ANALYSES OF THE RELATIONSHIP BETWEEN THE DISTRIBUTION OF SEARCHING EFFORT, TUNA CATCHES, AND DOLPHIN SIGHTINGS WITHIN INDIVIDUAL PURSE SEINE CRUISES

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ABSTRACT

The fine scale distribution of searching effort within individual purse seine cruises in the eastern tropical Pacific is analyzed in relationship to sightings of spotted dolphin, *Stenella attenuata*, and tuna catches. The data for these analyses were derived from detailed observations made by National Marine Fisheries Service observers aboard U.S. purse seiners. A clustering algorithm is developed which separates the activity of a vessel into areas where sets were common and areas where they are infrequent. Within clusters of high set densities, vessels tend to concentrate their searching effort. Vessels searched proportionately greater distances relative to the physical distances between sets while within clusters than when outside clusters. Encounter rates with schools of spotted dolphins tend to be either much higher or much lower within defined clusters than outside them. Clusters with low encounter rates were clusters in which non-dolphin associated tuna sets predominated. Because of this dichotomy in the magnitude of the dolphin encounter rates within clusters, overall encounter rates appeared to have relatively small biases if the concentration of searching effort within clusters is ignored. The average catch of tuna per set was higher within the defined clusters than between them. The overall results suggest that fine scale geographic effects need to be considered when using data from purse seiners to examine changes in relative abundances of either dolphins or tuna.

Catch and effort data underlie most indices of abundances used for assessing the status of commercially exploited fish stocks. The validity of using catch and effort data from commercial harvests has long been questioned because of the likelihood that fishermen concentrate their effort in areas of high fish densities (Helland-Hansen 1909). Yet, almost nothing is known about the allocation of effort by individual vessels. If data are available on the activity of individual vessels, these data have been mainly used for standardization of effort. The catch and effort activities within individual cruises have not been examined in detail (in part because the data for such an examination generally do not exist). The purpose of the present paper is to examine the searching behavior of tuna purse seiners in the eastern tropical Pacific (ETP) based on detailed data compiled by the National Marine Fisheries Service (NMFS). The main questions addressed are whether seiners concentrate their effort and what is the relation between searching behavior, encounter rates for dolphins, and tuna catches.

The maximization of profit is presumably a strong influence on the behavior of commercial fishermen. Upon leaving port, the catch rate realized by a fisherman is probably the most important factor affecting his profits. Given this orientation, it is reasonable to assume that fishermen have developed strategies of when and where to fish that increase their catch rates beyond that achieved by random search. There is little empirical information to support this assumption other than correlations, which have been noted for some fisheries, between the spatial distribution of catch rates and effort for the fleet as a whole (Gulland 1955; Calkins 1963).

In a fishery where the detection of fish depends upon visual cues, searching would be expected to be located in the vicinity of previously located fish, if there is a tendency for the underlying population to be spatially clustered. The search path for a vessel in such a fishery might be expected to look something like the hypothetical one depicted in Figure 1. The amount of crisscrossing or zigzagging in the vicinity of a catch and the area over which the search extends would be expected to vary between fishermen. The solution to the optimal searching strategy for such a situation is nontrivial and depends upon information on the

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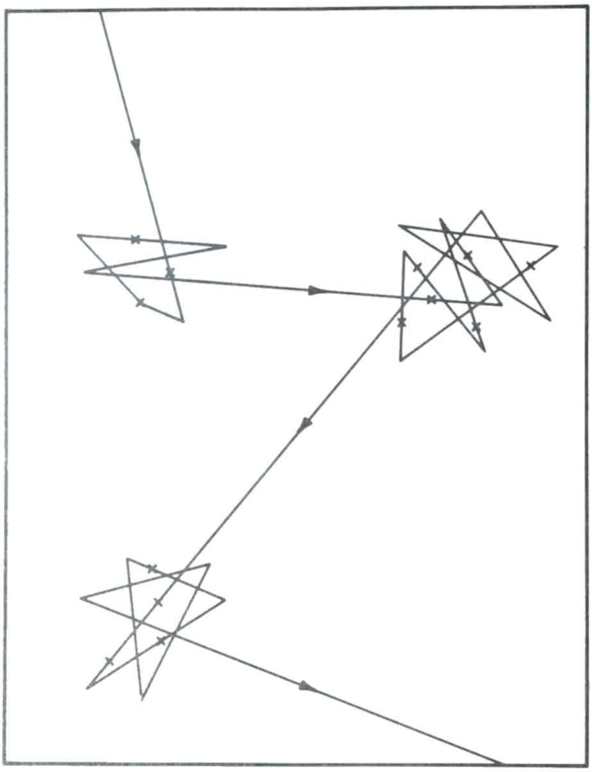

FIGURE 1.—A hypothetical cruise track for a vessel searching for clustered prey. The location of catches are indicated by ×s.

underlying distribution of the fish population (Koopman 1980). The question of optimal searching strategies for fishermen has been receiving increased attention (Pazynich 1966; Salia and Flowers 1979; Clark and Mangel 1983). These studies are primarily theoretical at this time and their application to actual fisheries requires knowledge of the spatial distribution of the fish population.

Locating schools of tuna (e.g., yellowfin, *Thunnus albacares*, and skipjack, *Katsuwonus pelamis*) in the purse seine fishery in the ETP depends on visual cues. Fishermen use a variety of cues including birds which feed on the same prey as tuna, disturbances on the surface of the water, floating debris which frequently have associated tuna, and schools of dolphins which are often associated with tuna (primarily yellowfin). Fishermen have names for the different types of sets depending upon what is associated with the tuna school. They refer to sets associated with floating debris as log sets, sets associated with dolphins as porpoise sets, and sets not associated with other animals (except possibly birds) as school sets. Fishermen when not engaged in a set usually spend their day actively searching for signs of tuna. They use 25× binoculars to scan the water while the boat cruises at speeds generally between 10 and 12 knots.

The distribution of schools of tuna, as well as schools of the most commonly associated dolphins (i.e., the spotted dolphin, *Stenella attenuata*), appears to be spatially and temporally clustered within the ETP considered as a whole (Calkins and Chatwin 1967, 1971; Blackburn and Williams 1975; Suzuki et al. 1978; Au et al. 1979[2]; Polacheck 1983). At finer geographic scales, there is little available information although Au et al. (fn. 2) suggested that schools of spotted dolphin tend to be locally concentrated in areas of convergences and fronts.

Given the above observation, it is not surprising that the detection or encounter process for tuna or dolphins does not, in general conform to a Poisson process when the distribution of searching times, searching distances, or physical distances between nearest encounters are analyzed (Polacheck 1983; Allen and Punsely 1984). In such analyses it is impossible to separate or distinguish the effects of nonrandom search from nonrandom distributions of tuna or dolphins.

In the harvesting of tuna schools associated with dolphins, fishermen chase and capture the associated dolphins (Perrin 1968, 1969), and some dolphins may be incidently killed. NMFS, as part of its responsibility under the Marine Mammal Protection Act of 1972 for managing and monitoring the status of dolphin populations, placed trained observers aboard tuna purse seiners. From the data collected by these observers, approximate cruise tracks can be drawn by connecting all positions that were recorded. Many of these approximate cruise tracks (e.g., Figure 2) have superficially a strong similarity to the hypothetical one depicted in Figure 1. It was this similarity that provided the impetus for the analyses presented below.

METHODS

NMFS observers aboard tuna purse seiners collected a wide variety of information, both on the sightings of marine mammals and fishing opera-

[2]Au, D. W. K., W. L. Peryman, and W. F. Perrin. 1979. Dolphin distribution and the relationship to environmental features in the eastern tropical Pacific. Natl. Mar. Fish. Serv., Southwest Fish. Cent., Adm. Rep. LJ-79-43, 59 p.

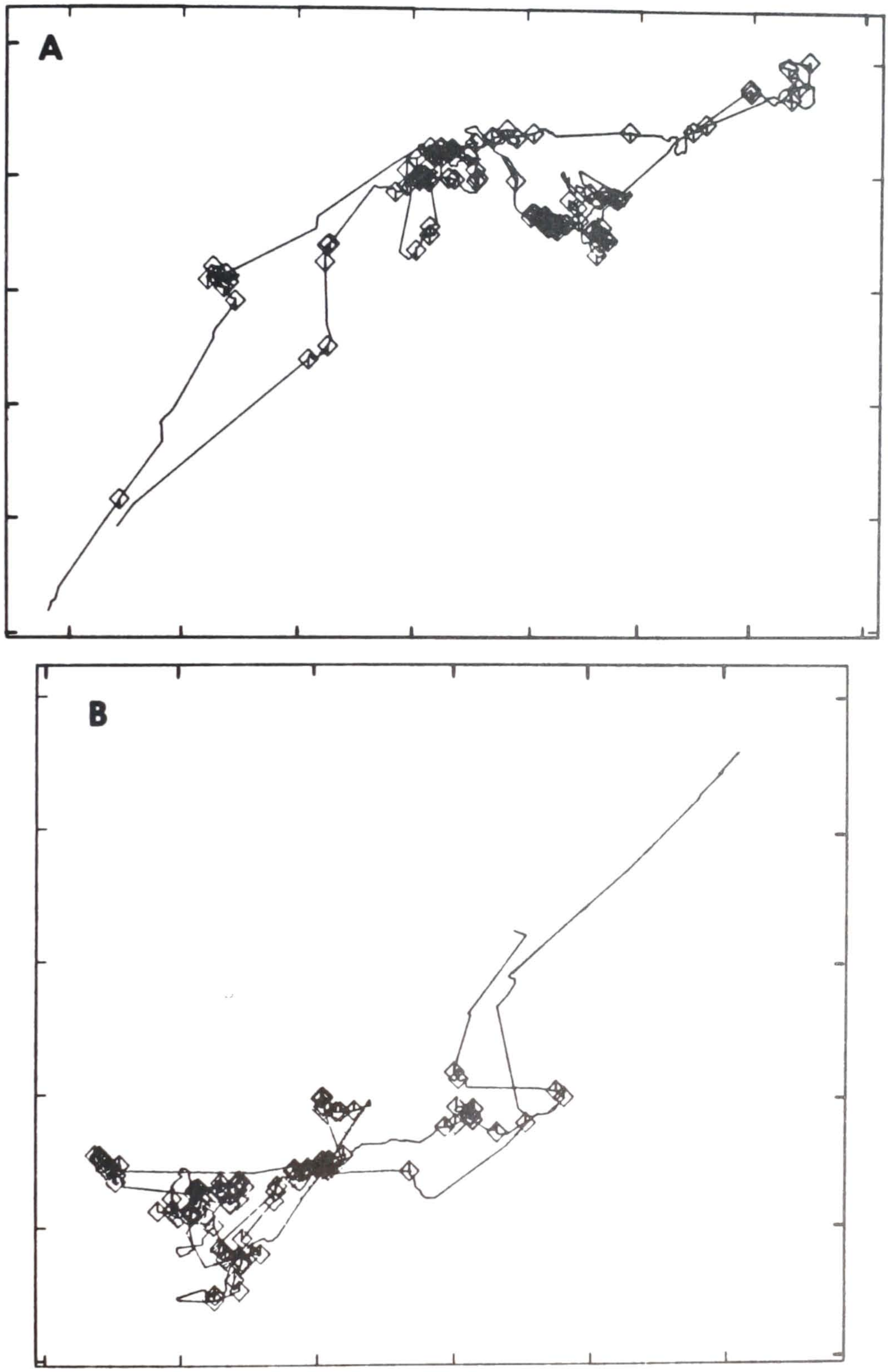

FIGURE 2.—Examples of the approximate cruise track for two tuna purse seiners. Diamonds represent the location of a set or chase. No geographic coordinates are given, and the orientation of figures were rotated at random so as not to compromise any proprietary fishing information. The distance between tick marks equals 300 nautical miles.

tions. Included in the recorded data are information on all changes in a vessel's activity; the location, type, and catch of all purse seine sets; and the location and identity of all marine mammal sightings. In these data, a vessel's activity is classified into one of five mutually exclusive categories: searching, running, setting, chasing, or resting. Searching is defined to be whenever a vessel is moving and the crew are actively searching for signs of tuna; running, anytime the vessel is moving but not actively searching for signs of fish (e.g., moving locations at night); chasing, anytime schools of dolphins are being pursued before the net has begun to be set. More detailed descriptions of the available data, collection procedures and their preparation for the analyses below can be found in Polacheck (1983, 1984[3]). The analyses in this paper were part of a larger project on the use of these observer data for assessing the relative abundances of dolphin stocks. As such, the emphasis in this paper is on the encounter rate for the most important dolphin species for the fishery (spotted dolphin), although catch rates for tuna are also considered. The results presented in this paper are based on two different approaches for analyzing the data. The first method is a set of nearest neighbor calculations, and the second is a cluster analysis.

The nearest neighbor calculations were performed in order to get an indication whether vessels tend to search in the vicinity of a previous encounter (either a sighting of marine mammals or a set on tuna). In these calculations, the physical distance between either the next or preceding encounter is compared with the distance to the nearest other encounter made within the entire cruise. Also, the proportion of times in which the nearest encounter is not either the next or preceding one is calculated. For a vessel that never returned to the area of an encounter, this proportion would equal 1. Similarly, if a vessel never returned to the area of an encounter, the ratio of the distance between either the next or preceding encounter and the distance to the nearest other encounter within an entire cruise would also equal 1. Note that the expected values for these proportions with random search are not necessarily 1. The expected value will be dependent both on the distribution of potential encounters and the definition of random search (see Discussion). These calculations were performed separately for sets and chases for tuna and for the sightings of spotted dolphin. In performing these nearest neighbor calculations, the first and last encounter during a cruise were not included.

The other main approach used for examining the data is a form of cluster analysis. When the sequences of distances between sets and chases within any cruise were examined, they appeared to be spatially and temporally clustered in the sense that sets and chases in which the distance to the next set or chase was small tended to be clumped sequentially. This observation led to the development of an algorithm for clustering sets and chases that were spatially and temporally related. Standard clustering algorithms were not appropriate in this situation because of the problem of scaling spatial and temporal distances within a common metric (i.e., how much time should be equal to a given distance).

Note that the term "clustered" or "clustered distribution" is used in this paper to refer to any distribution in which high- and low-density areas are more frequent than would be expected if the distribution was generated by a Poisson process. The term is not meant to refer to any particular nonhomogeneous process. A cluster is considered as an area of high density and should not be construed as referring to a discrete unit.

The primary purpose of the clustering algorithm was to define areas which a fisherman might have thought to have a high density of potential fishing targets so that the searching behavior of a vessel could be compared between these areas and outside them. This analysis exploits the fact that the physical distance between events is partially independent of the distance that a vessel travels to locate them. Since the purpose of the algorithm was to define areas of potentially good fishing, chases of dolphin, as well as sets, have been included as events in the clustering algorithm. (Sets made for the purpose of washing the net were not used.) The clustering algorithm began with consideration of the distance between the first and second set and/or chase. If this distance was less than a specified amount, then these two events were placed in the same cluster, and the distance between these two and the third event were examined. This specified amount will be referred to as the clustering parameter. If the distance between the third event and either of the events within the cluster was less than the value of the clustering parame-

[3]Polacheck, T. 1984. Documentation of the time sequential files created from the tuna boat observer data bases for analyzing relative abundances. Natl. Mar. Fish. Serv., Southwest Fish. Cent., Adm. Rep. LJ-84-33, 26 p.

ter, this third event was included in the cluster and the fourth event was examined. Whenever a set or chase was found for which the distance between it and all members of the last defined cluster exceeded the clustering parameter, a new cluster was formed. This process was repeated until all sets and chases within a cruise were placed in a cluster.

Using this algorithm, all the activities within a cruise could be considered to occur either between or within clusters. Isolated sets or chases (i.e., clusters containing only a single event) were considered as occurring between clusters. Distances travelled (i.e., distance searched and distance run) within a cluster were defined as the distances travelled after the first set or chase until the last set or chase in that cluster. Distances travelled between clusters were defined from the last event of the previous cluster to the first event of the subsequent cluster. The distances travelled until the location of the first set or chase and after the last one were not included because of the large distances involved in reaching the fishing grounds.

The location of a cluster was estimated by calculating the centroid for all sets and chases within it. The size of a cluster was estimated by determining the radius of the smallest circle with a center at the centroid that encompassed all sets and chases within it.

The sensitivity of this algorithm to the value of the clustering parameter was examined for values of 50, 75, 100, and 150 miles. For most of the results, only clusters with at least three members are considered as clusters. Clusters with only two members have been excluded from most of the summary results describing a cluster and also in the comparisons of results between and within clusters. This was done because two physically close events did not seem to warrant being called a cluster. Yet, given the relative difficulty in locating potential sets, two close events might be considered as areas of potentially good fishing. Clusters with only two members contained 18% of all sets and chases when the cluster parameter equalled 50 miles and 6% of all sets when the value equalled 150 miles. The overall results and conclusions are robust to whether or not clusters with two members are included or excluded.

An average intercluster distance for a cruise was calculated in order to get an indication of the stability of the clustering algorithm to the value of cluster parameters. The intercluster distance was defined as the distance from the nearest member of a cluster or isolated set to the next set and represents the minimum value that the cluster parameter would have to be for a cluster or isolated set to be combined in a single cluster with the next set.

Encounter rates for schools of spotted dolphin for each cruise were calculated between and within clusters as the total number of sightings divided by the total distance searched. In these rates, if the first chase or set within a cluster was based on a sighting of spotted dolphin, this sighting was included in the encounter rates between and not within a cluster. For the analysis of these encounter rates, clusters were classified according to the percentage of the total number of sets and chases within a cluster that involved schools of dolphins. In calculating the number of events that occurred within a cluster, sequential nondolphin sets in which no searching was done between them were counted as a single event. This was done to reduce the effect of multiple sets on the same floating object counting as a large cluster.

In order to see whether the searching behavior within the defined clusters resulted in biased estimates of encounter rates for dolphins if the clusters were ignored in the estimates, two different estimates for the overall encounter rate for a cruise were calculated and compared. The first estimate, which will be referred to as the unadjusted rate, was simply the total number of encounters divided by the total distance searched for an entire cruise. This would be an unbiased estimate if search was in fact random. The second estimate, which will be referred to as the adjusted encounter rate, was calculated as the weighted average of the encounter rate within and between clusters. The weights for the encounter rate within clusters were equal to the diameter of the cluster. The weights between clusters equalled the total distance searched between clusters. In effect, this adjusted encounter rate is an estimate of what the encounter rate would have been if a vessel had made a straight line crossing of each cluster. (In the calculation of these adjusted encounter rates, clusters with two members were treated the same as other clusters to simplify the calculations.)

The analyses in this paper are based on 35 cruises. This represents a subset of the cruises in 1979 with NMFS observers, which in turn is a subset of all purse seine cruises for tuna in the ETP during 1979. Analyses were restricted to 1979 because only for this year have the data been carefully edited for positional errors. Cruises from 1979 were excluded either because of insufficient positional data or because the vessel made port stops during the middle of the cruise. Inclusion of the time spent searching on the way in and out of port could distort the results on searching and encounter rates between clusters. Preliminary analyses suggested that there is little difference in the results between vessels that went into port and those that did not. However, to avoid further complicating the analyses, these cruises have not been included (see Polacheck 1983 for more detail).

RESULTS

Is Effort Concentrated?

The percentage of sets or chases for which the nearest one was not the preceding or next set or chase ranged from 12 to 77 among cruises (Fig. 3). The mean percentage was 41 (SE = 1.9, n = 35). The average ratio of the physical distances between the next or preceding set or chase compared to the distance to the nearest set or chase within a cruise was 1.45 (SE = 0.044, n = 35) and ranged from 1.00 to 2.24. Consideration of the same statistics for the distances between sightings of spotted dolphin indicates an even more concentrated pattern. The mean percentage of sightings for which their nearest neighbor was not either the next or preceding one equalled 80 (SE = 2.8, n = 34, note one cruise recorded no sightings of spotted dolphins) and ranged from 25 to 100 (Fig. 4). The average ratio of the distance between the next or preceding sighting compared with the nearest sighting was 4.05 (SE = 0.261, n = 34) and ranged from 1.14 to 7.82. For these sighting statistics, low percentages and ratios near 1.00 are found in vessels with few sightings (Fig. 4). These results suggest that in general vessels return to the area of a previous sighting and/or set and search in that area at least 41% of the time.

There appears to be large differences among vessels in their ability and success at locating potential fishing targets. Thus, the average distance searched between sets or chases varies by about a factor of 4 among cruises, while the average physical distance between sets or chases varies by about a factor of 6 (Fig. 5). There is little relationship between the average distance searched between sets and chases and the average distance to the next one. However, vessels

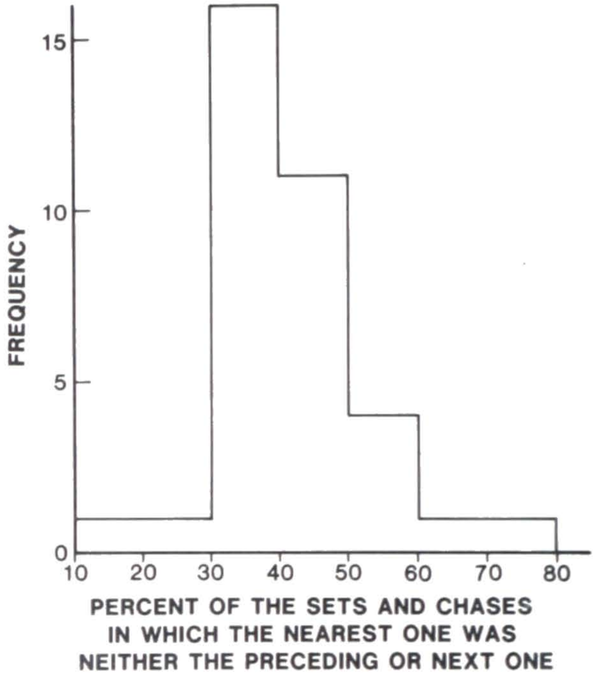

FIGURE 3.—The frequency distribution for the percentage of the sets and chases within a cruise for which the nearest other set or chase was neither the preceding or next one.

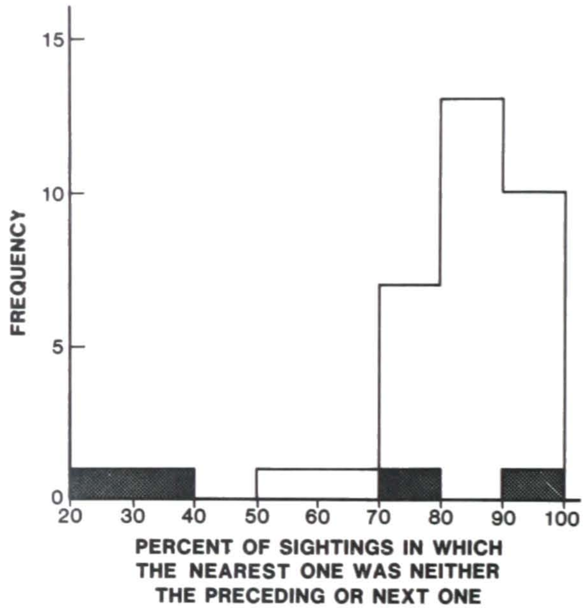

FIGURE 4.—The frequency distribution for the percentage of sightings of schools of spotted dolphins, *Stennella attenuata*, within a cruise for which the nearest other sighting was neither the preceding or next one. Shaded portions represent cruises with less than 15 sightings (note one cruise had no sightings of spotted dolphins).

with the largest distances between sets also have large average search distances, but the converse is not true (Fig. 5). The importance of dolphin fishing as compared to log and school fishing appears not to be related to these differences among cruises (Fig 6). It should be noted that the points in Figure 5 must lie above the straight line with a slope of 1.0. The expected relationship between the variables in Figure 5 depends upon both the underlying searching process and the spatial distribution of potential sets. While a positive relationship would be expected if both of these are random, a more precise definition is beyond the scope of this paper. The purpose in presenting Figures 5 and 6 is to display the range of differences in the success of vessels in locating potential fishing targets. The large variation among cruises suggests that all vessels may not be using the same searching strategy and is an important factor to keep in mind when considering the results from the clustering algorithm.

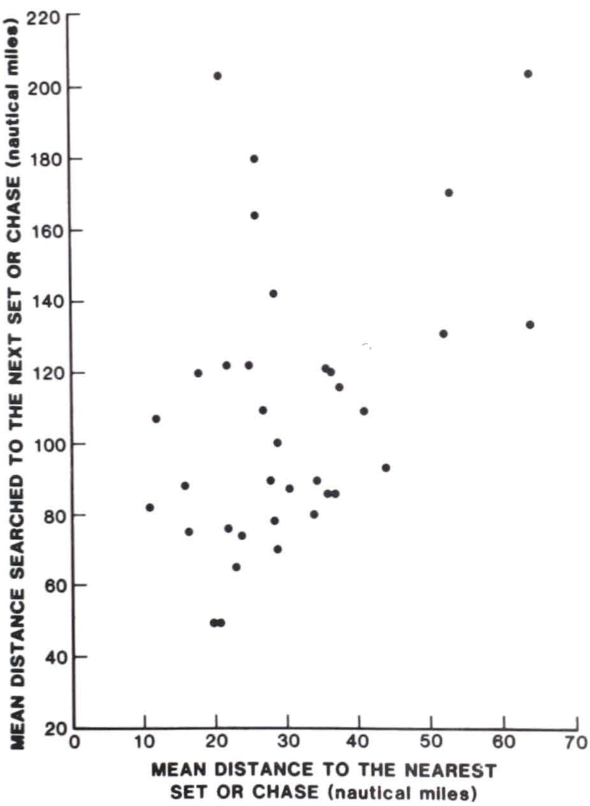

FIGURE 5.—The relationship between the average distance searched between sets and chases within a cruise and the average distance to the nearest one.

Description of Clusters

The clustering algorithm grouped between 30 and 100% of all sets and chases within a cruise into clusters with at least three members (Table 1). The percentage of all sets and chases that are included in clusters increases with the value of the cluster parameter so that 60–100% of all sets and chases within a cruise occur within 150 miles of another one. These percentages can only increase with increases in the value of the cluster parameter (i.e., a set that is included within a cluster for a lower value of the cluster parameter will always be included in a cluster at a higher value). Similarly, the average cluster size and the total percentage of the distance searched that occurs within clusters must be nondecreasing functions of the clustering parameter (Table 1). However, even when the clustering parameter equals 150 miles so that most sets occur within clusters, the percentage of the total distance searched within clusters averages only 59% of the total distance searched during the cruise. This indicates that substantial searching activity occurs far from any set or chase.

The average intercluster distance for a cruise ranged from 134 to 425 miles for clusters defined

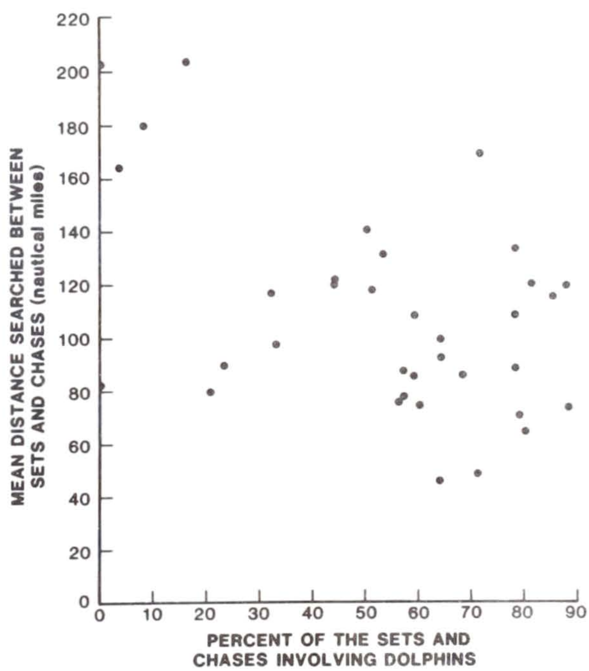

FIGURE 6.—The relationship between the average distance searched between sets and chases and the proportion of sets and chases in which schools of dolphins were associated for a cruise.

TABLE 1.—Statistics summarizing the results of the clustering algorithm showing the sensitivity to a range of values for the clustering parameter. Standard deviations are given as opposed to standard errors to provide an indication of the variation between cruises. All means are the simple average for 35 cruises.

		Cluster parameter			
		50	75	100	150
Percent of sets within clusters with at least 3 members	Mean	64	75	81	88
	SD	14.1	13.5	13.3	9.2
	Range	30–90	31–97	31–97	60–100
Average cluster radius for clusters with at least 3 members (nautical miles)	Mean	35	55	77	116
	SD	8.5	19.7	40.4	66.0
	Range	19–56	27–142	34–225	38–390
Percent of the searching within clusters with at least 3 members	Mean	25.8	39	47	59
	SD	12.6	16.4	16.1	10.6
	Range	9–61	16–91	19–91	31–91
Average intercluster distance (nautical miles)	Mean	210	261	297	356
	SD	65.9	75.9	82.2	100.9
	Range	134–425	155–465	173–513	196–691

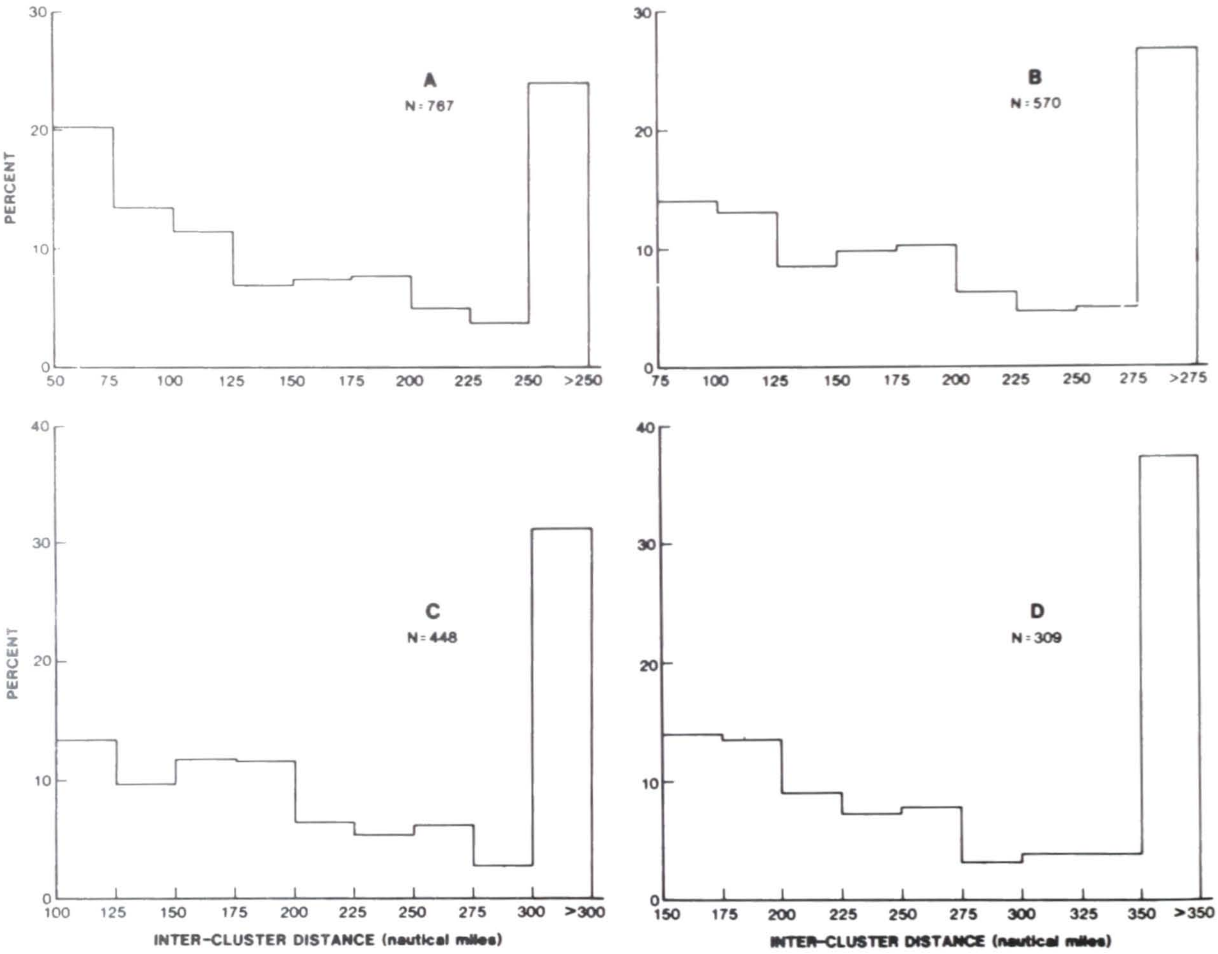

FIGURE 7.—The frequency distribution of intercluster distances. Distances from all cruises have been pooled. The values of the clustering parameter are A) 50, B) 75, C) 100, and D) 150.

by a value of 50 for the clustering parameter and from 196 to 691 miles for a value of 150 miles (Table 1). The frequency distribution of these intercluster distances (Fig. 7) is an indication of the stability of the clusters to the value of the clustering parameter. Thus, for a value of 100, over 65% of the clusters have an intercluster distance exceeding 175 miles. This suggests that 65% of clusters will be stable up to a value of 175 miles for the clustering parameter. (Note, this is not strictly true. If the set preceding the first member of a cluster was less than 175 miles away and this set was also less than 175 miles from the first set of the next cluster, this set plus these two clusters would be combined in a single cluster for a value of the cluster parameter less than 175.)

These statistics describing the characteristics of the defined clusters suggest that the algorithm used to create them successfully separates the activities of a cruise into areas where sets are common and areas where they are infrequent. The major differences in the clusters with different values for the clustering parameters result from the merging of two relatively close clusters or the inclusion of an isolated set or chase near the boundary of a cluster (e.g., for 80% of the cruises, the actual number of clusters decreases or remains the same over a range of 50–150 miles for the clustering parameter). However, the fact that many of these descriptive statistics vary continuously with the value of the clustering parameter suggests that these defined clusters do not represent distinct units, but areas of high concentration in a continuously grading system.

Cruises vary greatly with respect to the amount of variability they exhibit in response to changes in the value of the clustering parameter (Table 2). Such variability is to be expected since no single searching strategy is used by all vessels and vessels may change their strategy during the course of a cruise. In addition, the spatial distribution of potential sets probably also varies with time and space. These sources of variability among cruises, combined with the relatively small sample sizes within a cruise, may be part of the reason that the descriptive statistics characterizing clusters vary continuously with the value of the clustering parameter.

The lack of any sharp demarcation in the clusters as a function of the clustering parameter, combined with the large amount of variability exhibited among different cruises, creates a problem in presenting results based on the clustering algorithm. Consequently, whenever summary statistics are presented, results are given for a range of values for the clustering parameter.

TABLE 2.—Examples of the effect of changes in the value of the clustering parameter for 5 arbitrarily selected cruises.

Cruise	Value of the cluster parameter	Number of clusters with at least 3 members	Percent of sets and chases with clusters with at least 3 members	Average cluster radius for clusters with at least 3 members (nautical miles)	Percent of the searching within clusters with at least 3 members	Average intercluster distance (nautical miles)
1	50	4	90	32	61	171
	75	1	96	142	91	298
	100	1	96	142	91	298
	150	1	96	142	91	298
2	50	10	85	27	34	210
	75	7	97	61	60	294
	100	4	97	105	68	397
	150	4	98	126	71	443
3	50	5	30	27	9	402
	75	5	31	36	16	450
	100	5	31	46	19	479
	150	5	60	68	36	614
4	50	4	78	30	36	425
	75	4	80	39	41	465
	100	4	82	38	45	513
	150	4	82	38	45	513
5	50	1	65	45	38	302
	75	3	79	45	43	362
	100	3	79	45	43	362
	150	3	79	45	43	362

Whenever it seemed important to display the results by cruise, a value of 100 miles for the clustering parameter was used. It should be emphasized that the general patterns appear to be independent of the exact value of the clustering parameter.

Is Searching Different in Clusters?

To determine whether vessels tended to increase their searching effort in the vicinity of sets, the ratio of the total distance travelled (i.e., the distance searched plus the distance run) to the actual physical distances between sets was compared between and within clusters. This ratio is about 1.7 times greater in clusters than between clusters (Table 3). Also for no more than 7 cruises is the ratio within clusters less than the ratio between clusters (Table 3). By a sign test (Snedecor and Cochran 1967), these results imply that this ratio is significantly greater than 1.00 ($P < 0.005$).

In addition, the proportion of the total distance travelled that is devoted to searching is much greater when a vessel is between than when it is within clusters (Table 4). The fact that vessels run, and are not actively looking for tuna, proportionately more between than within clusters is an indication that clusters are areas in which a vessel has decided to remain. Vessels tend only to run at night. Usually, as long as the vessel is moving during daylight, the crew will be searching. Thus, large amounts of running tend to occur when vessels are actively moving to new areas.

TABLE 3.—Comparison between and within clusters of the ratio of the total distance travelled (i.e., distance searched plus distance run) to the actual physical distance between sets and chases. Means are the average values of the ratio for the 35 cruises being considered.

		Value of the cluster parameter			
		50	75	100	150
Between	Mean	1.79	1.70	1.65	1.59
	SD	0.064	0.062	0.060	0.065
	Range	1.24–2.70	1.13–2.71	1.12–2.68	1.11–2.81
Within	Mean	3.08	2.84	2.79	2.68
	SD	0.343	0.254	0.250	0.239
	Range	1.13–11.03	1.16–8.67	1.09–8.67	1.12–8.67
Number of cruises out of 35 in which the ratio is greater within than between clusters		[1]28	[1]31	[1]32	[1]31

[1]$P < 0.05$ of observing this many ratio greater within clusters than between if they were in fact equal based on a sign test (Snedecor and Cochran 1967).

TABLE 4.—Comparison between and within clusters of the ratio of the distance run without searching to the distance searched. Means are the average values of this proportion for the 35 cruises being considered.

		Value of the cluster parameter			
		50	75	100	150
Between clusters	Mean ratio	0.85	0.93	0.97	1.06
	SE	0.063	0.068	0.067	0.095
	Range	0.35–1.94	0.26–1.94	0.26–2.05	0.26–3.45
Within clusters	Mean ratio	0.29	0.33	0.38	0.46
	SE	0.040	0.036	0.042	0.048
	Range	0.01–0.88	0.04–0.98	0.04–1.13	0.05–1.06
Number of cruises out of a total of 35 in which the proportion is greater between clusters than within them		[1]34	[1]34	[1]34	[1]34

[1]$P < 0.001$ of observing the portion being greater between clusters than within 34 out of 35 cruises, if in fact the proportion was equal based on a sign test (Snedecor and Cochran 1967).

However, some running can still be expected within clusters because vessels mark favorable logs with radio transmitter in order to return to them at a latter time. It should be noted that three or more sets or chases rarely occur on the same day (Fig. 8). Therefore, the proportionately smaller amount of running that occurs within clusters is not an artifact resulting from clusters that do not span more than a single day.

Are Clusters Areas of High Spotted Dolphin Densities?

Encounter rates (total number of sightings of spotted dolphins divided by the total distance searched) tend to be much greater within clusters dominated by sets in association with dolphins than either within clusters dominated by non-dolphin sets or while searching between clusters (Table 5). The clustering algorithm would tend to ensure that such differences are likely to occur, but the magnitude of the differences is large and

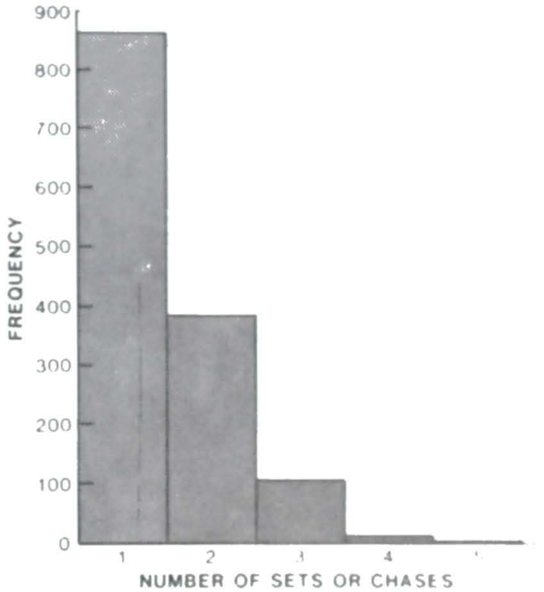

FIGURE 8.—The frequency distribution of the number of sets or chases during a day for all days on which there was at least one chase or set.

TABLE 5.—Comparison of encounter rates (number of schools of spotted dolphins, *Stenella attenuata*, per 100 miles searched) while searching within clusters classified according to the percentage of sets involving dolphins, and while searching between clusters. Unweighted means are the average value of the encounter within each cruise. Weighted means are based on the encounter rate weighted by the distance searched by a cruise and are equivalent to the total number of sightings divided by the total distance searched pooled across all vessels.

Value of the cluster parameter		Within clusters in which the percent of sets on dolphins ranged from 0–25	25–75	75–100	Between clusters
50	Unweighted mean	0.17	1.45	2.74	0.52
	SE	0.070	0.182	0.219	0.046
	Weighted mean	0.10	1.04	2.46	0.50
	SE	0.047	0.120	0.205	0.046
	Number of cruises	27	22	30	35
	Total distance searched (thousands of miles)	17.9	10.0	23.1	148.2
75	Unweighted mean	0.15	1.32	2.32	0.47
	SE	0.051	0.191	0.188	0.044
	Weighted mean	0.12	0.88	2.16	0.46
	SE	0.039	0.111	0.166	0.044
	Number of cruises	25	22	31	35
	Total distance searched (thousands of miles)	28.2	15.1	33.0	125.4
100	Unweighted mean	0.14	1.15	2.08	0.46
	SE	0.046	0.181	0.174	0.045
	Weighted mean	0.15	0.81	1.82	0.45
	SE	0.043	0.117	0.148	0.044
	Number of cruises	25	20	31	35
	Total distance searched (thousands of miles)	35.1	16.0	45.0	106.7
150	Unweighted mean	0.10	0.73	1.83	0.43
	SE	0.040	0.106	0.159	0.049
	Weighted mean	0.11	0.68	1.63	0.40
	SE	0.037	0.096	0.114	0.041
	Number of cruises	24	18	32	35
	Total distance searched (thousands of miles)	33.9	27.2	57.1	85.7

relatively insensitive to the value of the clustering parameter. However, the fact that a large percentage of the clusters tend to be dominated by either dolphin or non-dolphin sets is not a necessary consequence of the clustering algorithm and suggests that the two types of methods for locating and catching tuna tend to be spatially and temporally distinct. Encounter rates are substantially lower in clusters dominated by non-dolphin sets than when a vessel is searching between clusters (Table 5). This result is also not a necessary consequence of the clustering procedure and suggests that these clusters not only define areas of high densities of spotted dolphin schools but also areas of low densities.

Encounter rates could be lower in non-dolphin areas because of differences in detectability not related to the density of schools. For example, Hammond[4] suggested that the crew may scan closer to the vessel when searching in non-dolphin areas (see also Polacheck 1983). It seems unlikely that such factors could account for all of the differences between the encounter rates in Table 5.

Differences in detectability due to differences in weather conditions between and within clusters could also affect the results in Table 5. Encounter rates do decrease at higher Beaufort sea states (Polacheck 1983). However, little searching occurs above Beaufort state 4. The difference in encounter rates at Beaufort 0–2 compared with Beaufort 3–4 (about a factor of 1.28) is insufficient to explain the difference in Table 5 (Polacheck 1983). Moreover, areas of non-dolphin sets tend to be in nearshore areas with calmer seas and fishermen do not consider Beaufort 4 conditions as being too rough to fish.

Do Tuna Catches Differ Between and Within Clusters?

The average tons of tuna caught per set tend to be greater for sets which occur within clusters than sets between clusters (Fig. 9). For all values of the clustering parameter, the average catch per set was greater within than outside of clusters in approximately 70% of the cruises (Table 6). Parametric statistical comparisons of the average tons per set are not appropriate because of the large differences in the average catch per set among vessels (Fig. 9). A nonparametric sign test (Snedcor and Cochran 1966) suggests that the differences in catch per set between and within clusters are significant at least at the 0.05 probability level for all values of the clustering parameters that were considered.

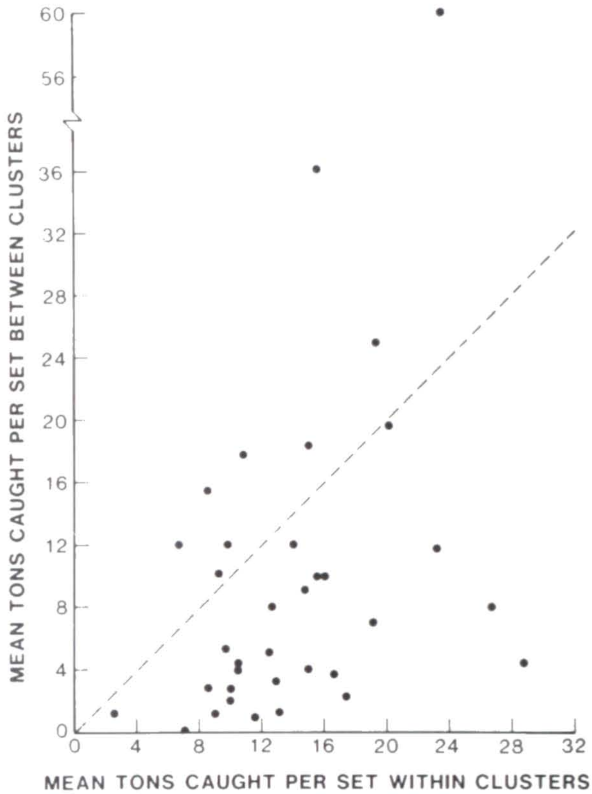

FIGURE 9.—The average tons of tuna caught per set while a vessel was travelling between clusters versus the average tons per set within clusters with at least three members. The dashed line represents the expected value if the catch rates were equal. The value of the cluster parameter equals 100.

TABLE 6.—The ratio of the tons of tuna caught per set within clusters with at least 3 members compared to tons caught per set between clusters. The means are the average values for the ratio within a cruise. Cruises in which 100% of the sets were within clusters are not inlcuded in the results.

	Value of the cluster parameter			
	50	75	100	150
Mean	1.73	2.02	2.98	2.76
SE	0.22	0.379	0.476	0.499
Range	0.41–6.83	0.23–11.18	0.39–11.68	0.43–8.43
n	35	34	34	25
Number of cruises in which ratio was greater than 1	[1]25	[1]25	[1]25	[1]19

[1]P < 0.05 of getting the observed number if the ratio equaled 1 by a sign test (Snedecor and Cochran 1966).

[4]Hammond, P. S. 1981. Some problems in estimating the density of dolphin populations in the eastern tropical Pacific using data collected aboard tuna purse seiners. Inter-Am. Trop. Tuna Comm. Intern. Rep.

Does Searching Behavior Bias the Overall Estimate of Dolphin Encounter Rates?

When the two different methods of estimating the overall encounter rates within a cruise are compared, the adjusted encounter rates tend to be smaller (Table 7). However, the differences are not large, not because the biases are necessarily small, but because positive and negative effect of concentrating searching effort tend to cancel each other. Positive biases would be expected in the unadjusted rate due to concentrating of searching effort in clusters dominated by sets made in association with dolphins, since these appear to be areas of high dolphin densities (Table 5). Similarly, negative biases would be expected due to searching in non-dolphin clusters. For the data considered here, substantial and roughly equal amounts of searching occurred in both types of clusters. The effects of concentrating searching effort within the two types of clusters tended to cancel each other. This suggests that the major effect of nonrandom searching on measures of relative abundance of dolphins will change in relationship to the importance of dolphin and nondolphin fishing. Such changes tend to occur with changes in the relative abundance of large yellowfin tuna compared to skipjack and small yellowfin tuna.

DISCUSSION

The fundamental question in interpreting the results of this paper is whether the clusters that have been defined bear any relationship either to the searching strategy of the vessels or to the underlying distribution of dolphin and tuna schools. Two factors hamper answering this question: The first is the large variability among vessels; the second is the lack of appropriate null hypotheses by which to test the results. The large variability is to be expected and is inescapable. Not only is there a large stochastic element in the catch and encounter process, but large differences can be expected in searching strategies among vessels. Thus, a large range exist in skill and experience among fisherman. In addition, the amount of information, which is shared among vessels varies and some vessels may be acting as scouts for other vessels (Orbach 1975).

The specification of null hypotheses is difficult because an infinite number of searching models are compatible with the definition of random search (i.e., defining a random search as one in which the search path is independent of the distribution of the objects being sought). In order to actually model a random searching process, the probability of changing the direction of the search path needs to be specified. A random search could encompass anything from Brownian motion to random straight line crossings of an area. With a finite amount of searching, these will not necessarily yield the same results.

Most of the results from this paper are compatible with a model of clustered searching for clustered prey, and some of them seem hard to explain unless the searching and the schools of dolphins are nonrandomly distributed. That the distance travelled relative to the actual distances between sets tends to be greater in areas where the density of sets is high, as is the proportion of this distance which is spent searching, are unlikely results unless searching is concentrated in these areas. Also, the higher encounter rates in clusters dominated by dolphins, the comparisons of the distances and frequency of the nearest set with the preceding or next set, and the high percentage of sets which fall into clusters are results that would be expected if searching, tuna, and dolphins were

TABLE 7.—Comparison between the unadjusted overall encounter rate (number of schools of *Stenella attenuata* per 100 miles of searching) for a cruise and the encounter rate adjusted for possible bias due to the concentration of searching within clusters.

	Cluster parameter	Mean	SE	Range	Number of cruises out of 34 in which the corrected estimate was less than the uncorrected one[1]
Unadjusted		0.80	0.078	0.00–1.77	
Adjusted	50	0.73	0.074	0.00–1.66	27
	75	0.74	0.074	0.00–1.60	24
	100	0.75	0.077	0.00–1.73	21
	150	0.76	0.078	0.00–1.78	21

[1]One cruise had no recorded sighting of spotted dolphin schools.

spatially clustered. Perhaps the most surprising result in this context is that the average catch per set tends to be greater within the defined clusters than outside of them. There is nothing in the clustering algorithm that would tend to produce this result. If these larger catches per set reflect large schools of tuna, this argues that these defined clusters are areas where tuna tend to concentrate and not just areas of high densities of sets that could be found in any random distribution.

Within many of the cruises, the locations of two or more of the defined clusters overlap spatially (Fig. 10), indicating that vessels often return to an area after a period of searching elsewhere. In addition, clusters from different cruises overlap spatially and temporally. This overlapping of clusters indicates that the overall searching behavior is even more nonrandom than the results from this paper suggest. The overlapping both within and among cruises is a dimension that should be considered in future extensions to the present work.

Orbach (1975), in a nonquantitative, anthropological study of the purse seine fishery, included a general qualitative description of the searching behavior of the fishermen which supports many of

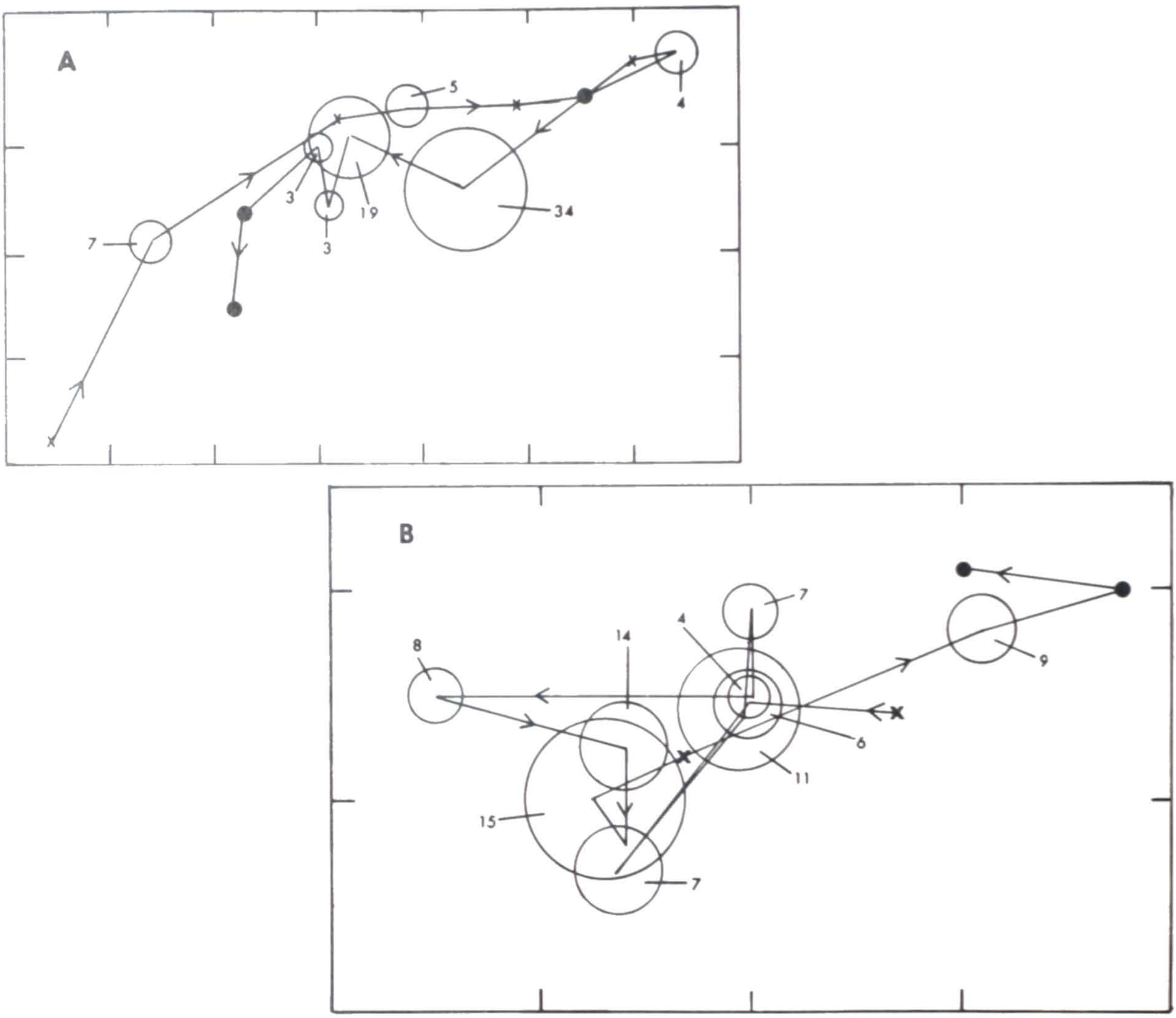

FIGURE 10.—Examples of the spatial relation between clusters for the two cruises depicted in Figure 2. Open circles indicate the position of all clusters with at least three members. The radius of each circle is scaled to the estimated radius of a cluster. The associated numbers are the number of sets and chases within a cluster. Solid circles indicate the position of clusters with only two members. Isolated sets are indicated by an ×. The value of the clustering parameter equals 100. Arrows indicate the order of movement between clusters. Note A and B are drawn to different scales. Distance between tick marks equals 300 miles. No geographic coordinates are given and the orientations were rotated at random so as not to compromise any proprietary fishing information.

the quantitative results in this paper. He stated that fishermen perceive two kinds of areas: The first, in which fishermen refer to their activity as "scratching", are regions where isolated schools of fish are encountered; the second, which fishermen refer to as an "area", are portions of the ocean where schools of tuna are congregated. He also reported that isolated tuna schools tend to be small. Fishermen prefer to concentrate in an "area" and actively search for them. I did not become aware of this study by Orbach until the final calculations of this paper were completed. Thus, his description is an independent indication that the results are not an artifact of the clustering algorithm.

The method used for estimating the location and size of a cluster could be refined. Such refinements were beyond the scope of the present work and would not affect any of the main results. However, such refinements might be important if the method used for calculating the adjusted encounter rates (Table 7) was used to develop relative abundance indices for dolphins in the ETP. As pointed out by one reviewer, the problem of estimating the shape, size, and location of a cluster is analogous to the problem of determining the home range for an animal from a set of observed positions over time (Sanderson 1966; Cooper 1978; Schoener 1981; Swihart and Slade 1985) and is part of the more general problem of how to estimate the limits and size of clusters from any clustering algorithm. The methods used for estimating home ranges cannot be directly applied to the tuna boat observer data but might provide a basis for developing a better estimator for these statistics relating to cluster size in any extension to the present work.

To the extent that the results from this paper indicate that searching is clustered, they suggest that when these data are used for estimating relative densities of dolphin schools, or when catch and effort data from purse seiners are used to assess tuna stocks, rather fine geographic stratifications are needed to avoid biases from the nonrandom searching within a cruise. The estimates of the cluster radius could be considered as a guide to appropriate levels of stratification. For example, from 31 to 46% of all clusters with at least three members had a radius of less than 60 miles (Fig. 11). This suggests that at a minimum,

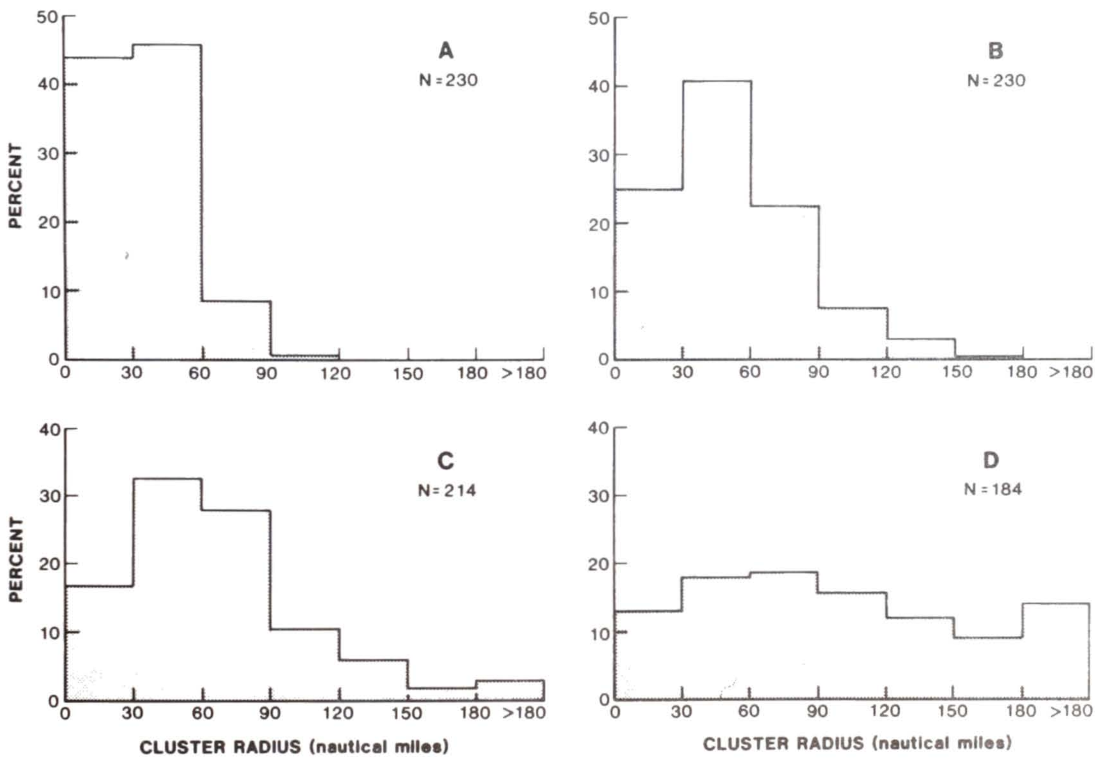

FIGURE 11.—The frequency distribution for estimated radii for all clusters with at least three members. Estimates from all cruises have been pooled. The values of the clustering parameter are A) 50, B) 75, C) 100, and D) 150.

a 2° stratification would be necessary to avoid biases in these areas.

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