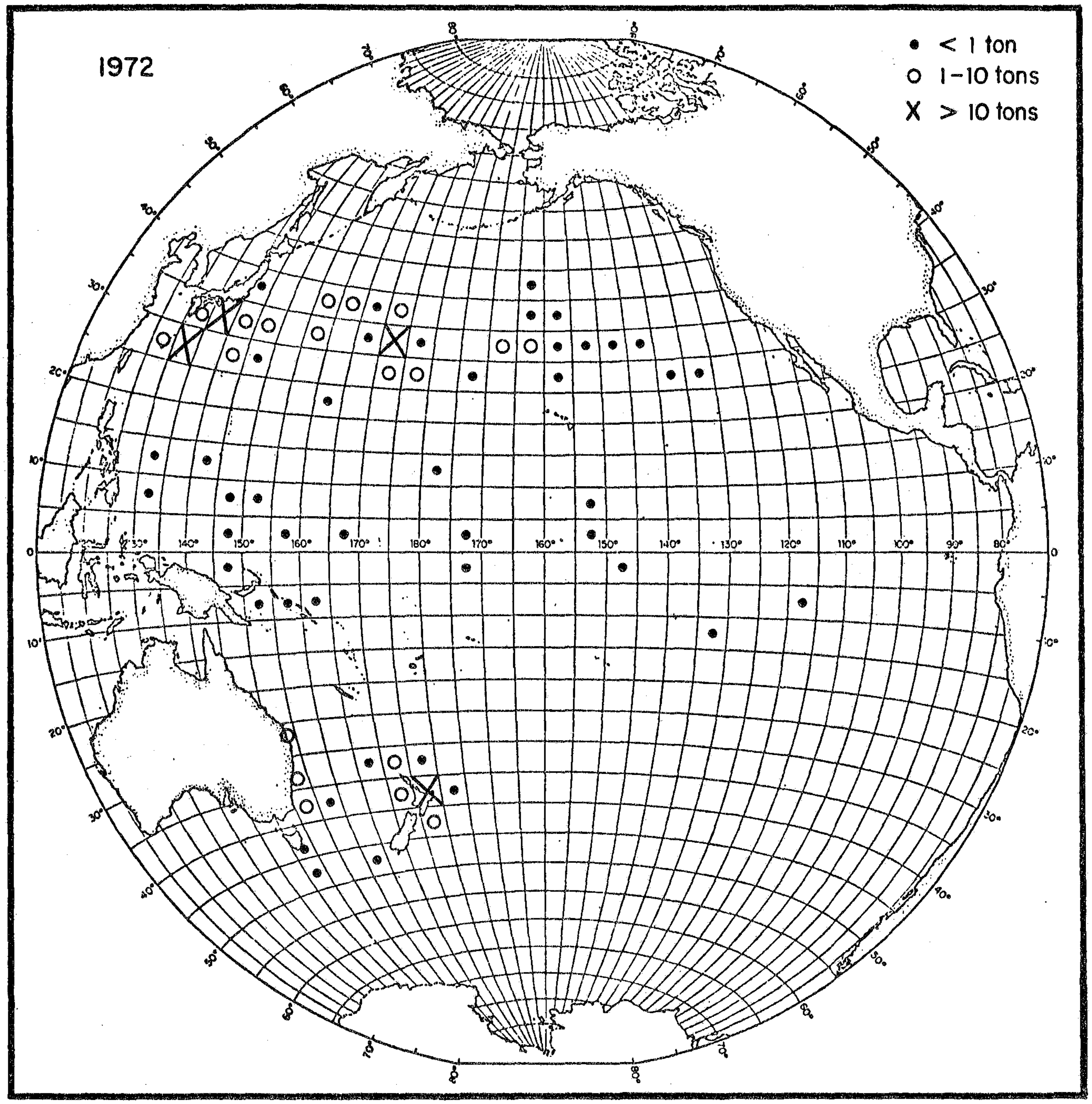
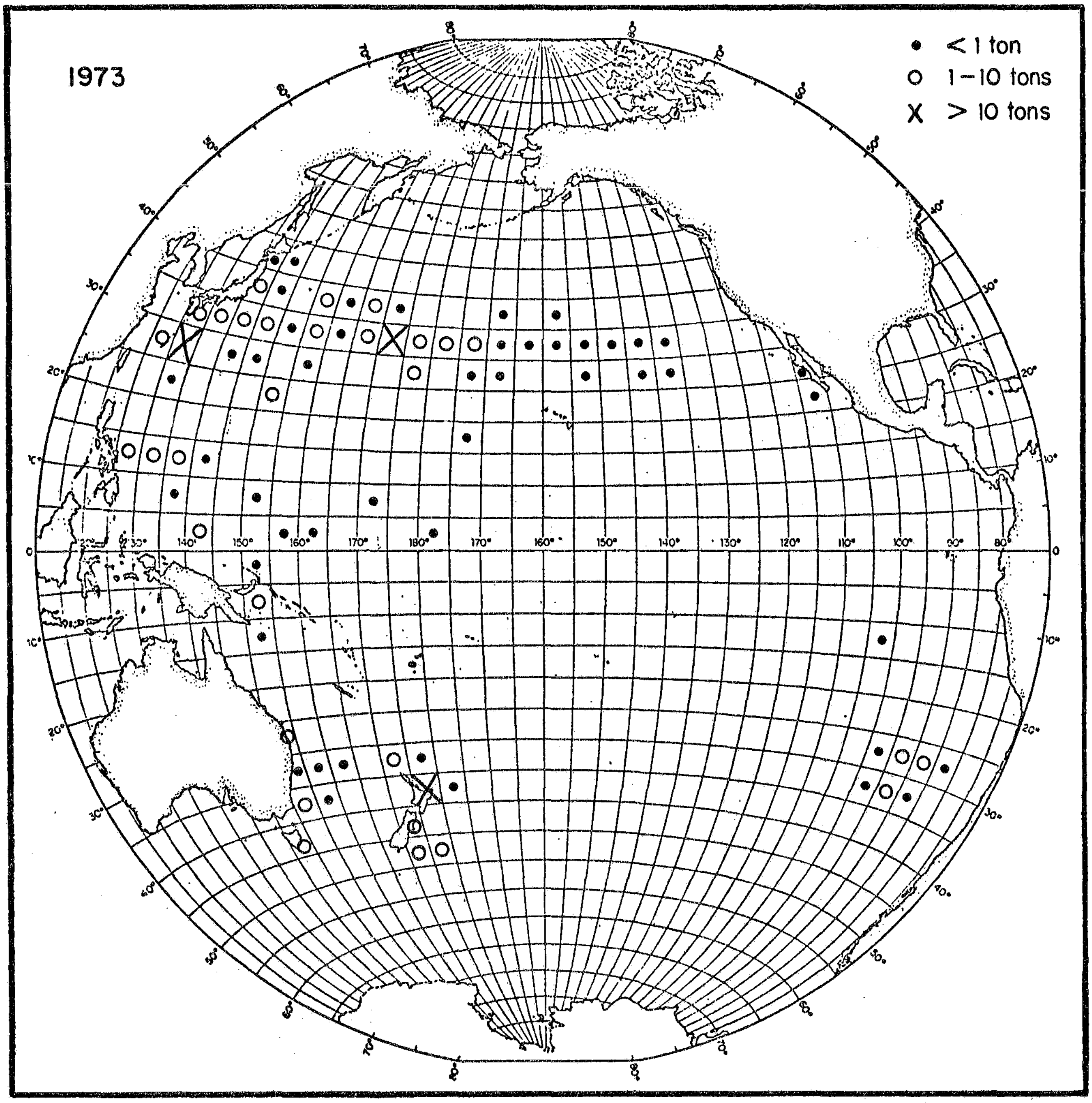


FIGURE 2. Distribution of northern bluefin caught by Japanese longliners during 1972-1976.



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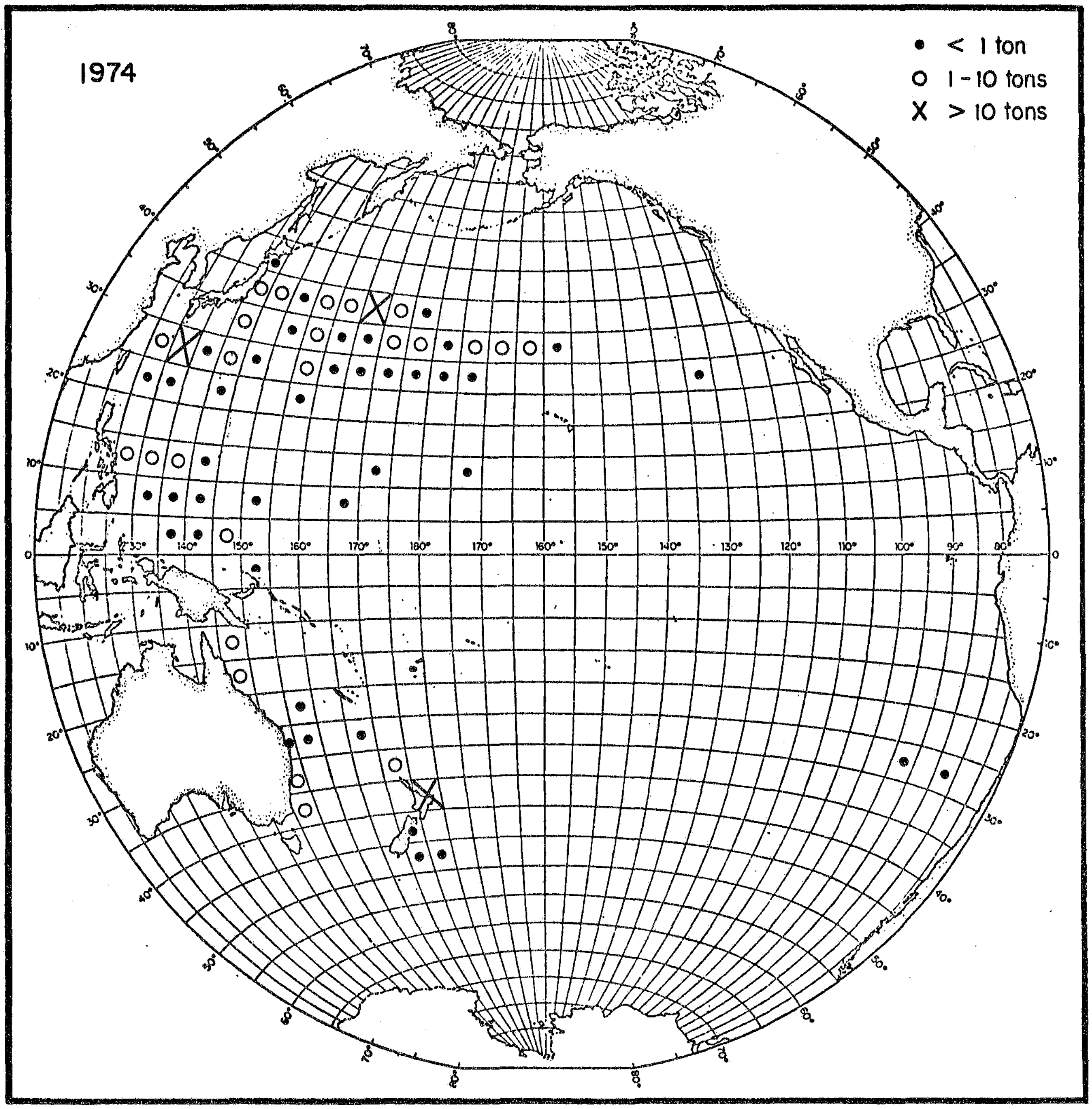

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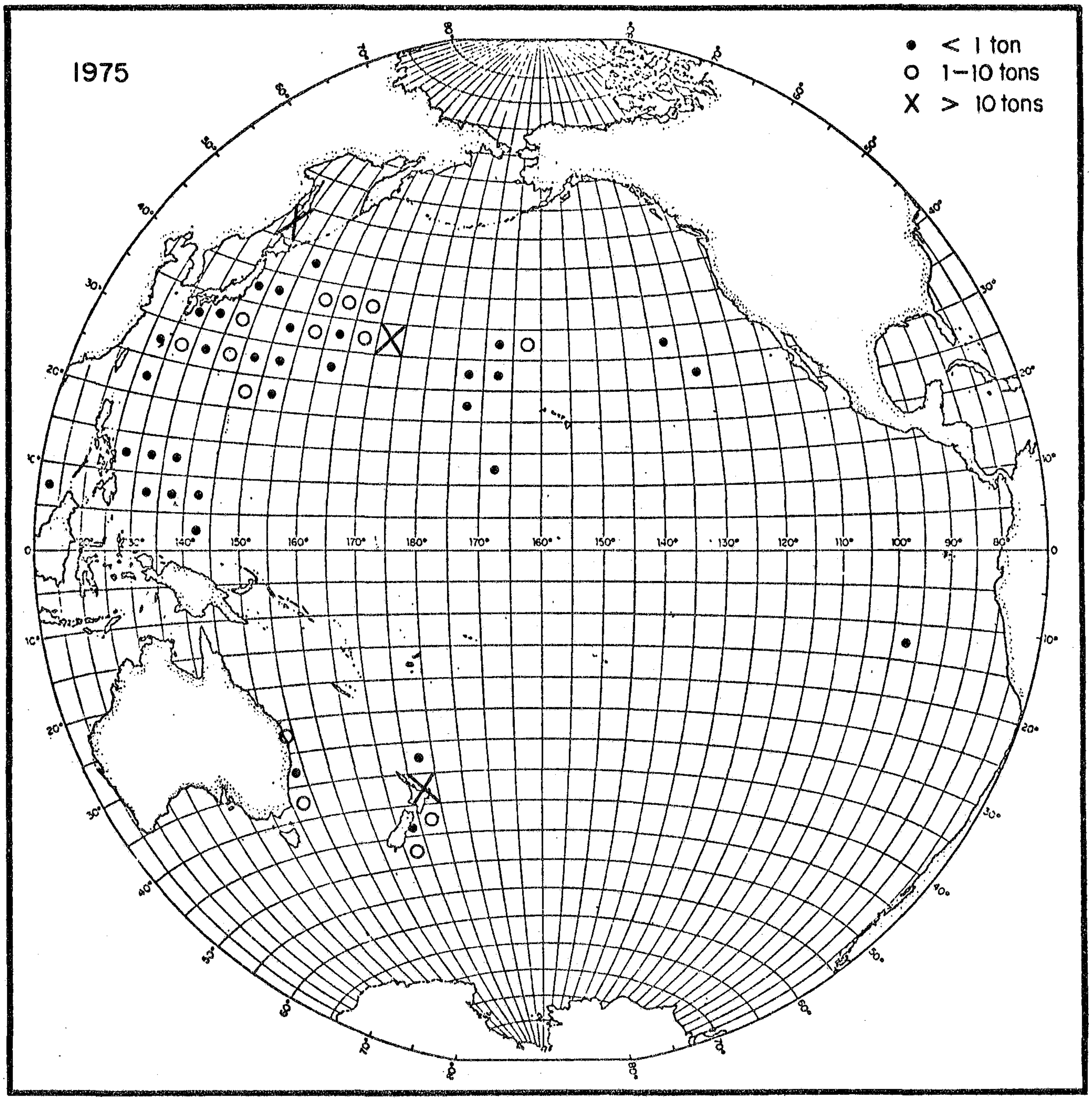

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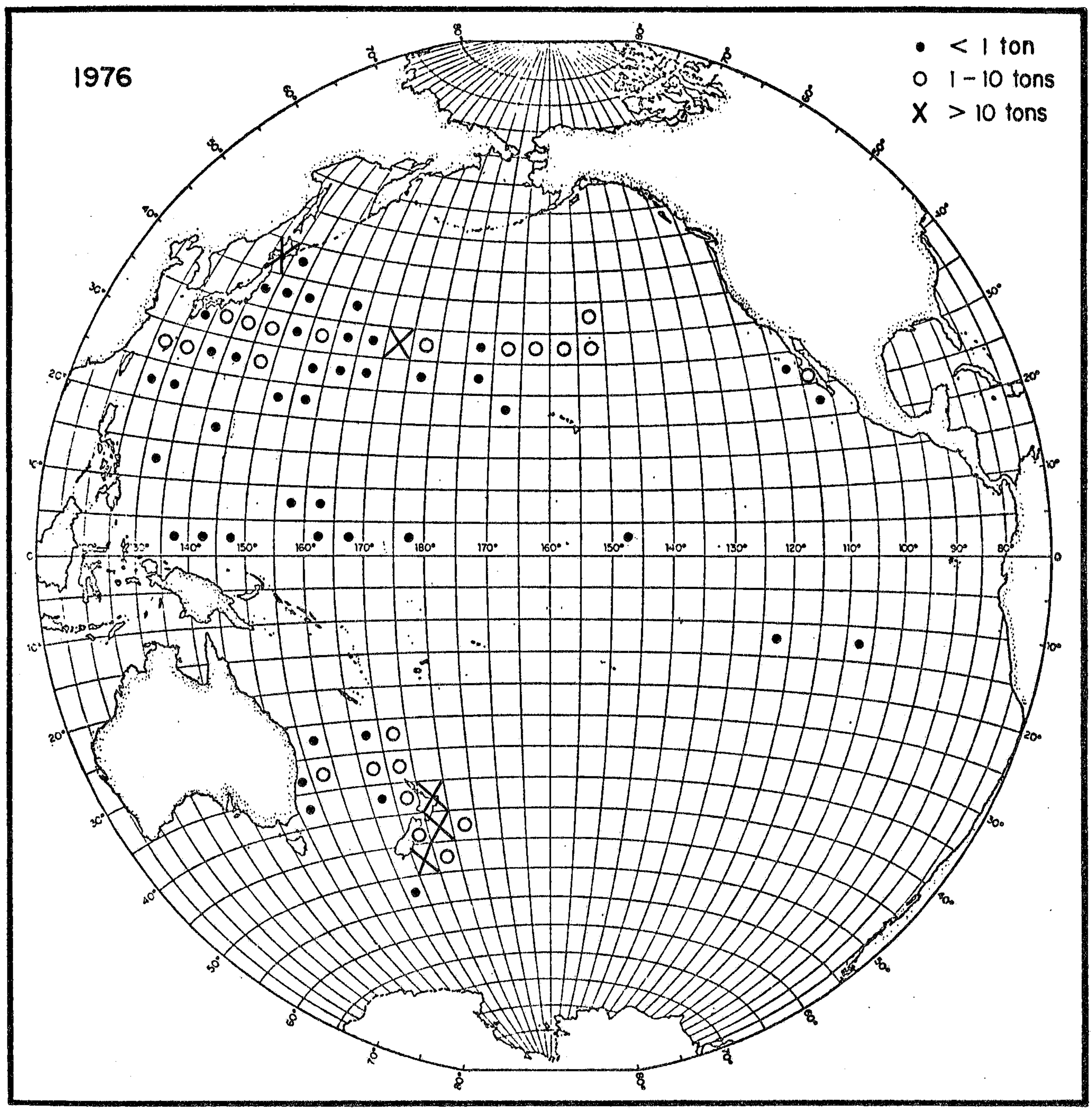

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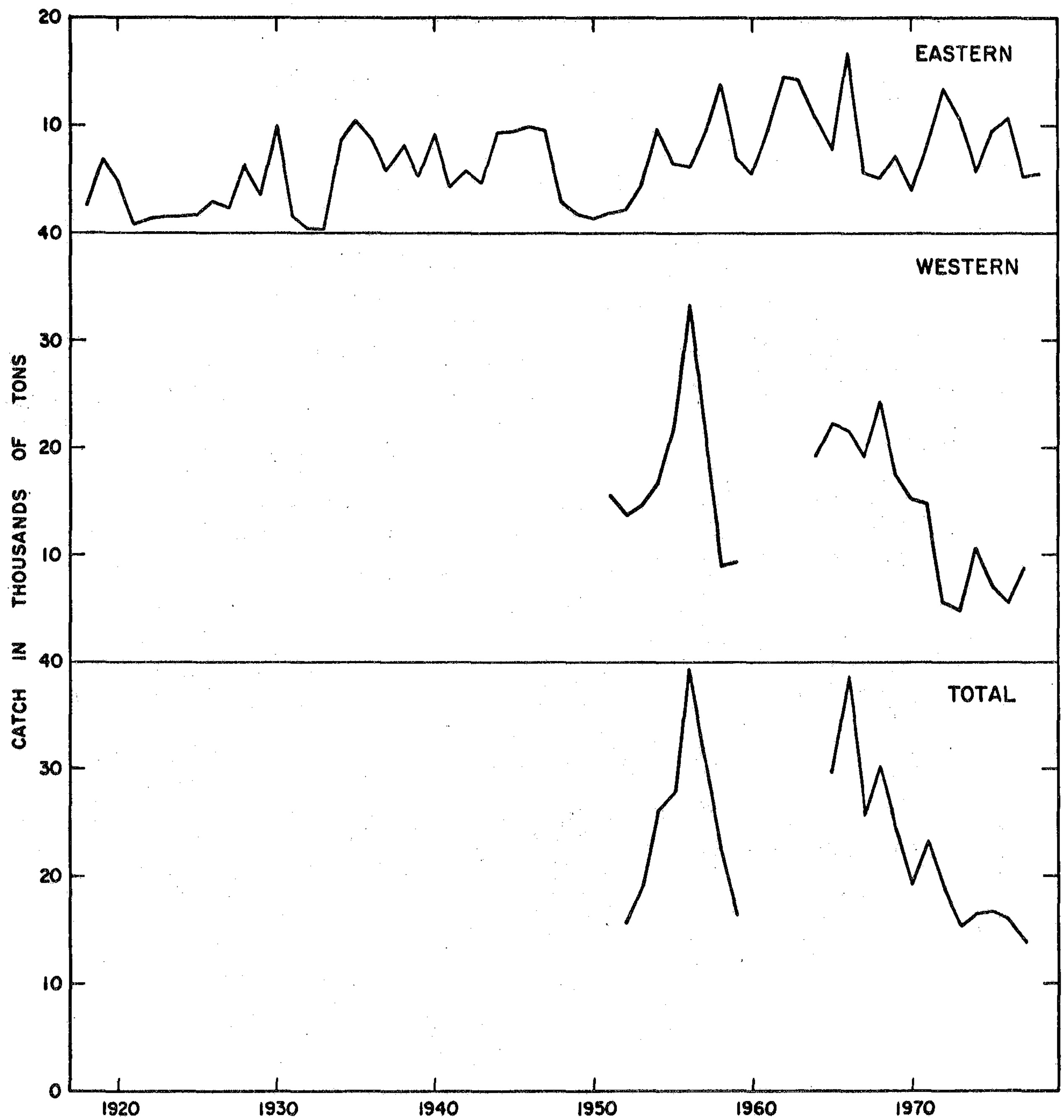


FIGURE 3. Catches of northern bluefin in the Pacific Ocean in metric tons.

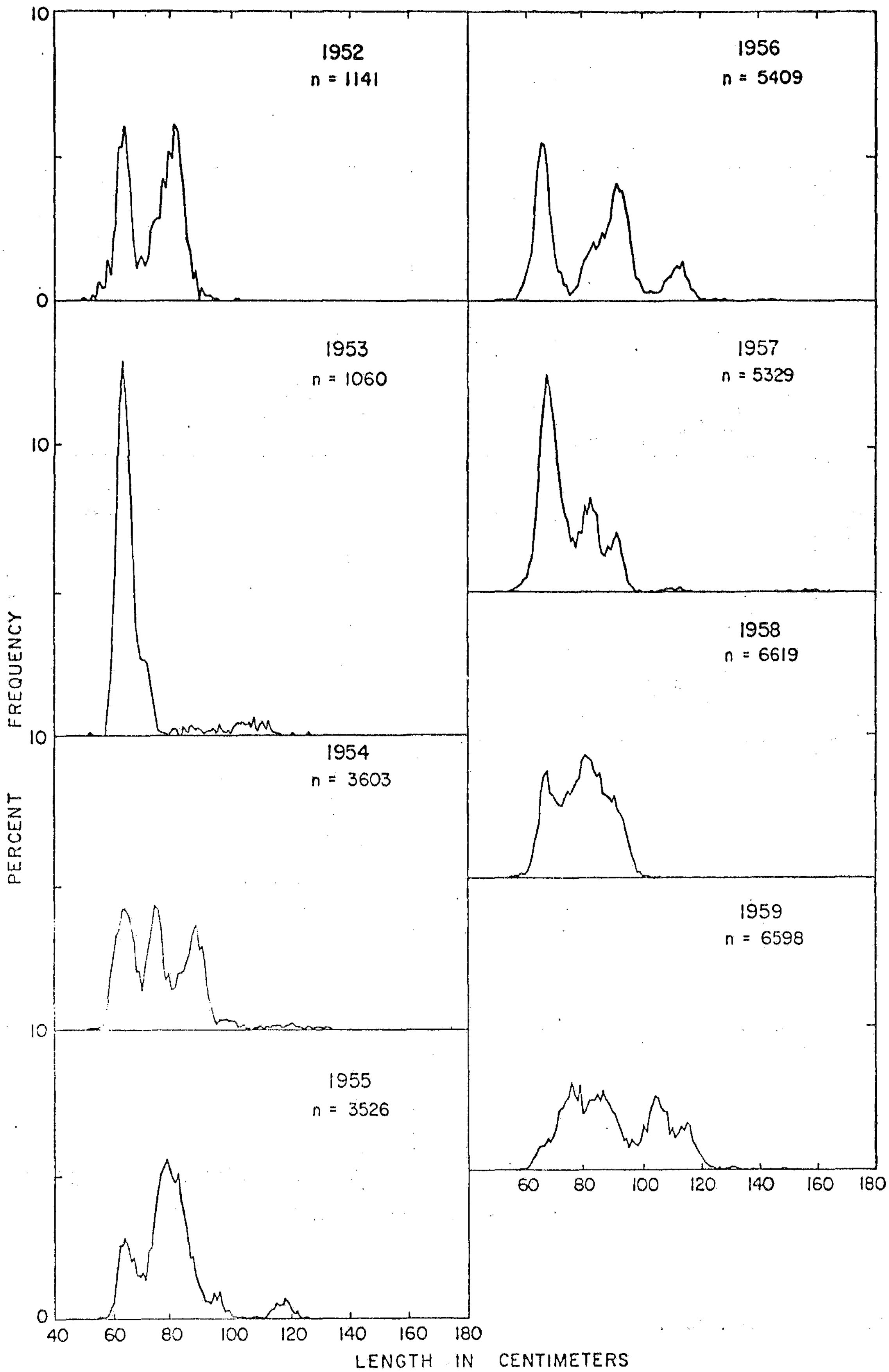


FIGURE 4. Annual length-frequency distributions for surface-caught northern bluefin of the eastern Pacific Ocean during 1952-1965.

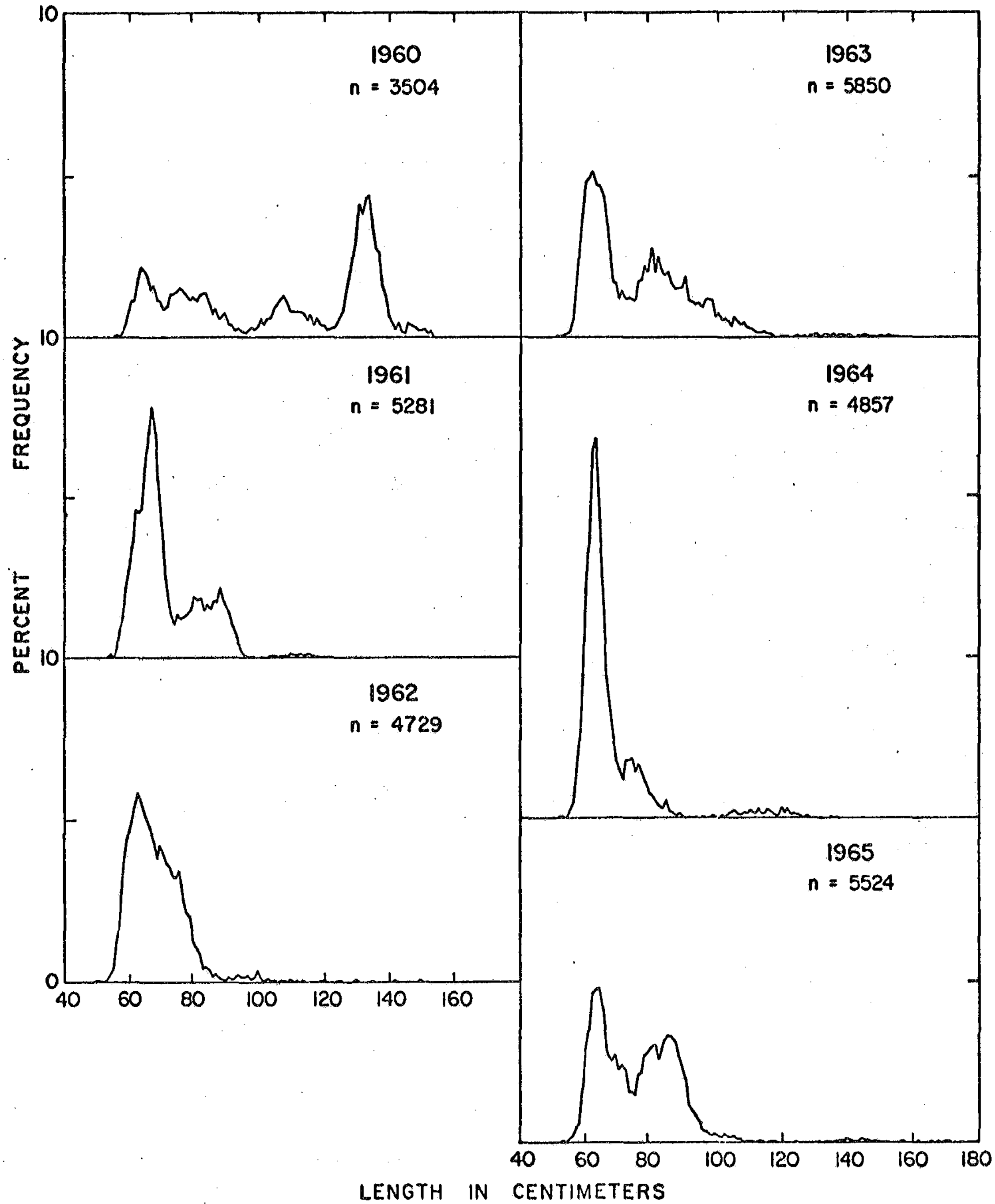


FIGURE 4 (continued).

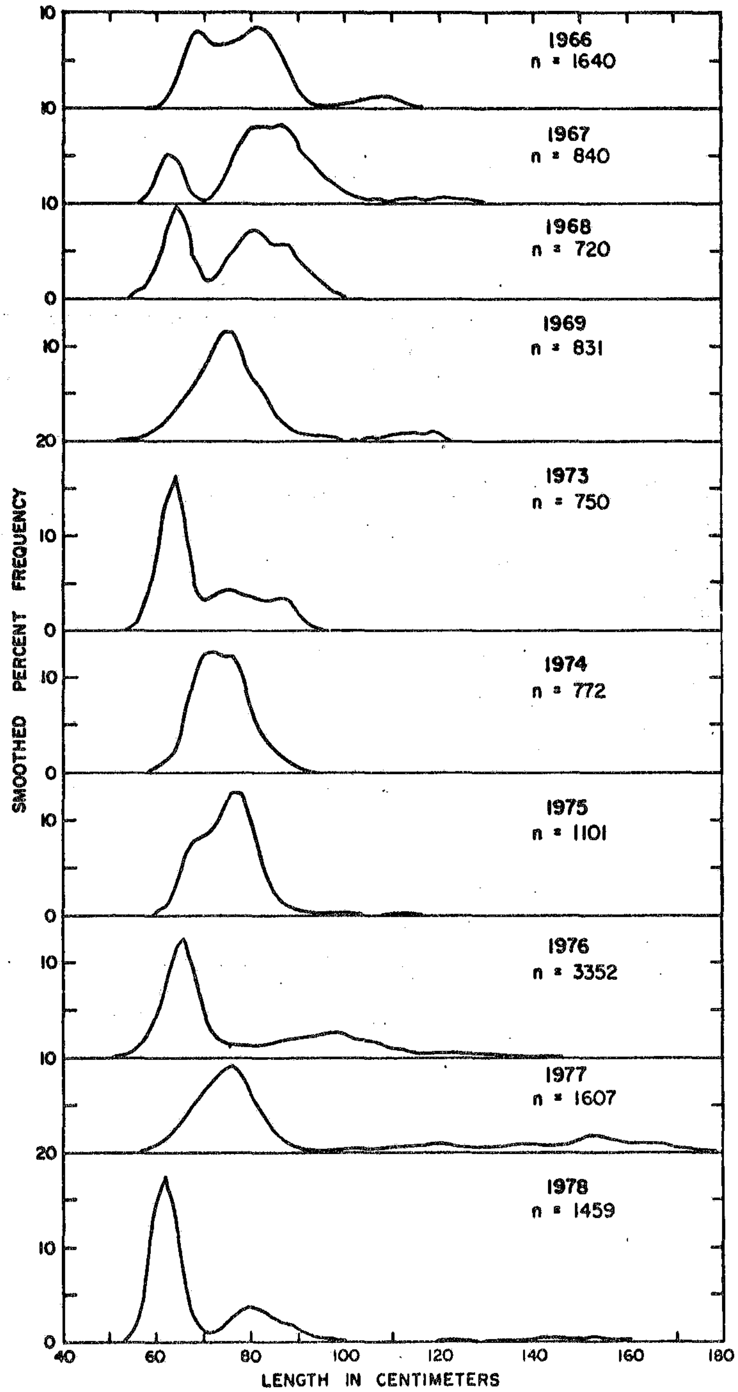


FIGURE 5. Annual length-frequency distributions for surface-caught northern bluefin of the eastern Pacific Ocean during 1966-1969 and 1973-1978.

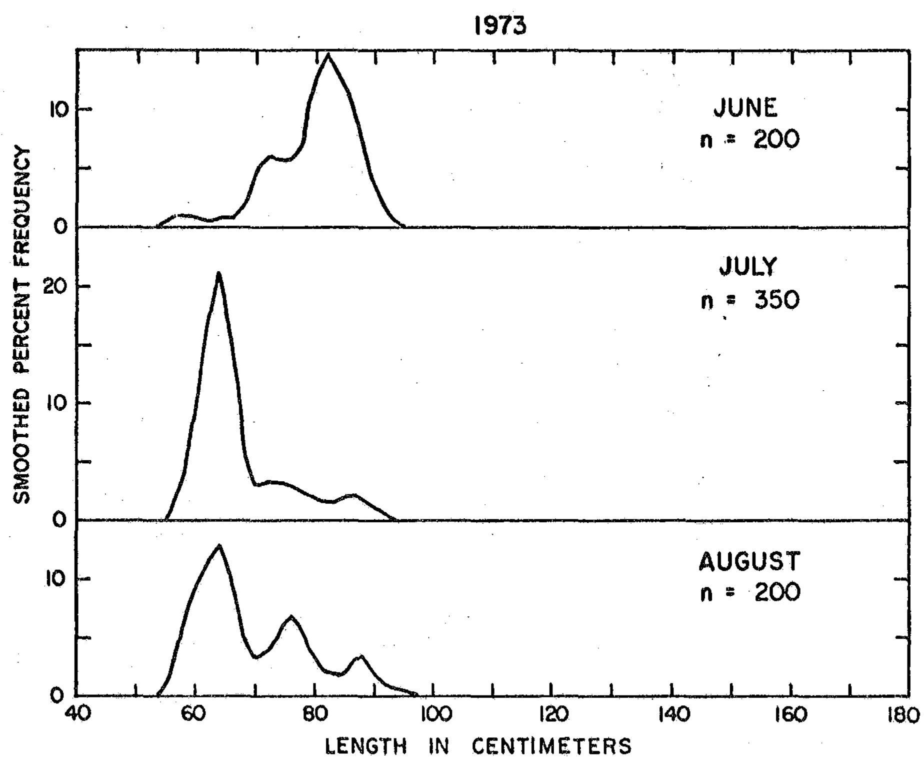


FIGURE 6. Monthly length-frequency distributions for surface-caught northern bluefin of the eastern Pacific Ocean during 1973-1978.

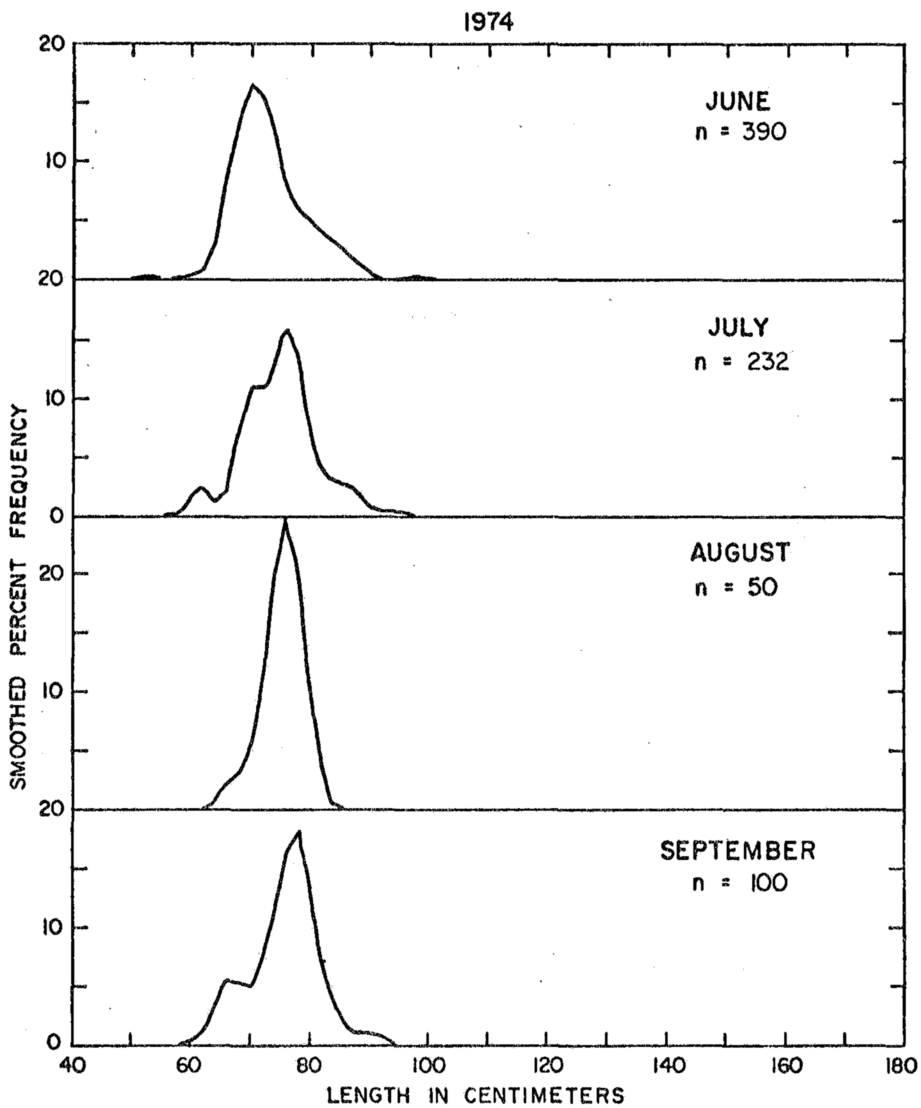
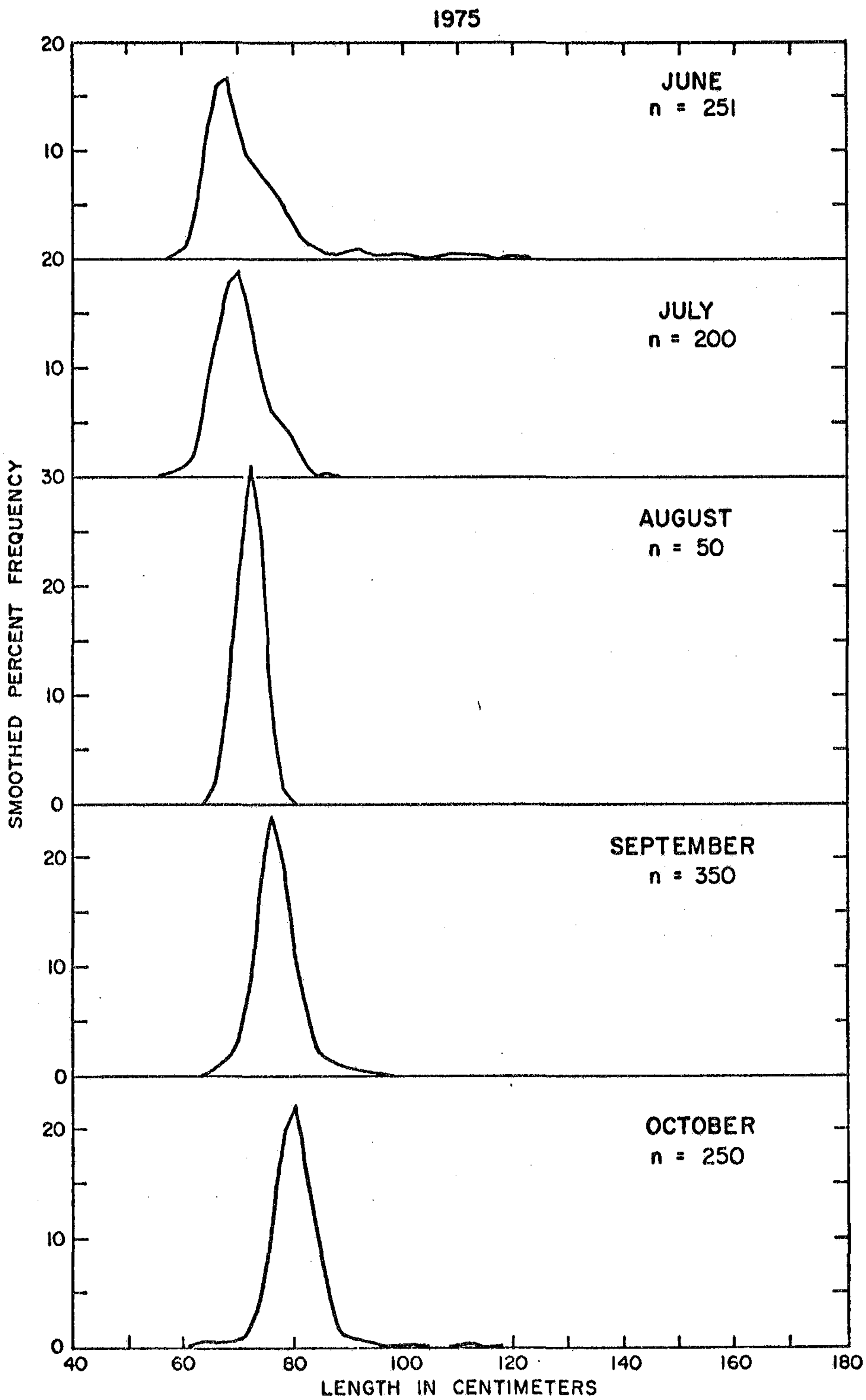


FIGURE 6 (continued).



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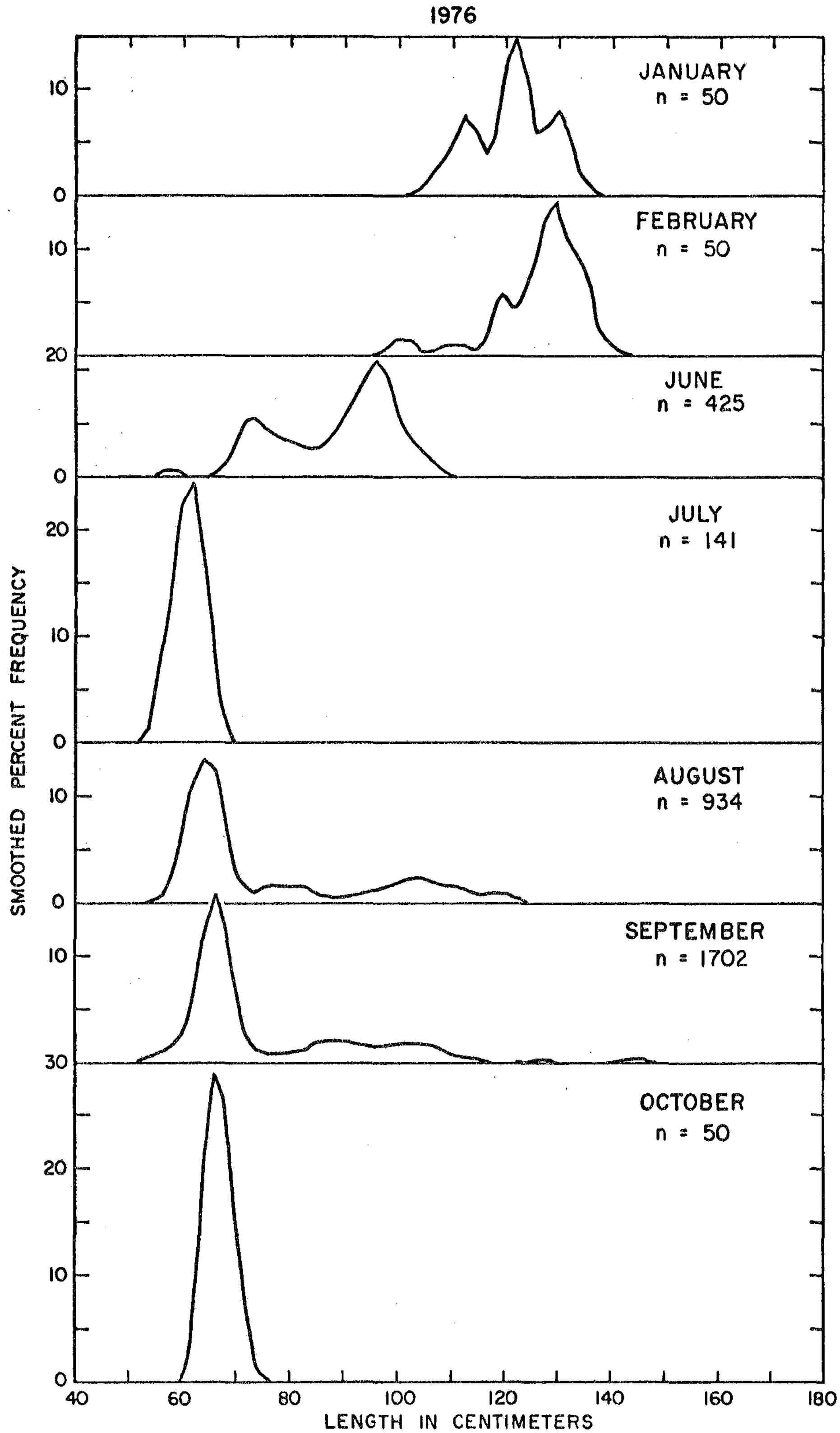

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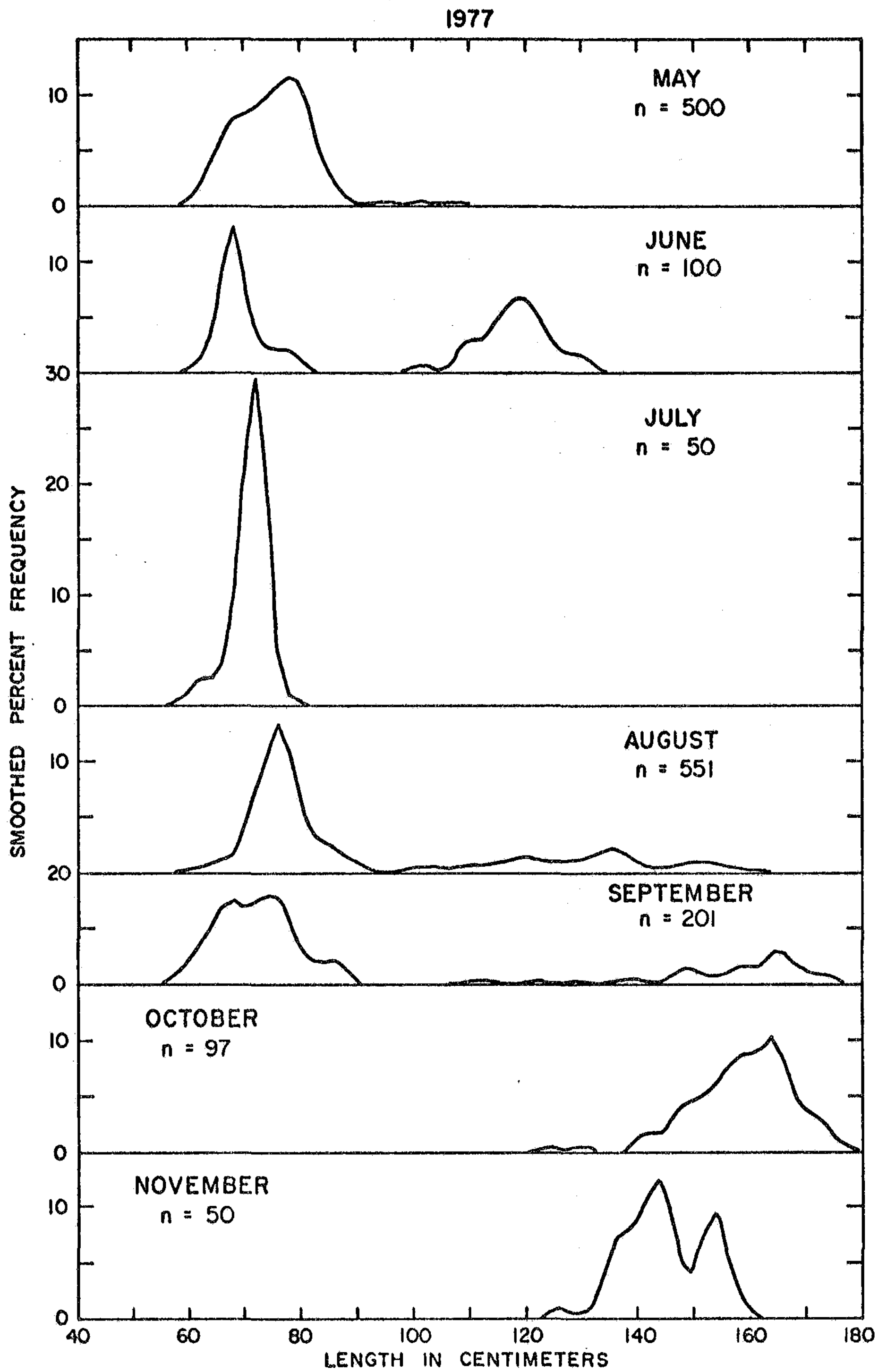

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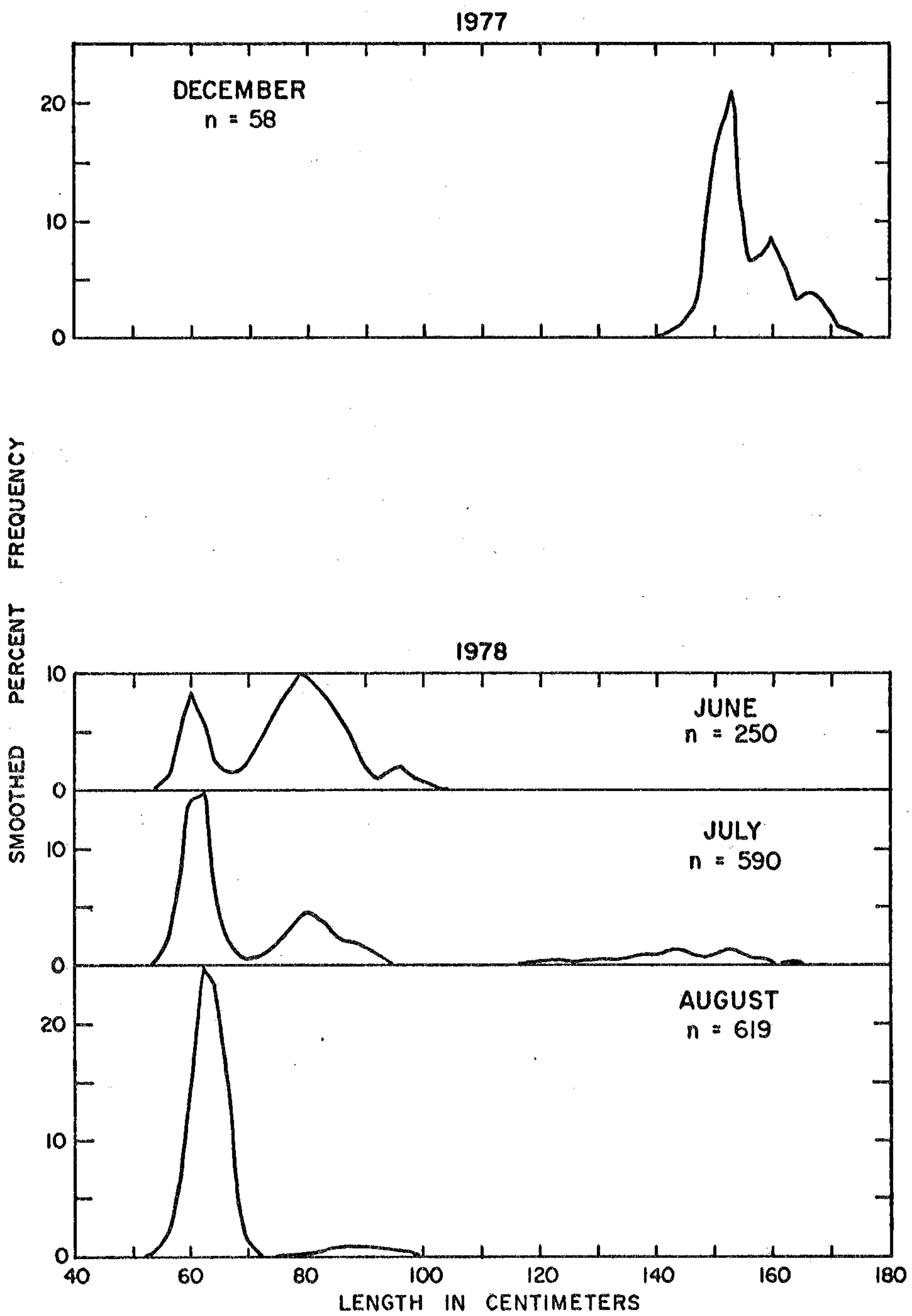

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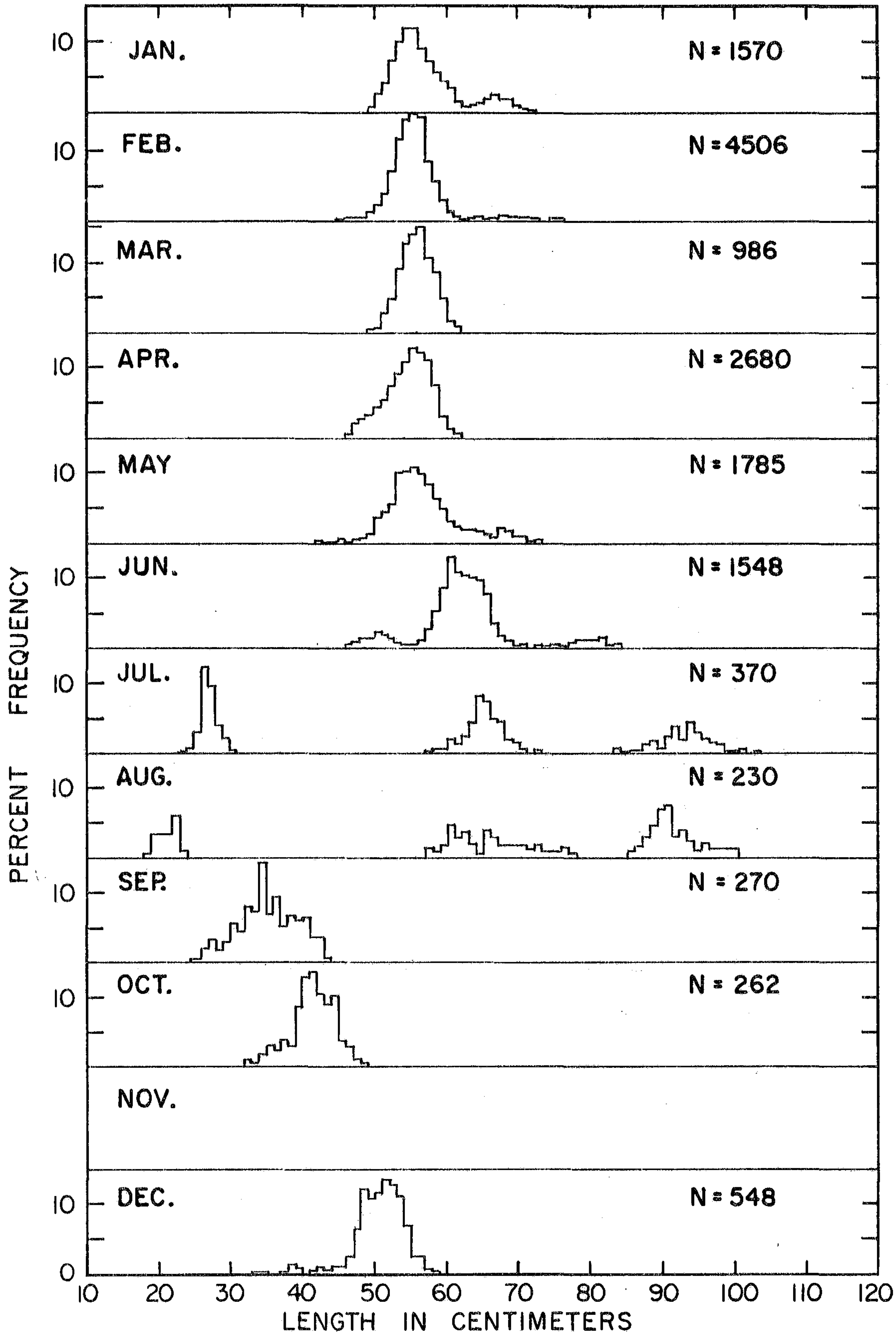

FIGURE 7. Average monthly length-frequency distributions for northern bluefin caught by surface gear north of Satunan during 1953-1963 (modified from Yukinawa and Yabuta, 1967).

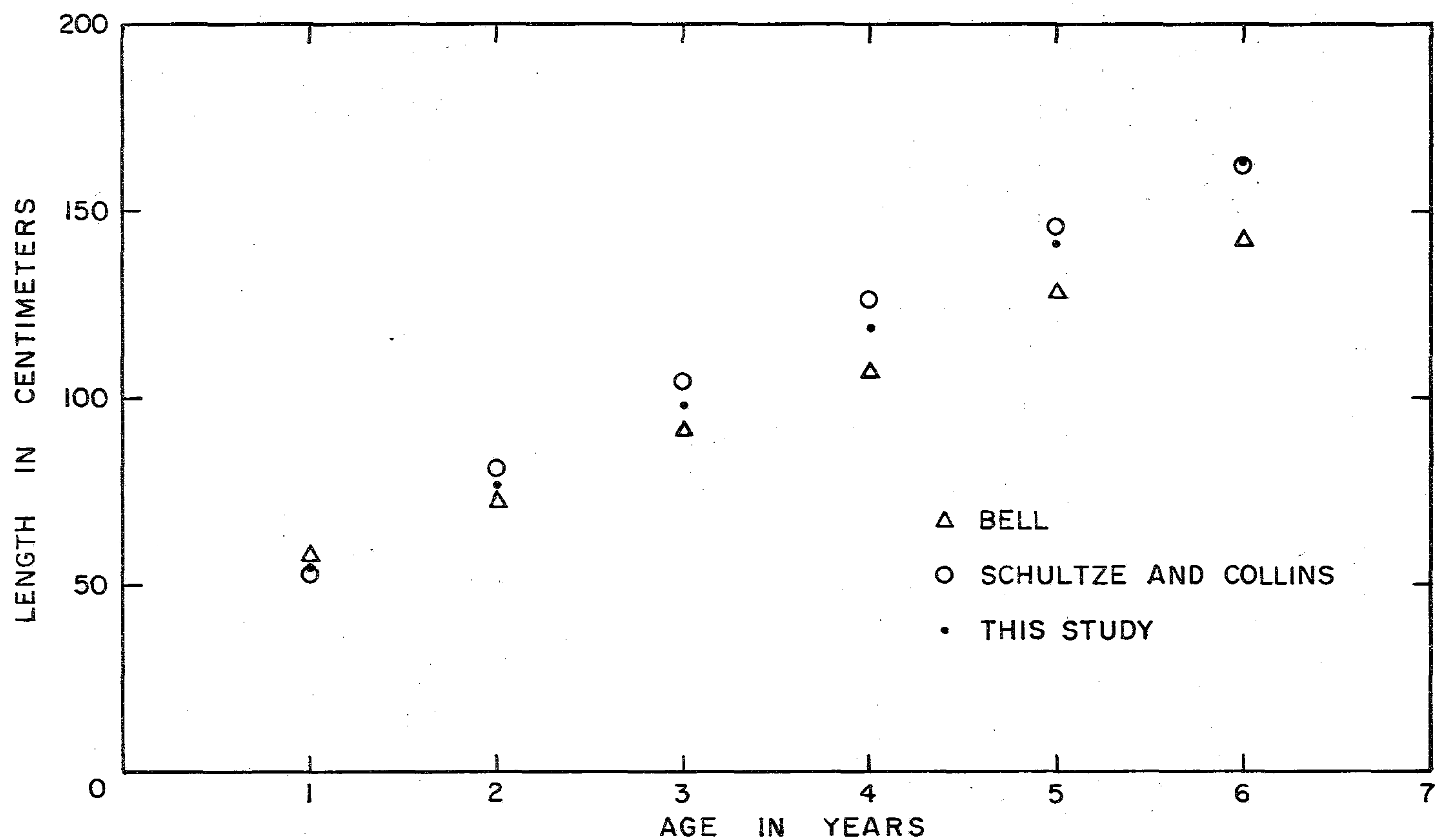

FIGURE 8. Growth of northern bluefin in the eastern Pacific Ocean.

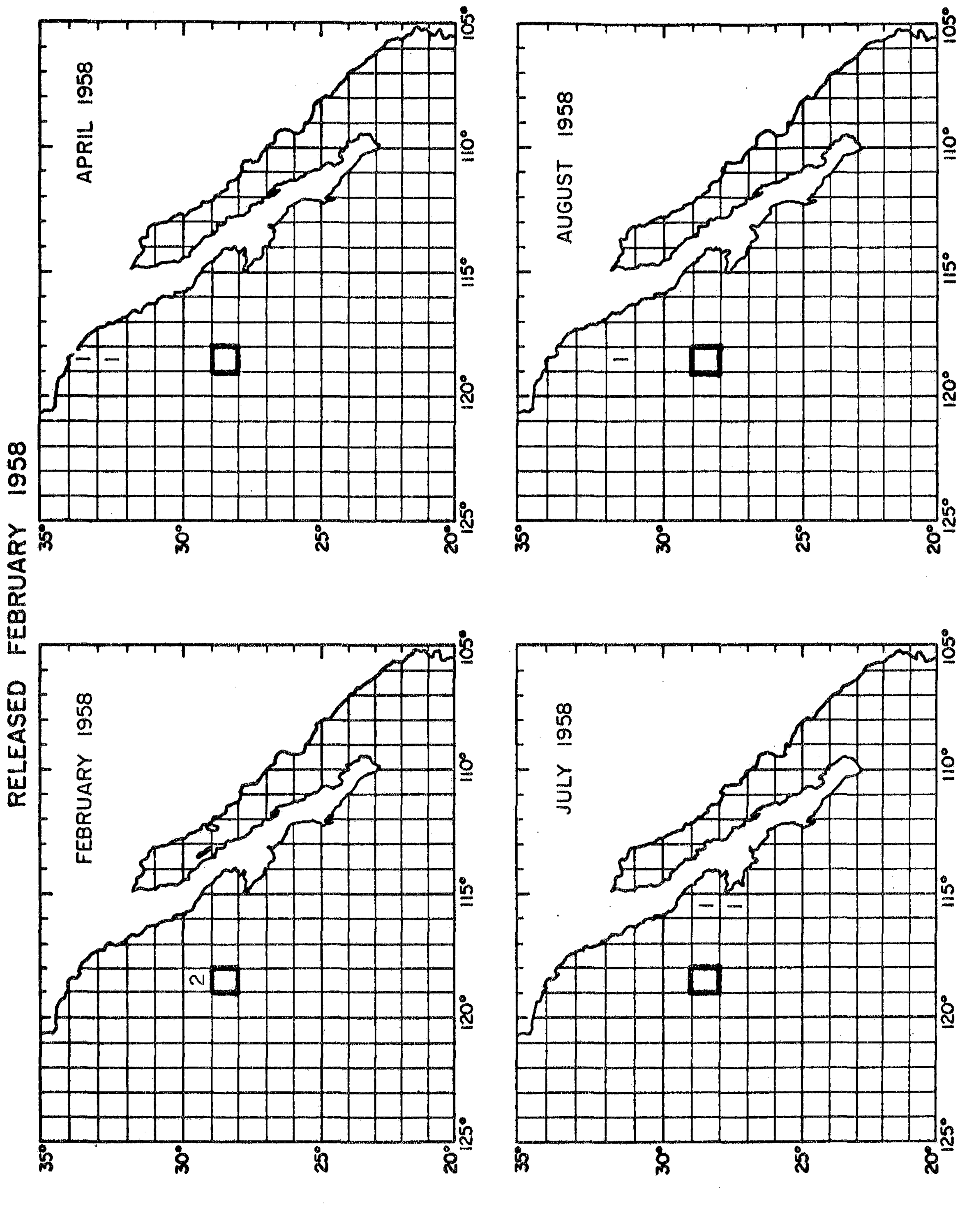

FIGURE 9. Areas and dates of recapture of tagged northern bluefin released in the eastern Pacific Ocean during 1958-1968. The 1-degree areas of release are delineated by heavy lines, and the numbers of fish recaptured in each 1-degree area are indicated by numerals.

RELEASED AUGUST 1962

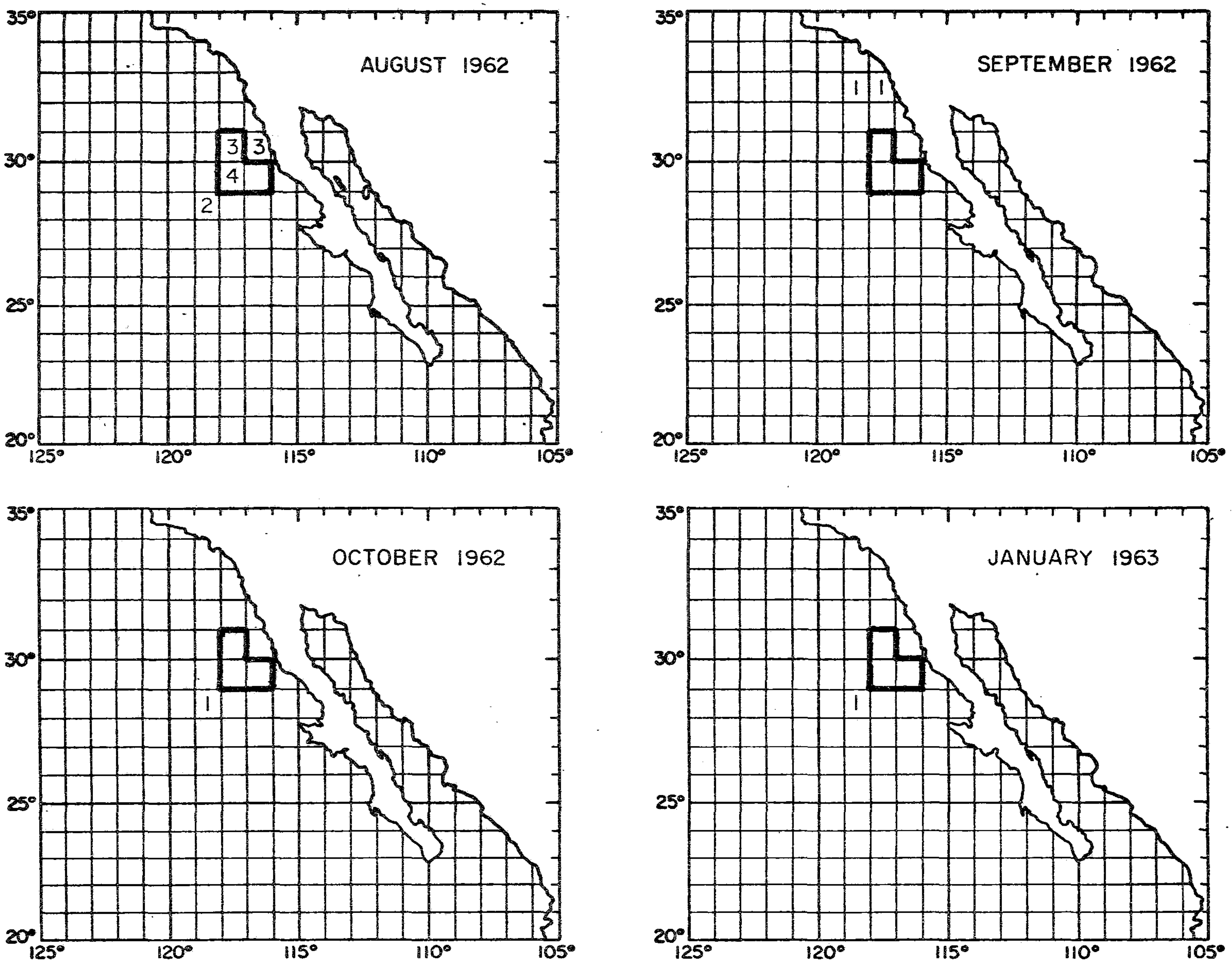

FIGURE 9 (continued).

RELEASED AUGUST 1962

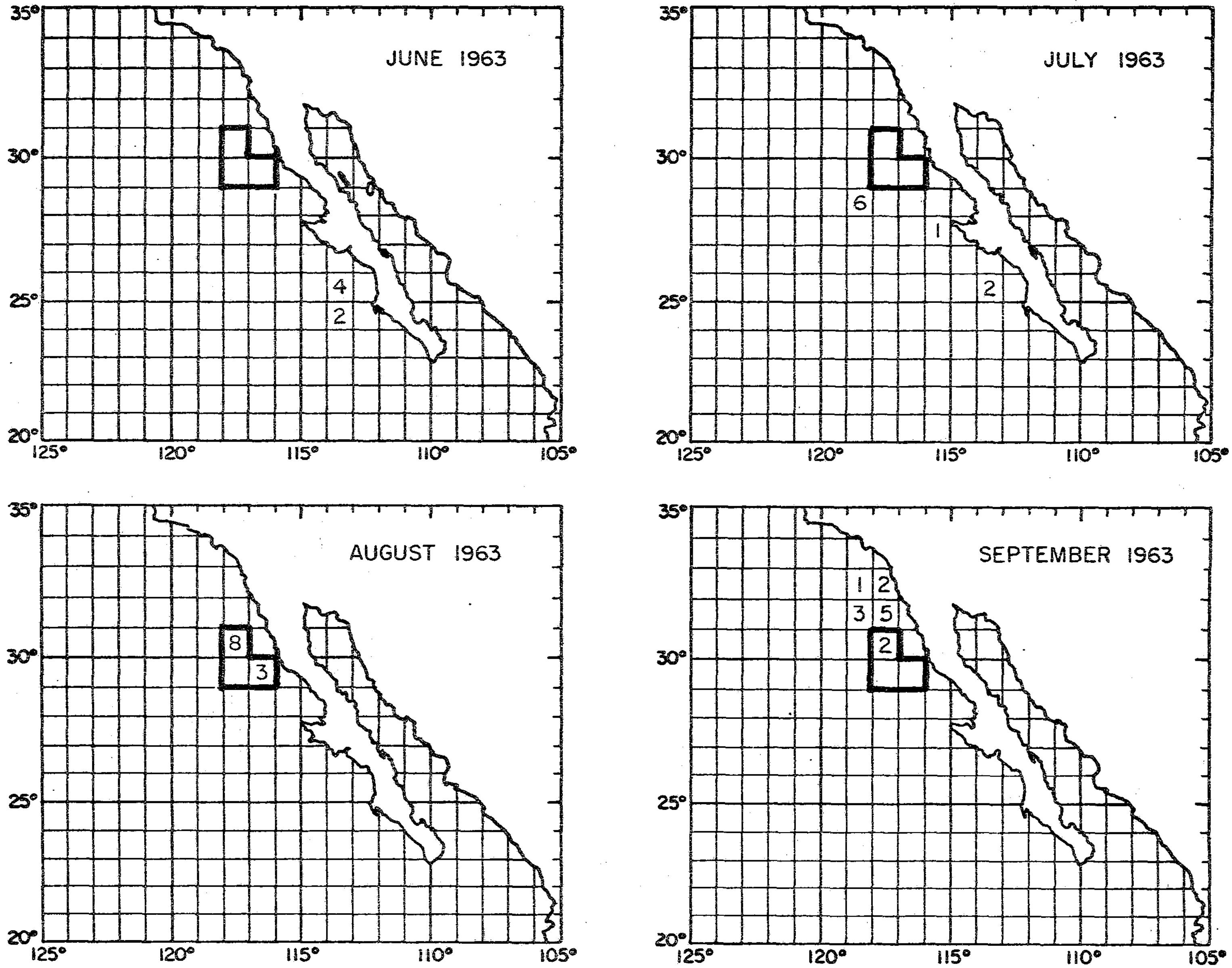

FIGURE 9 (continued).

RELEASED AUGUST 1962

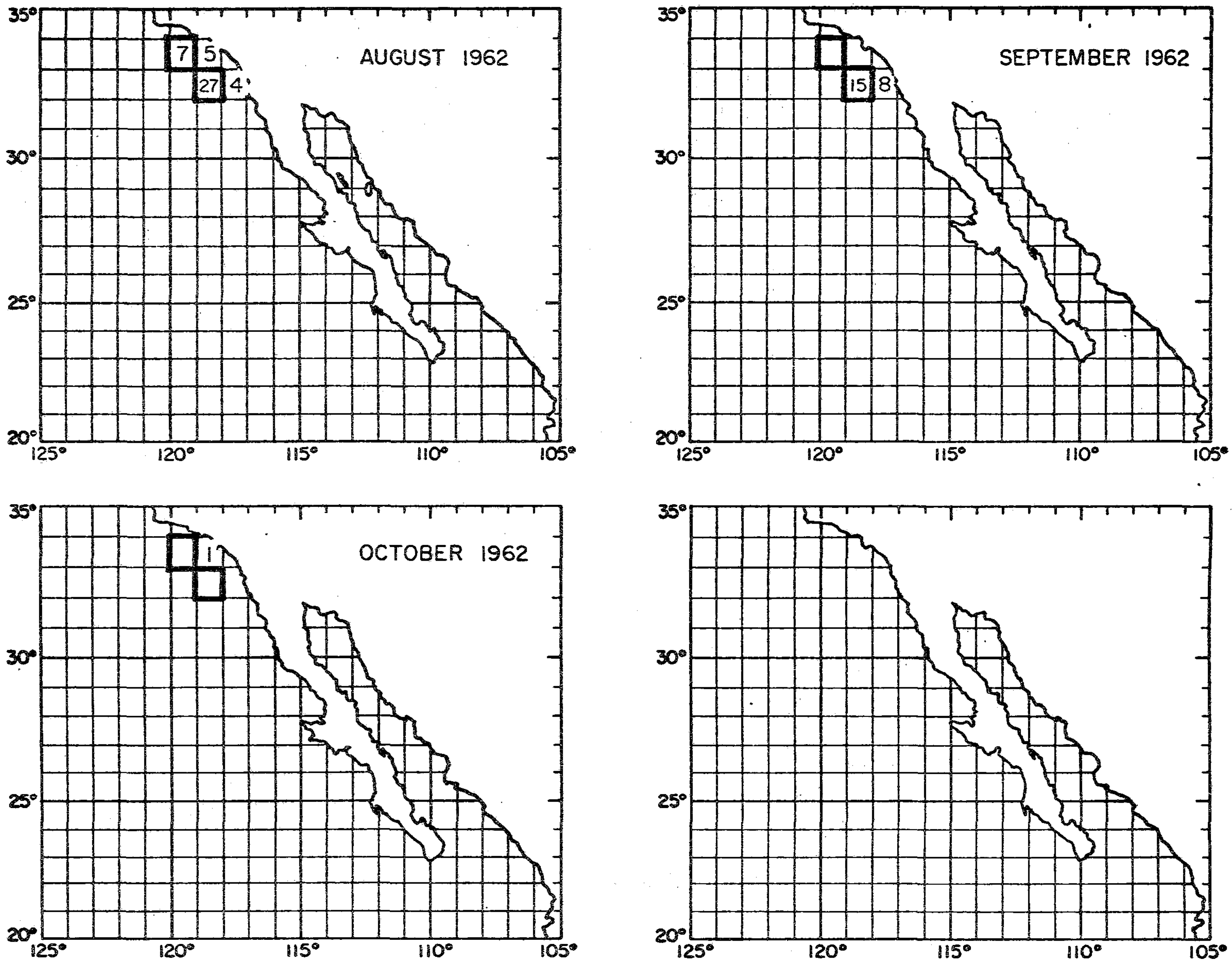

FIGURE 9 (continued).

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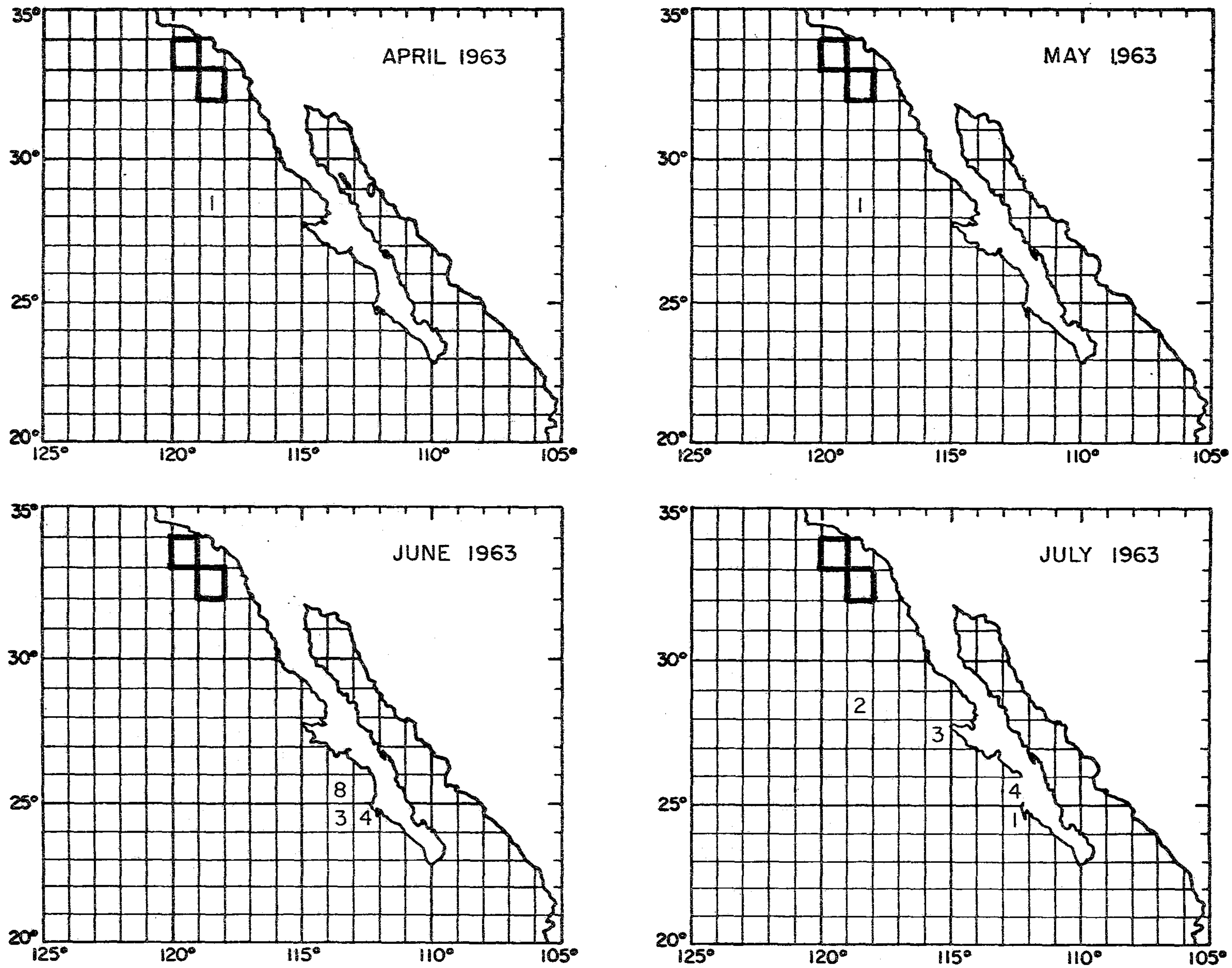

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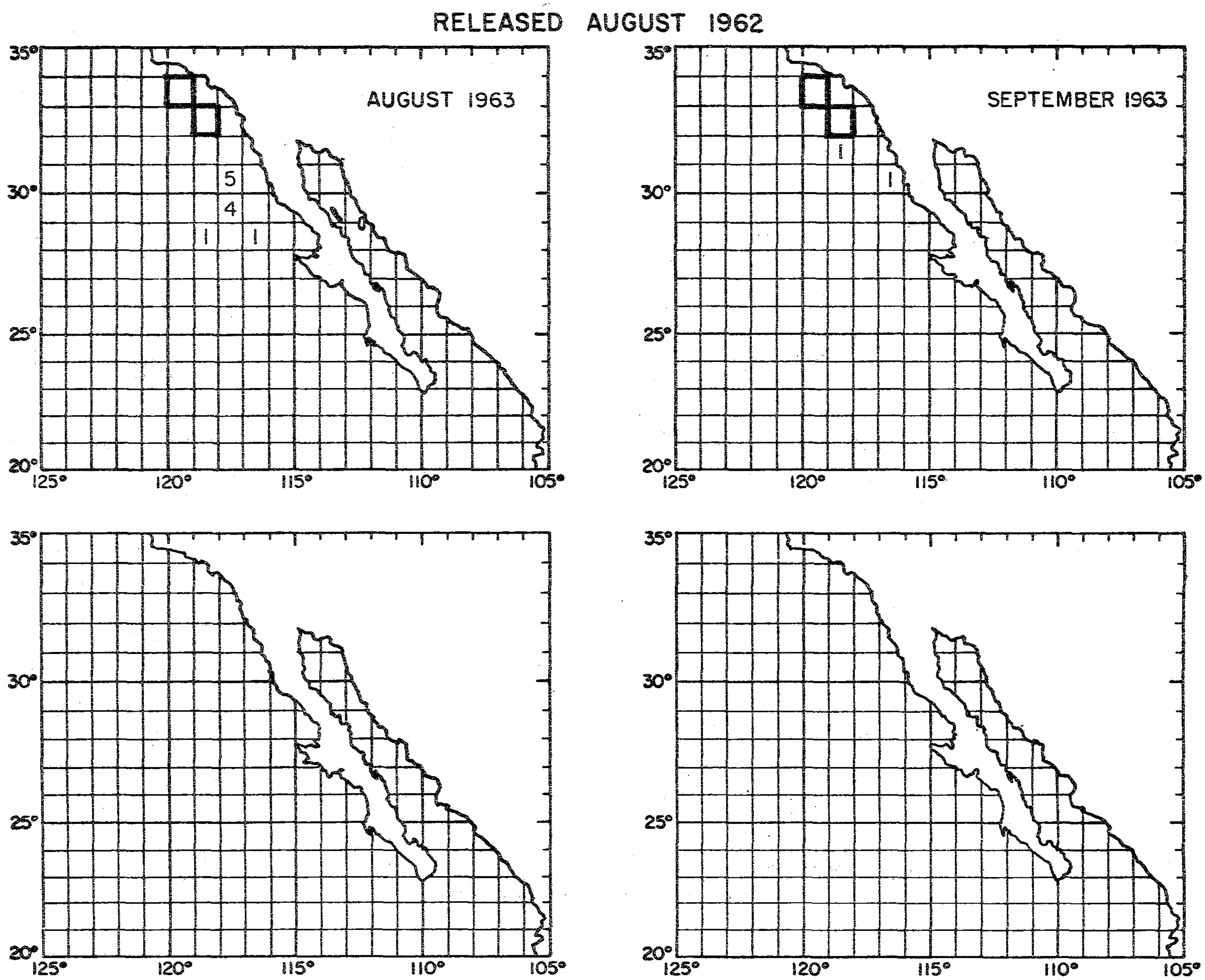

FIGURE 9 (continued).

RELEASED JULY 1963

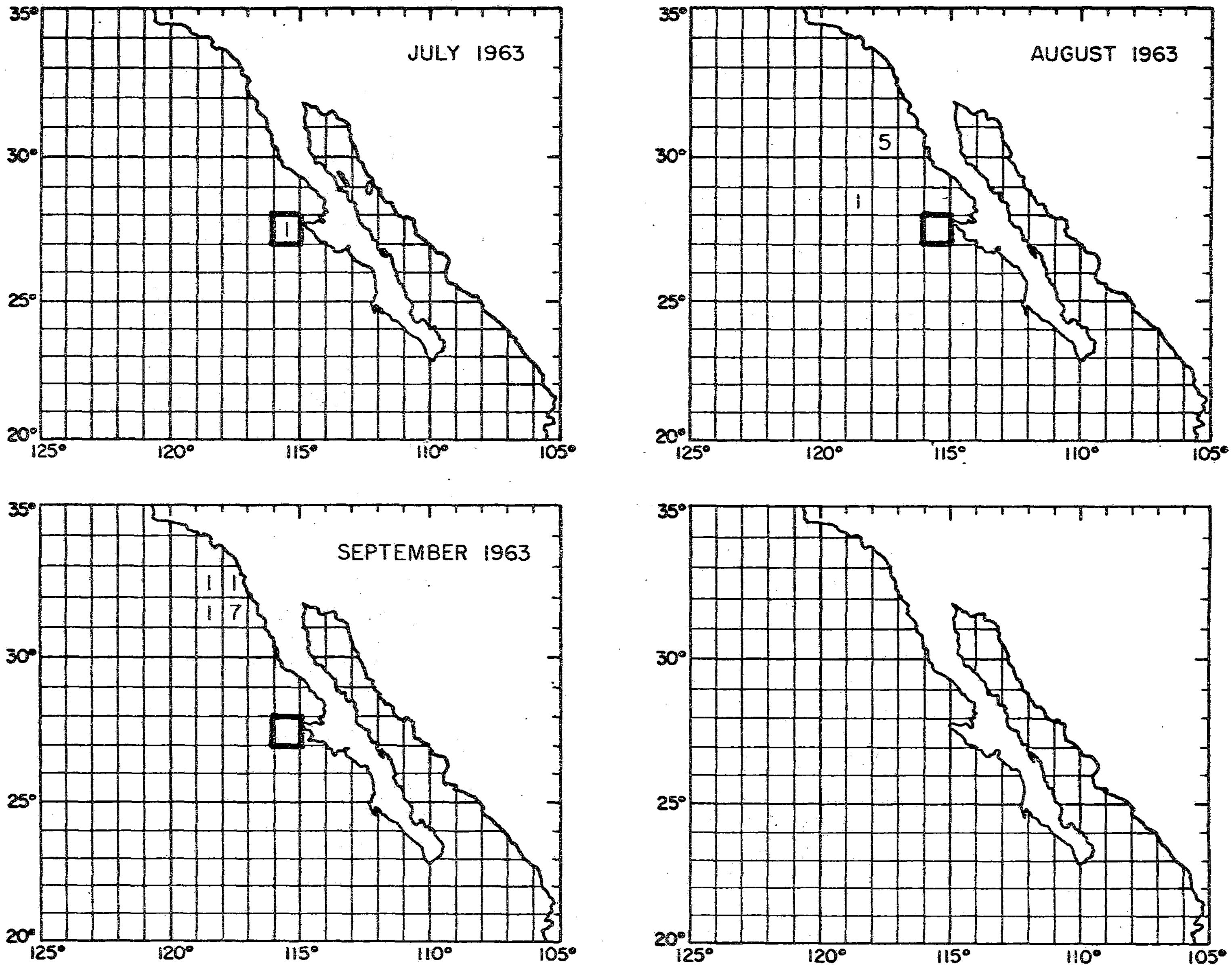

FIGURE 9 (continued).

RELEASED JULY 1963

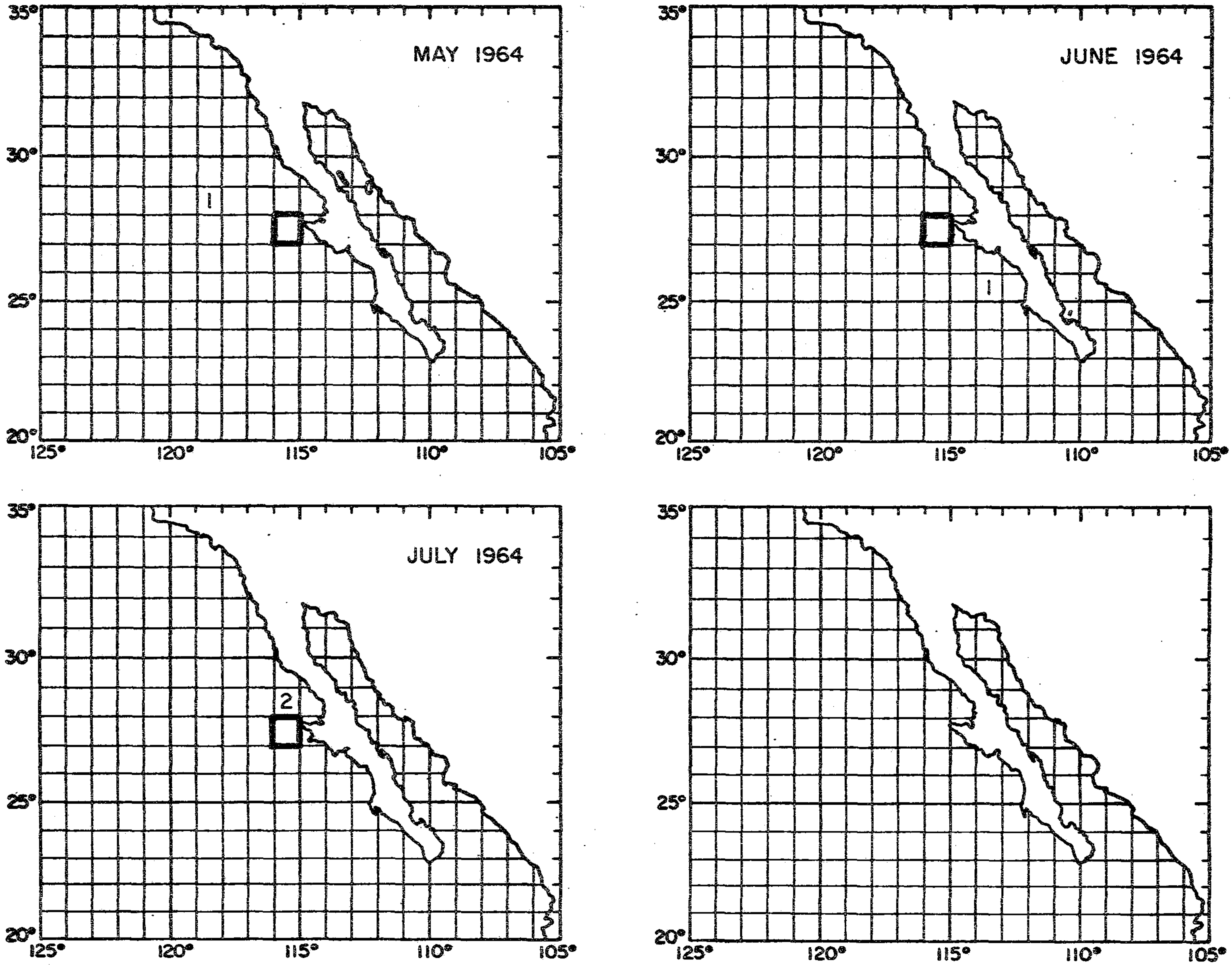

FIGURE 9 (continued).

RELEASED AUGUST 1963

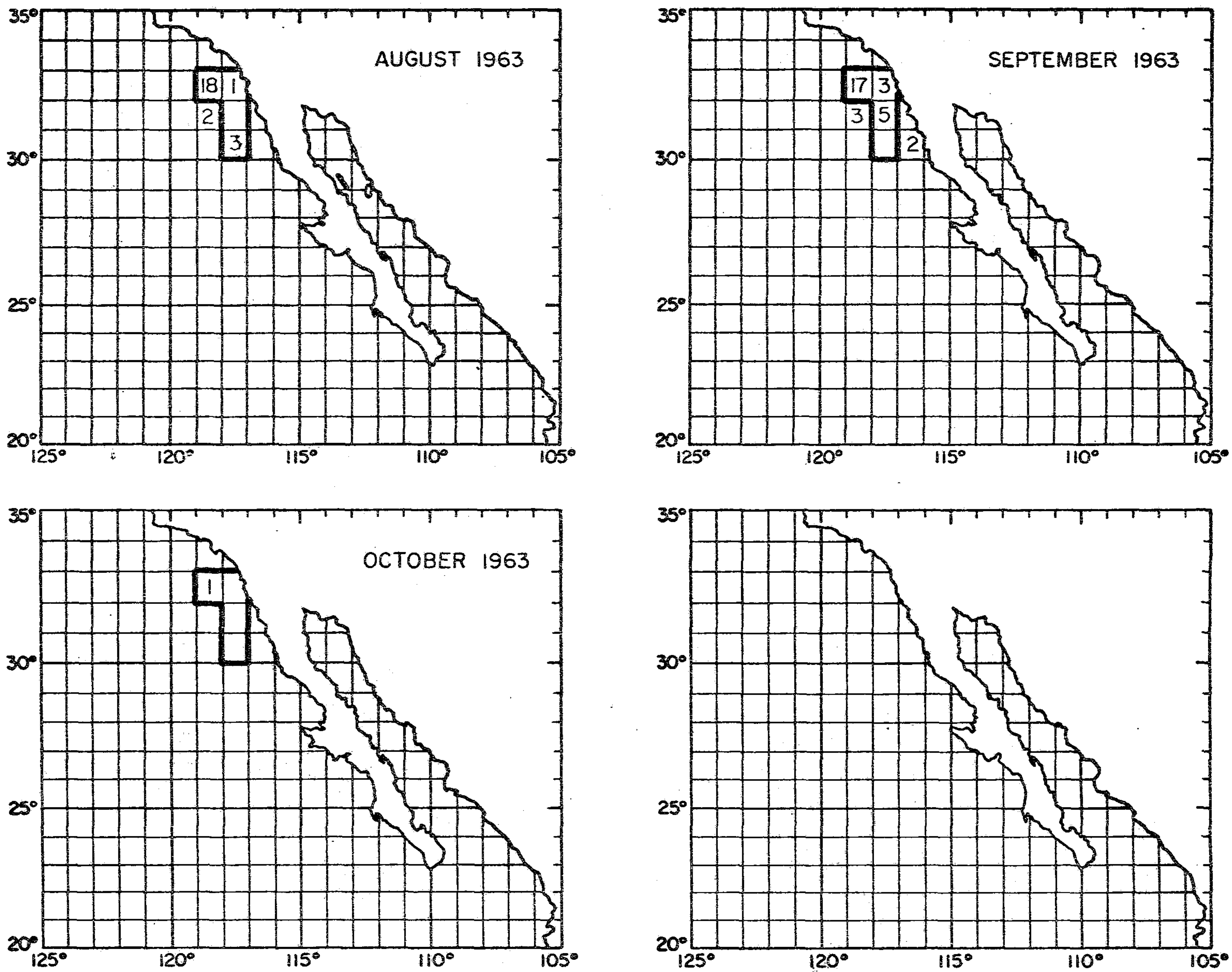

FIGURE 9 (continued).

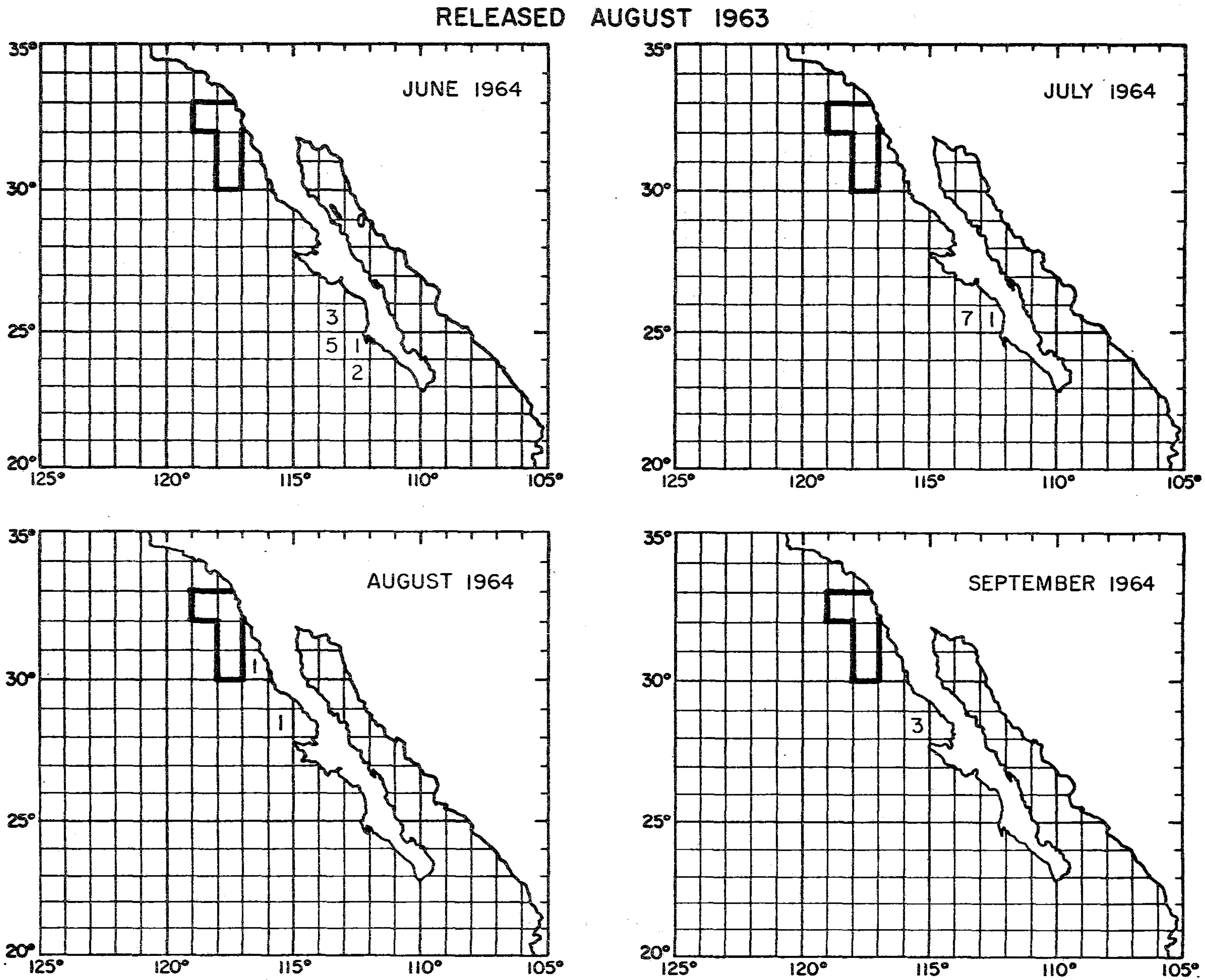

FIGURE 9 (continued).

RELEASED AUGUST 1964

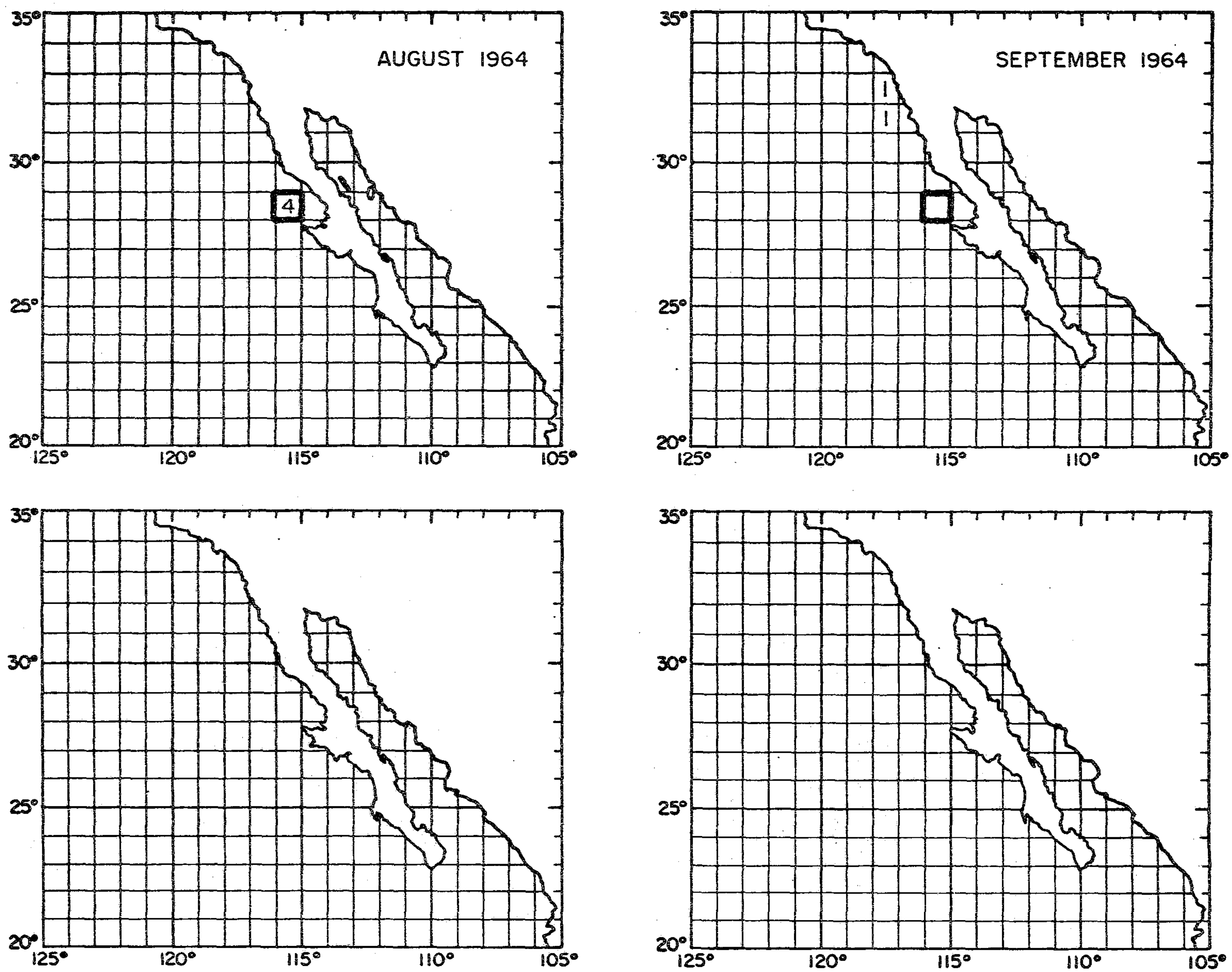

FIGURE 9 (continued).

RELEASED AUGUST 1964

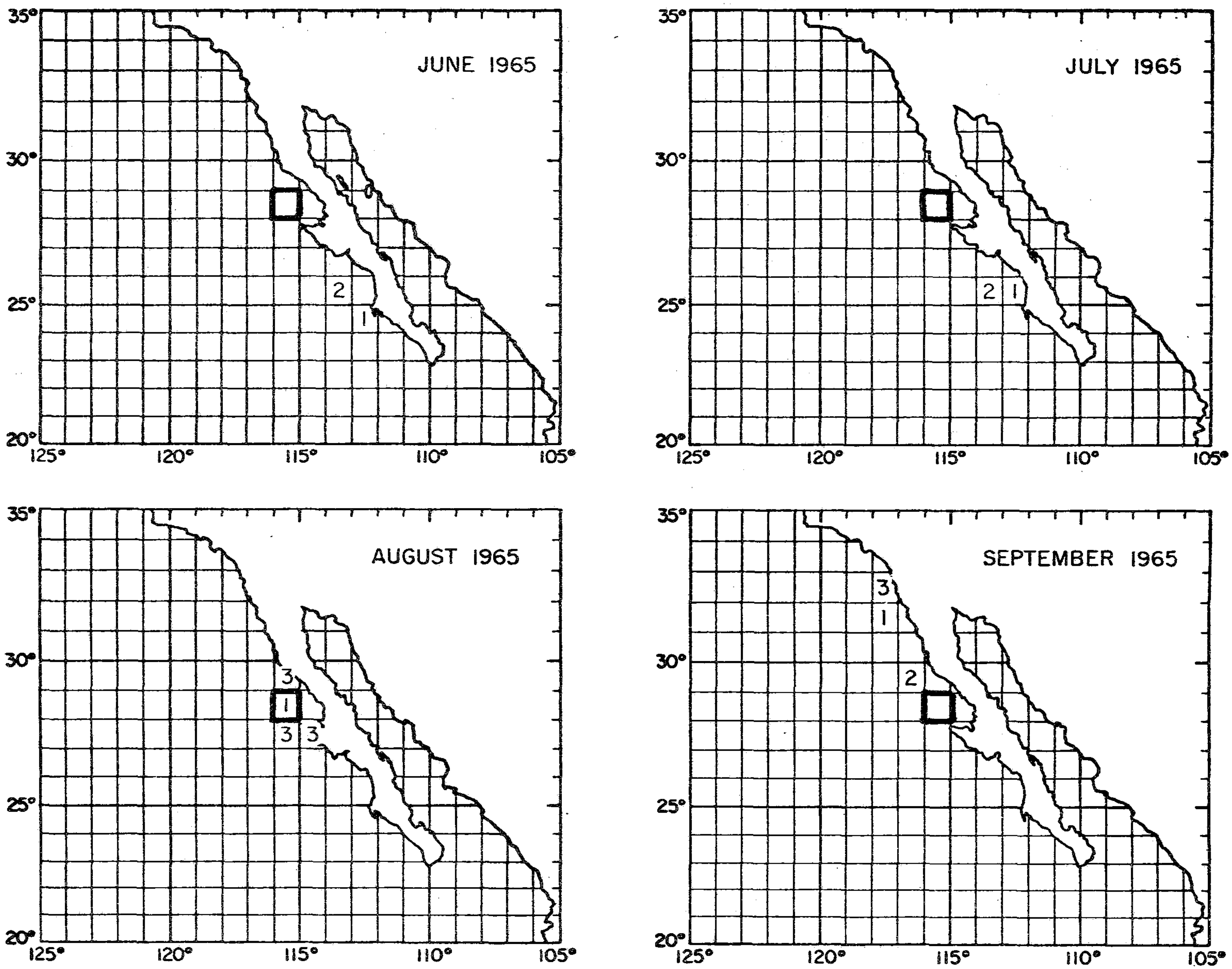

FIGURE 9 (continued).

RELEASED AUGUST 1964

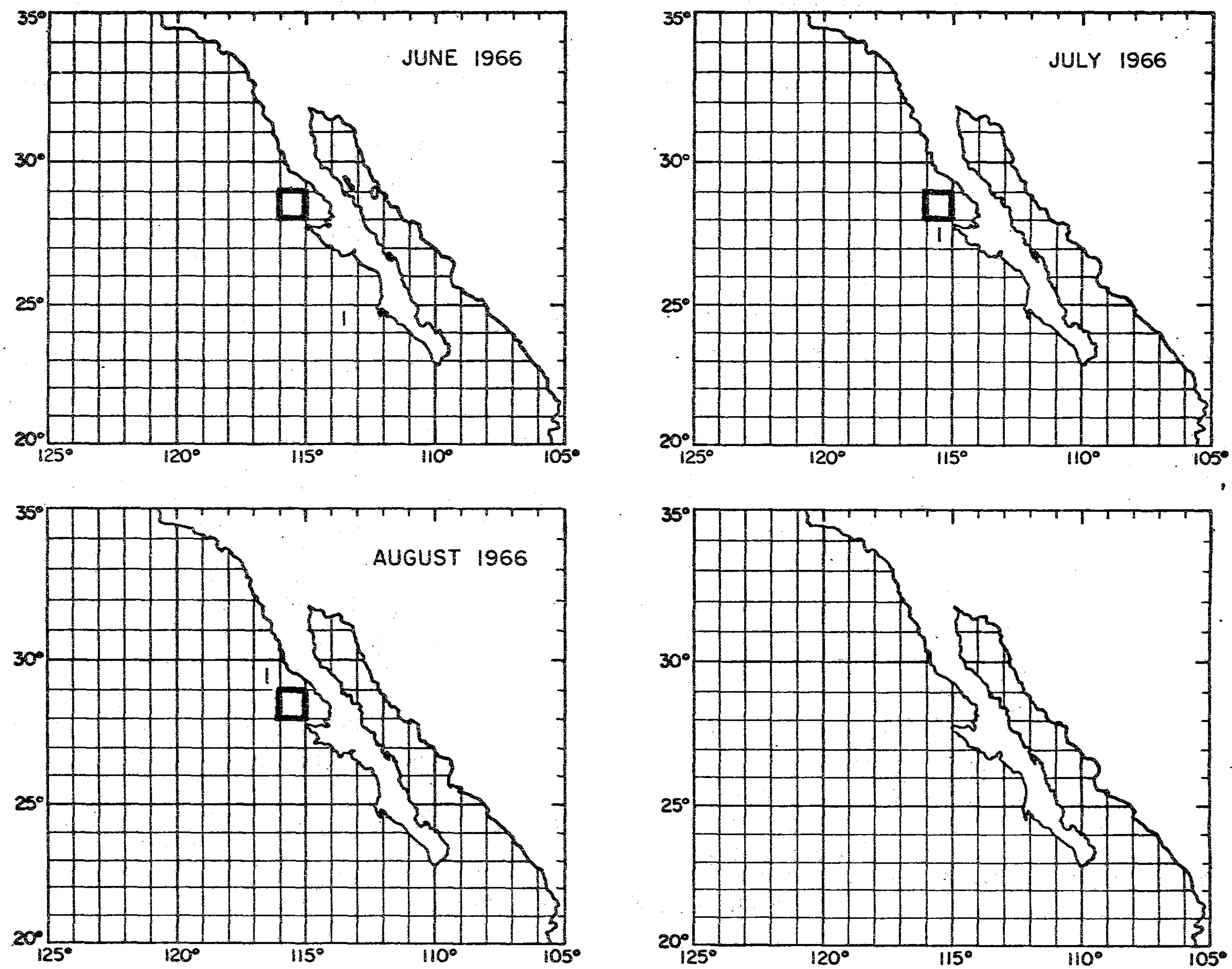

FIGURE 9 (continued).

RELEASED AUGUST-SEPTEMBER 1964

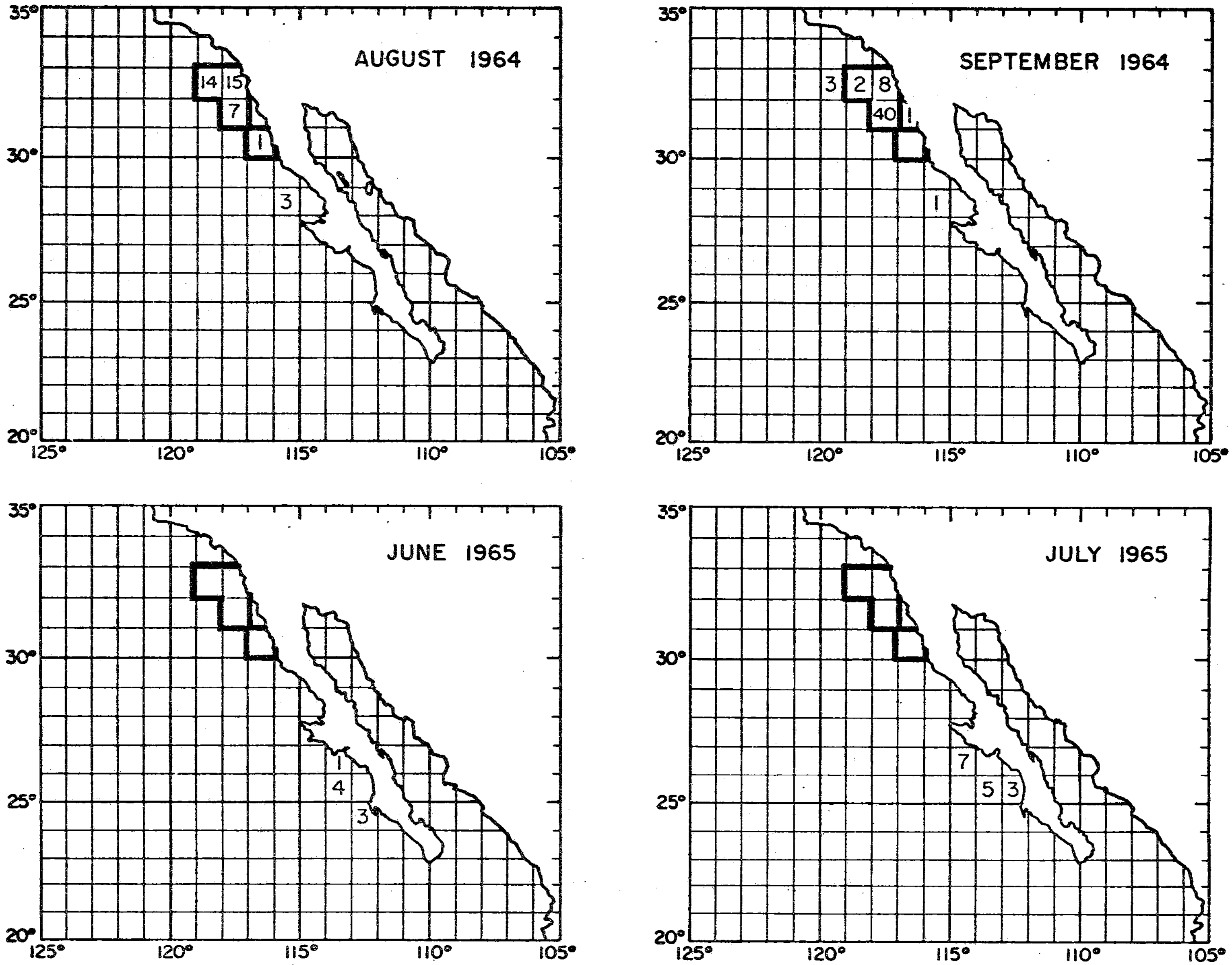

FIGURE 9 (continued).

RELEASED AUGUST-SEPTEMBER 1964

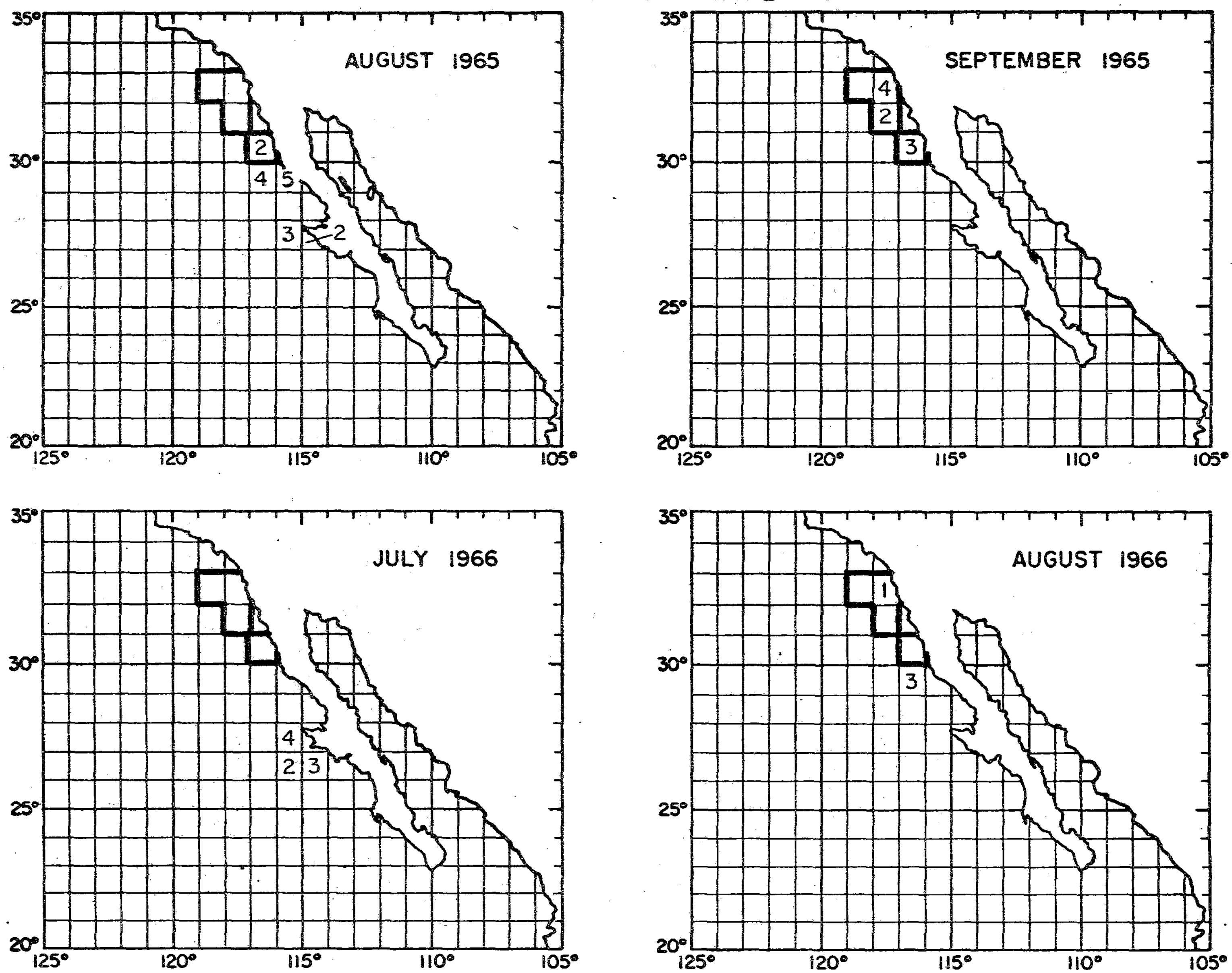

FIGURE 9 (continued).

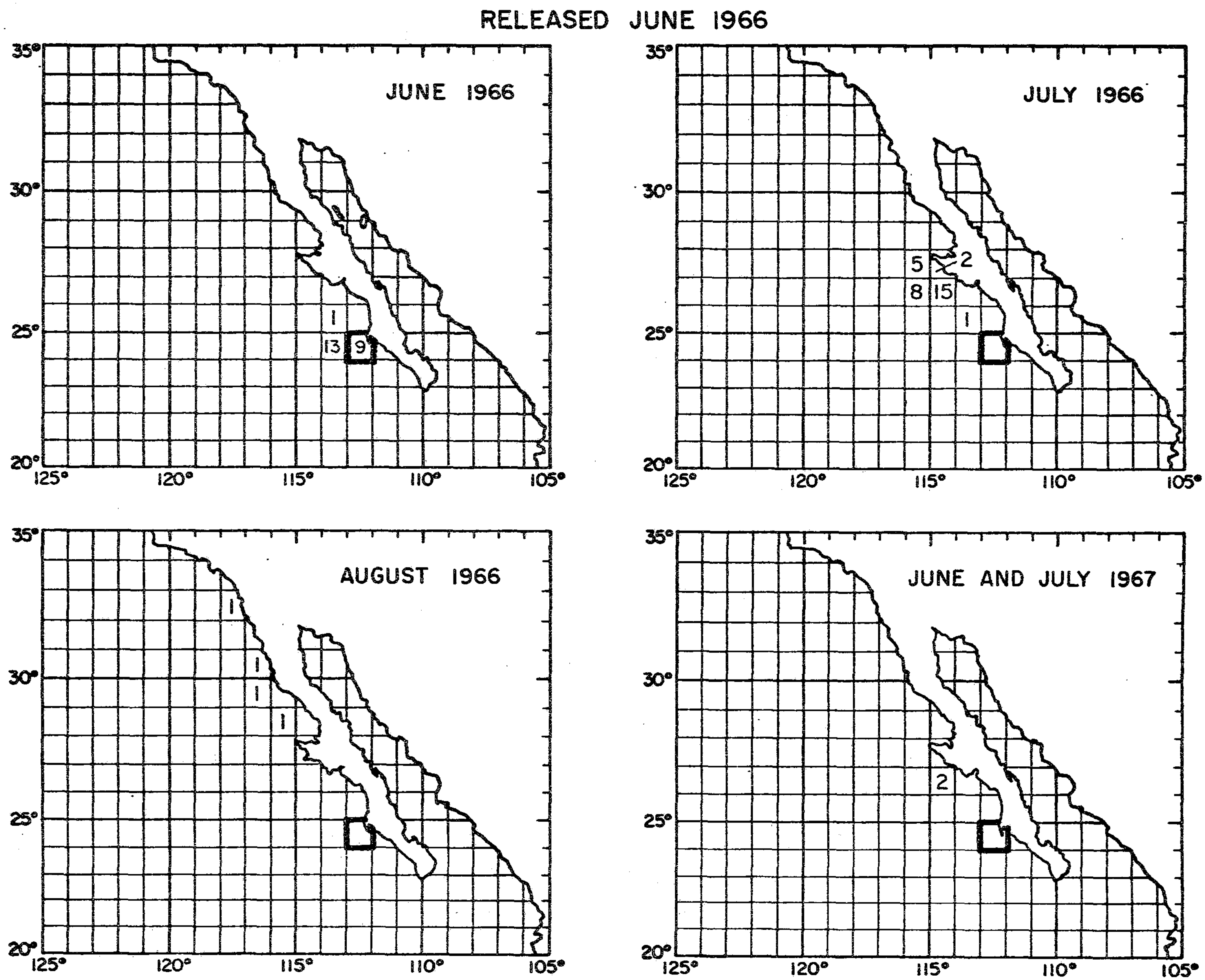

FIGURE 9 (continued).

RELEASED JULY 1968

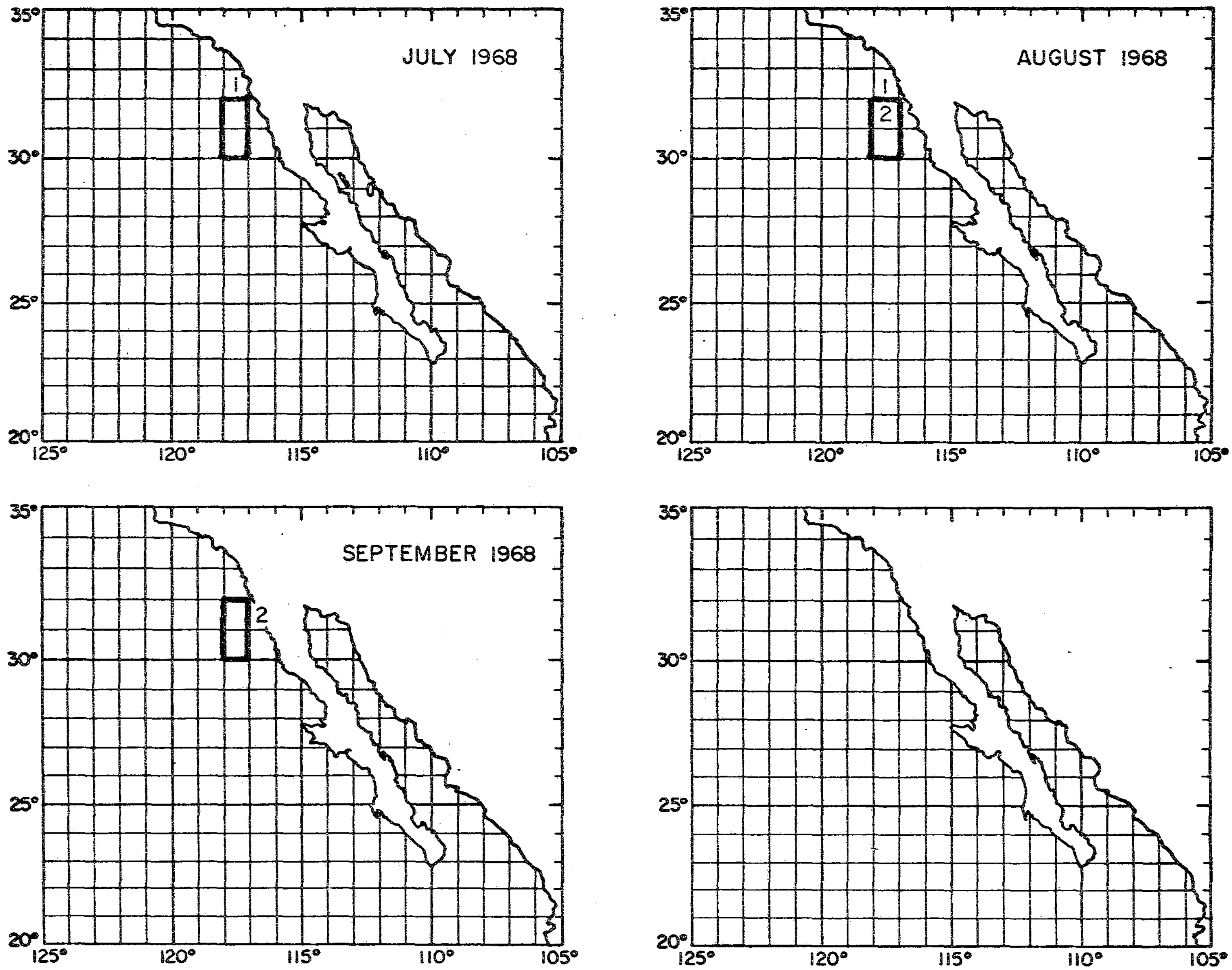

FIGURE 9 (continued).

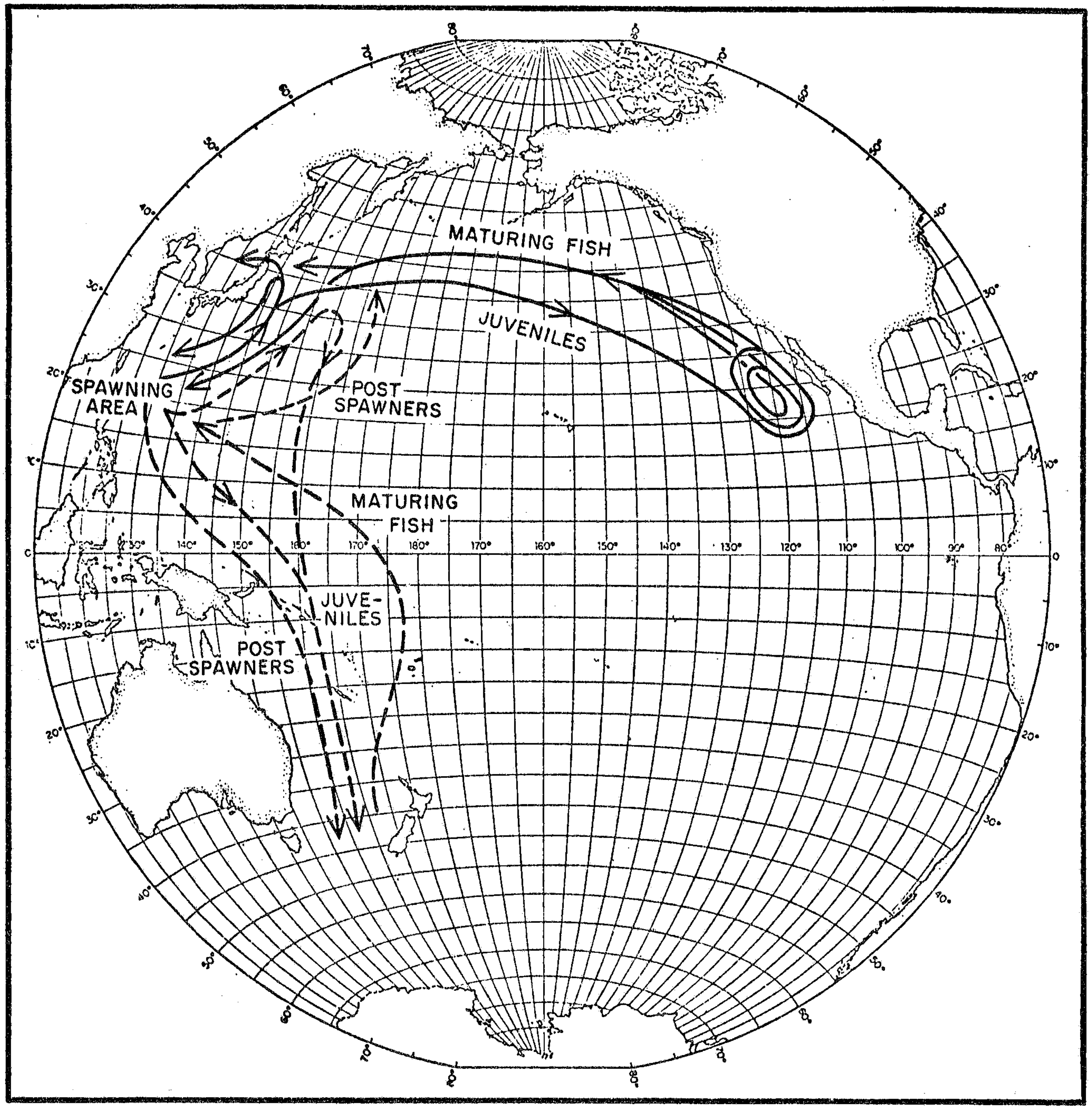

FIGURE 10. A model for northern bluefin migration in the Pacific Ocean.

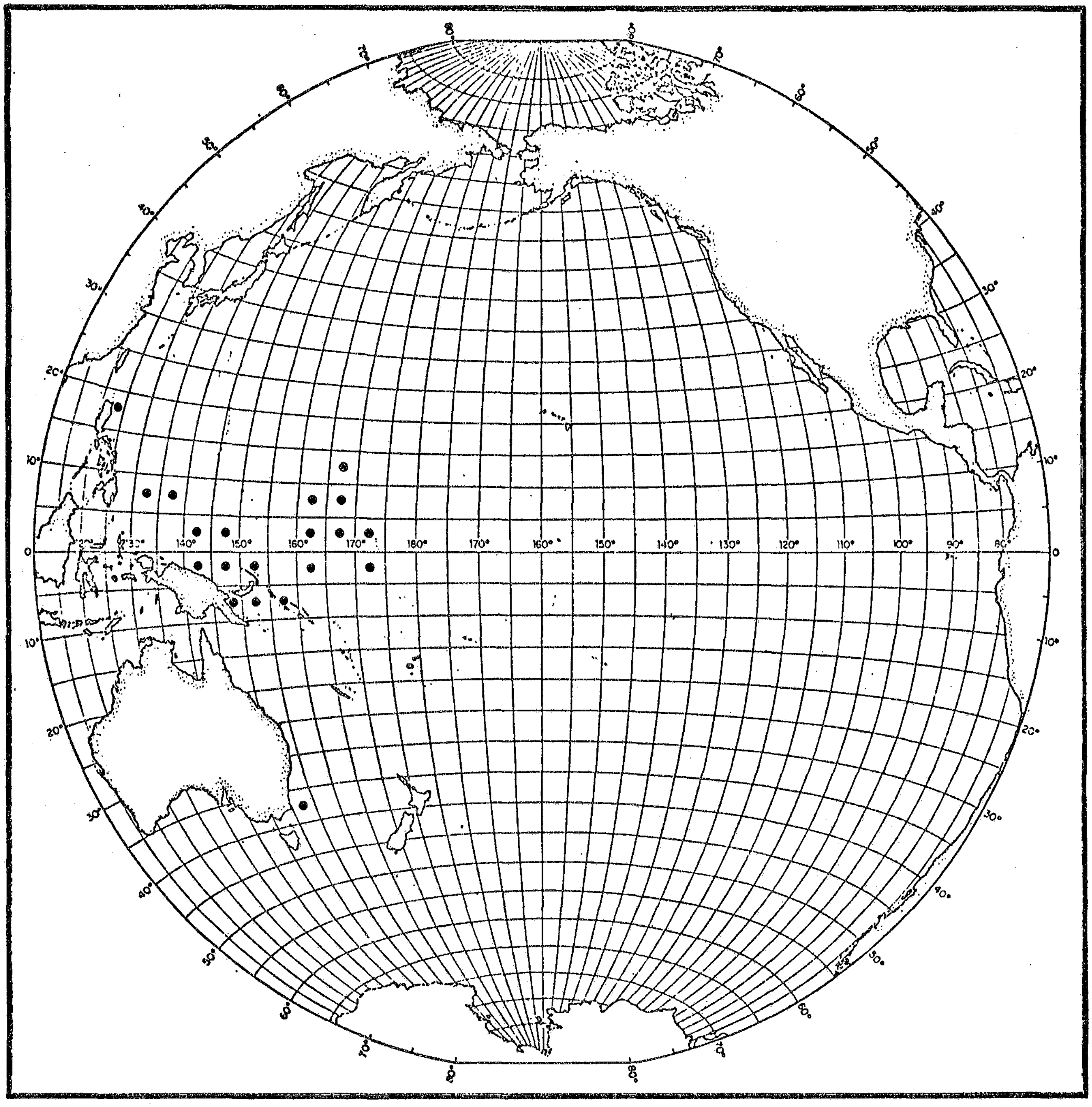

FIGURE 11. Areas south of 20°north latitude in which northern bluefin were caught by surface gear during 1972-1976.

TABLE 1. Catches of northern bluefin in the Pacific Ocean in metric tons. The 1978 value is preliminary.

Year	Eastern Pacific, surface		Western Pacific, surface and subsurface	Total
	Commercial	Sport		
1918	2,722			
1919	6,800			
1920	4,776			
1921	894			
1922	1,275			
1923	1,460			
1924	1,470			
1925	1,725			
1926	2,960			
1927	2,222			
1928	6,215			
1929	3,414			
1930	9,943			
1931	1,603			
1932	486			
1933	254			
1934	8,327			
1935	11,418			
1936	8,584	33		
1937	5,758	46		
1938	8,041	135		
1939	5,369	112		
1940	9,058	78		
1941	4,318			
1942	5,826			
1943	4,617			
1944	9,228			
1945	9,341			
1946	9,993			
1947	9,452	25		
1948	2,961	1		
1949	1,991	22		
1950	1,242	0		
1951	1,752	81	15,400	17,233
1952	2,076	2	13,700	15,778
1953	4,433	48	14,600	19,081
1954	9,537	11	16,600	26,148
1955	6,173	93	21,700	27,966
1956	5,727	388	33,100	39,215
1957	9,215	73	21,100	30,388
1958	13,934	10	9,000	22,944
1959	6,914	15	9,300	16,229
1960	5,422	1		

TABLE 1 (continued).

Year	Eastern Pacific, surface		Western Pacific, surface and subsurface	Total
	Commercial	Sport		
1961	9,603	26		
1962	14,651	28		
1963	14,189	8		
1964	10,642	8	19,300	29,950
1965	7,556	1	22,200	29,757
1966	16,846	23	21,800	38,669
1967	6,601	36	19,100	25,737
1968	6,063	14	24,300	30,377
1969	7,172	17	17,500	24,689
1970	4,024	21	15,200	19,245
1971	8,415	8	14,800	23,223
1972	13,390	17	5,400	18,807
1973	10,576	61	4,800	15,437
1974	5,748	65	10,629	16,442
1975	9,578	38	7,164	16,780
1976	10,561		5,498	16,059
1977	5,151		8,835	13,986
1978	5,325			

TABLE 2. Monthly logged commercial catches of northern bluefin in the eastern Pacific Ocean surface fishery during 1959-1968 and 1969-1978, with the monthly average catches expressed as percentages of the annual average catches.

	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	Total	Percent
January		110		20	44	4	2		12		191	0.2
February	125				31		8				164	0.2
March	9			91			14		4		117	0.1
April	1,473		10	37	84	5	10				1,619	1.9
May	10		32	326	91	17	1	211	48		736	0.8
June		1,769	1,263	1,927	2,235	1,526	523	4,532	2,937	720	17,432	20.0
July	1,760	1,755	1,491	4,215	1,795	2,122	899	6,802	2,432	2,125	25,396	29.1
August	2,045	852	4,946	5,360	5,665	4,443	2,478	3,385	95	1,645	30,914	35.5
September		221	1,254	386	3,448	546	1,569	153	449	837	8,865	10.2
October			162		10	6	971	2	16	343	1,510	1.7
November		114	64		19	6	2				206	0.2
December					29						29	0.0
Total	5,422	4,822	9,222	12,361	13,452	8,675	6,476	15,086	5,993	5,670	87,179	

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	Total	Percent
January	11	12						174		82	279	0.4
February			23		9		2	342			376	0.6
March											0	0.0
April	231	30									261	0.4
May	505		1,901	341	16		53	241	1,383		4,441	6.8
June	689	1,374	1,746	2,264	1,550	1,188	2,489	1,650	363	583	13,899	21.3
July	2,263	2,126	1,293	2,340	3,803	1,420	1,522	269	62	1,319	16,415	25.2
August	1,756	285	712	4,804	1,722	627	197	3,360	1,901	1,750	17,114	26.3
September	623	56	997	695	186	619	1,581	3,022	614	97	8,490	13.0
October			800	1,474		61	570	311	332	11	3,559	5.5
November							116	133			249	0.4
December	46		12				23	23			103	0.2
Total	6,125	3,883	7,483	11,919	7,287	3,915	6,553	9,525	4,655	3,842	65,186	

TABLE 3. Logged northern bluefin catch, effort, and catch per day's fishing 1966-1978.

Year	Months used	Days fishing	Catch	Catch per day's fishing
1966	5-9	2,791	14,129	5.06
1967	6-9	3,631	5,166	1.42
1968	6-10	2,408	4,980	2.07
1969	5-9	2,981	5,837	1.96
1970	6-8	2,209	3,786	1.71
1971	5-10	3,525	7,449	2.11
1972	5-10	3,694	11,919	3.23
1973	6-9	2,514	7,261	2.88
1974	6-9	2,203	3,854	1.75
1975	6-10	2,333	6,359	2.72
1976	5-10	2,969	8,926	3.00
1977	5-10	2,504	4,655	1.86
1978	6-9	2,315	3,749	1.62

TABLE 4. Growth of northern bluefin in the eastern Pacific Ocean.

Reference	AGE 1	2	3	4	5	6	l_∞	K
Bell, 1963	57.10	72.08	90.65	106.95	128.50	142.00	13,930.6	0.0013
Schultze and Collins, 1977	53.0	80.4	104.8	126.3	143.5	162.4	295.4	0.1204
this study	55.05	76.67	98.29	119.89	141.48	163.06	41,079.2	0.0005

TABLE 5. Relationship of weight in pounds to length in millimeters for northern bluefin in the eastern Pacific Ocean, 1962-1967.

Year	Sample size	Length range (mm)	Relationship
1962	295	541-1217	$w = 0.98404 \times 10^{-7} l^{2.89727}$
1963	367	558-1784	$w = 0.20334 \times 10^{-6} l^{2.79012}$
1964	479	592-1244	$w = 0.85161 \times 10^{-8} l^{2.91778}$
1965	300	529-1082	$w = 0.10065 \times 10^{-7} l^{2.89786}$
1966	1640	580-1280	$w = 0.21232 \times 10^{-7} l^{2.78035}$
1967	833	580-1585	$w = 0.13900 \times 10^{-7} l^{2.8486}$

TABLE 6. Summary of tagged northern bluefin released in the eastern Pacific Ocean and recaptured in the eastern and western Pacific. The names of the organizations which conducted the experiments are given in the text.

Date	Vessel	Organization(s)	Released	Returned
1953	N. B. Scofield	CDFG	3	*
1954	N. B. Scofield	CDFG	1	*
1955	Stella Maris	CDFG	50	*
1956	Nautilus	CDFG	9	*
1958	Columbia	IATTC	122	9
1961	John N. Cobb	USBCF	1	*
1962	West Point	USBCF-CDFG	960	175
1963	Elsinore	USBCF-CDFG	543	83
1963	Dorsal	CDFG-MBRF	100	32
1964	West Point	USBCF-CDFG	782	174
1964	Dorsal	CDFG-MBRF	175	27
1964	Seasco	CDFG-MBRF	2	1
1965	Dorsal-Seasco	CDFG-MBRF	1	0
1966	Dorsal	CDFG-MBRF	237	65
1967	Five Bells	CDFG-MBRF	0	-
1968	Sea Scout	CDFG	35	6
1976	Mary K.	IATTC	1	1
Total			3,022	573

* no information available

TABLE 7. Release and recapture data for northern bluefin which have made trans-Pacific migrations.

RELEASE			RECAPTURE				
Area	Date	Length	Area	Date	Length	Days	Miles
28°45'N-118°15'W	Feb. 2, 1958	?	29°03'N-139°42'E	Apr. 23, 1963	182.5	1,907	5,147
29°43'N-117°20'W	Aug.15, 1962	?	40°44'N-140°00'E	Jun. 18, 1964	?	674	4,781
29°43'N-117°20'W	Aug.15, 1962	?	41°39'N-141°09'E	Aug. 17, 1964	115	734	4,708
29°50'N-117°13'W	Aug.16, 1962	?	41°15'N-140°43'E	Aug. 29, 1964	?	745	4,737
29°48'N-116°57'W	Aug.14, 1962	?	34°16'N-136°54'E	Jun. 23, 1965	138	1,045	5,124
33°21'N-119°01'W	Aug.21, 1962	?	41°43'N-141°03'E	Aug. 10, 1965	120	1,086	4,514
32°41'N-117°55'W	Aug.20, 1964	60	38°25'N-139°15'E	Jul. 1, 1966	110	681	4,746
30°30'N-116°45'W	Aug.13, 1964	85	38°49'N-142°28'E	Jul. 4, 1968	?	1,422	4,734
32°41'N-117°55'W	Aug.20, 1964	65	39°37'N-143°16'E	Jul 14, 1968	158	1,425	4,549
35°31'N-140°46'E	Aug.27, 1965	36	27°00'N-114°34'W	Jul. 15, 1966	68	323	5,124
35°30"N-140°53'E	Aug.27, 1965	36	30°01'N-116°39'W	Aug. 9, 1966	71	348	4,923

TABLE 8. Estimated catches, in numbers of fish, of northern bluefin of the 1962 through 1965 year classes by California vessels.

Year class	Age group						
	0+	1+	2+	3+	4+	5+	6+
1962	-	535,900	79,500	22,300	0	150	0
1963	3,600	1,147,800	286,900	34,800	900	0	170
1964	0	282,100	715,000	33,900	0	500	-
1965	0	621,700	307,900	4,900	1,200	-	-

TABLE 9. Returns in the eastern Pacific Ocean, by year, for tagged northern bluefin released in the eastern Pacific Ocean in 1962, 1963, 1964, and 1966.

Year released	Returns by year			
	0		1	2
	Original	Adjusted		
1962	87	394.1	82	1
1963	79	138.0	30	6
1964	107	392.0	75	17
1966	63	66.4	2	0