

ESTIMATING DENSITY OF DOLPHIN SCHOOLS IN THE EASTERN TROPICAL PACIFIC OCEAN BY LINE TRANSECT METHODS

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ABSTRACT

Data were collected from aerial and research ship surveys to estimate density of dolphin schools in the eastern tropical Pacific using line transect (LT) theory. The surveys were conducted from 1977 through 1983. Several assumptions of LT theory were investigated for both aerial and ship data. Factors were developed to alleviate effects of suspected violations of the assumptions. I estimated densities from data stratified into an inshore area surveyed by planes and an offshore area surveyed by ships. The density estimate for the inshore area was 4.18 schools/1,000 km² and 2.04 for the offshore area. For the entire area, the density estimate was 2.71 schools/1,000 km². Adjustments for possible biases owing to adverse sea state and sun glare conditions increased the inshore estimate by 8% and the total area estimate by 4%.

The National Marine Fisheries Service (NMFS) is responsible for assessing the status of those dolphin stocks taken incidentally by tuna purse seiners in the eastern tropical Pacific (ETP) Ocean. Techniques used to assess these stocks (Smith 1979²) require estimates of school density, so density estimates were made in 1975 (Smith 1975³) and in 1979 (Holt and Powers 1982). Since 1979, NMFS has collected additional information to test the assumptions of its statistical methods and to further survey the areas inhabited by the dolphins. In this paper, I present analyses of data collected from 1977 through 1983 to determine density estimates of dolphin schools in the ETP. In addition, I investigate several factors which may bias the estimates.

To obtain estimates of density of dolphins (individuals) it is further necessary to consider school size, the proportions of various species in mixed schools, and areas inhabited by the various stocks. Estimation of these factors is complex; they are to be dealt with elsewhere and are not addressed in this paper.

MATERIAL AND METHODS

Surveys

Data used to calculate the density of dolphin schools were collected during several years. Aerial surveys were conducted in 1977 and 1979 (Fig. 1), and nine research ship cruises were made during 1977, 1979, 1980, 1982, and 1983 (Fig. 1). Most surveys were conducted between January and early April; one of the 1977 ship cruises was made in October and the two 1980 cruises were made from May through August.

A two-engine PBY amphibious patrol bomber was used in the 1977 aerial survey (SWFC 1978⁴), and a four-engine PBY bomber was used in the 1979 aerial survey (Jackson 1980⁵). Operating and viewing conditions aboard the two aircrafts were similar. Both planes cruised at 148-240 km/hour (80-130 kn) and had bubble-shaped waist windows. The PBY used in 1977 had a flat bow window which was shaped like an isosceles trapezoid. The 1979 PBY had a round bubble-shaped bow window. The round bubble window allowed

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²Smith, T. 1979. Report of the status of porpoise stocks workshop (August 27-31, 1979). Southwest Fish. Cent. Adm. Rep. No. LJ-79-41, La Jolla, CA, 120 p.

³Smith, T. 1975. Estimates of sizes of two populations of porpoise (*Stenella*) in the eastern tropical Pacific Ocean. Southwest Fish. Cent. Adm. Rep. No. LJ-75-65. La Jolla, CA, 88 p.

⁴SWFC (Southwest Fisheries Center). 1978. Aerial survey trip report, January-June 1977. Southwest Fish. Cent. Adm. Rep. No. LJ-78-01, 73 p. National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

⁵Jackson, T. 1980. Report: Porpoise population aerial survey of the eastern tropical Pacific Ocean, January 22-April 25, 1979. Southwest Fish. Cent. Adm. Rep. No. LJ-80-01, 74 p. National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

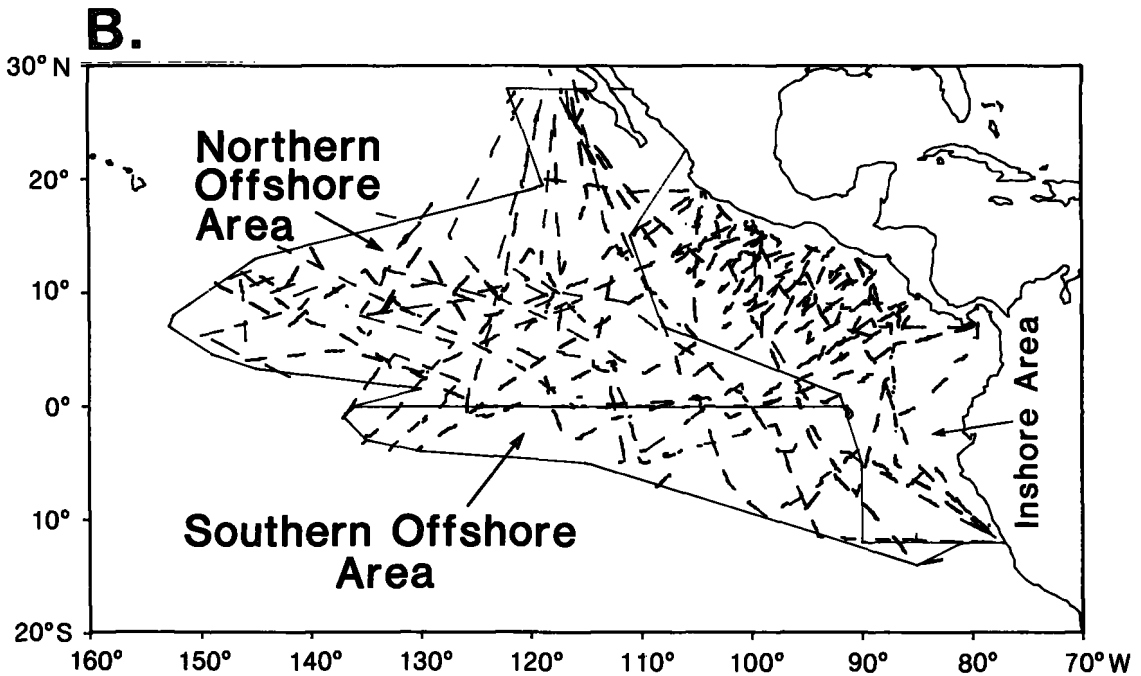
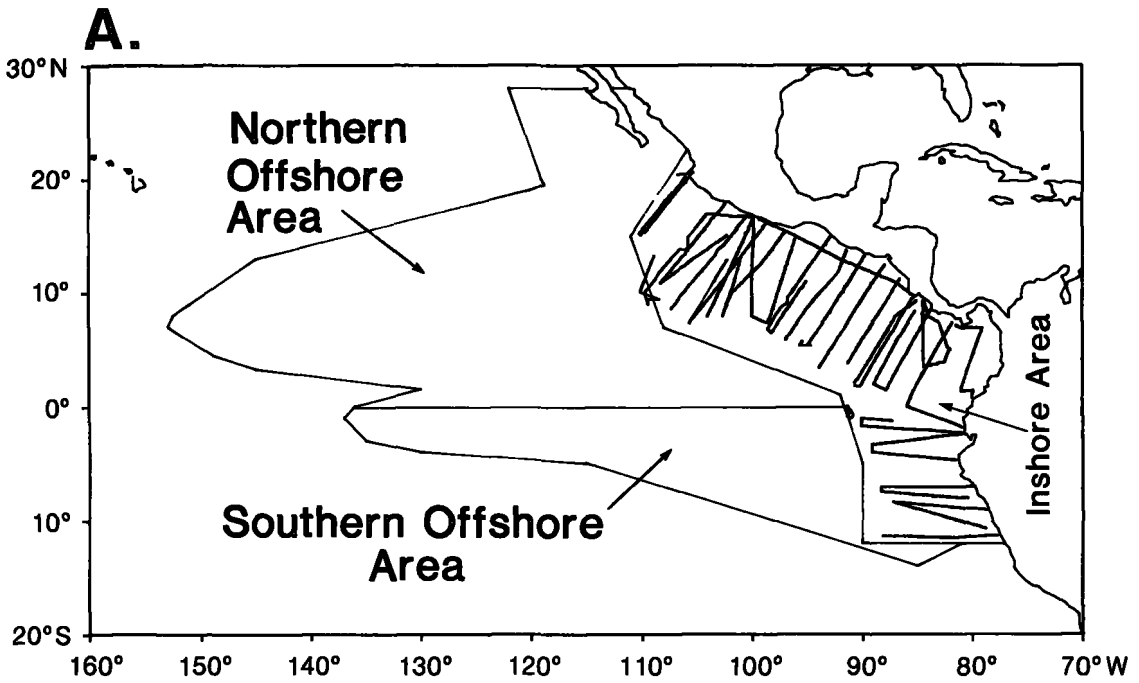


FIGURE 1.—Tracklines for 1977 and 1979 aerial (A) and combined 1977, 1979, 1980, 1982, and 1983 ship (B) surveys.

better lateral viewing, but both provided unobstructed forward and downward views.

Two research vessels were used to collect the shipboard data. The NOAA ship *David Starr Jordan* was used during all years and the NOAA ship *Townsend Cromwell* joined it in 1977, 1979, and 1980. Both vessels were similar in length and cruising ability. Binoculars used to locate animals were mounted approximately 10.7 m above the sea on the *Jordan* but were only 6.1 m above the sea on the *Cromwell*. In addition, observers aboard the *Jordan* used 20 \times binoculars during the 1977 surveys and 25 \times glasses on the rest of the surveys; observers aboard the *Cromwell* used only 20 \times glasses during their surveys. Consequently, viewing conditions were generally much better on the *Jordan*.

Study Area

Survey efforts traversed the combined range of ETP dolphin stocks defined by Au et al. (1979)⁶. The range was partitioned into "inshore" and "offshore" areas (Fig. 1). Airplanes were used to survey the inshore area, and ship surveys were conducted in both areas during each year, except during 1977 when ships surveyed only the offshore area.

Data Collection

Aerial Data

Data collecting procedures used during the aerial surveys are described by SWFC (fn. 4), Jackson (fn. 5), Holt and Powers (1982), and Cologne and Holt (1984)⁷. As the airplanes traversed predetermined tracklines (Fig. 1), the observers recorded schools on and to either side of the lines. Observers searched through the bow window and from windows located on either side of the plane. The bow observer was responsible for detecting schools on the trackline (a path underneath the plane 0.19 km wide). The searching mode was halted if environmental or oceanographic conditions restricted the observer's view of the trackline or when the plane was diverted from the trackline for closer examination of a

school. Additional schools detected during these diversions were not included in the density analysis.

Sea conditions were measured on the Beaufort scale (Bowditch 1966), which ranged from very flat, glassy seas (Beaufort 0 conditions) to rough seas with numerous large, white-capped waves (Beaufort 5 conditions). Sun location was described by horizontal and vertical position relative to the bow observer (Holt 1983a). These were recorded for each segment of effort.

Biological and environmental data were recorded at each sighting (Holt and Powers 1982). Data included species identification, school size estimates, sea state, sun position, and perpendicular distance to the school from the trackline. School size estimates consisted of an observer's "best" estimate plus an estimate of the minimum and maximum range.

Ship Data

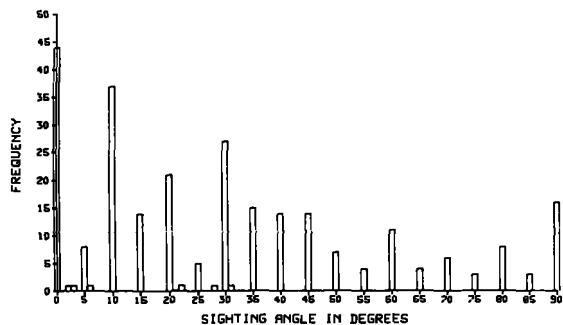
Shipboard collection procedures are described in the various cruise reports (unpublished documents available from the SWFC) and by Holt (1983b). Procedures and data recorded on shipboard surveys were similar to those for aerial surveys. Two observers used binoculars located on each side of the ship to search from directly ahead to abeam of their respective sides of the ship. Starting in 1979, sea state was recorded at the beginning of each effort segment (leg). Sun position was recorded during the 1982 and 1983 ship surveys.

The bearing (θ) and radial distance (r) to a school from the ship were recorded, and perpendicular distance (y) was then calculated as $y = r \sin \theta$. In surveys conducted before 1980, observers rounded estimates of sighting angles to multiples of 5° or 10°, and radial distances to multiples of 185 m (0.1 nmi) within the first 1.85 km (1 nmi), and to 0.93 km (0.5 nmi) multiples at larger distances (Fig. 2). During training, observers on the 1980 surveys were told of previous rounding inaccuracies and instructed to make estimates as precise as possible. However, they were still unable to make precise visual estimates of angles and distances for schools recorded at great distances from the ship (Fig. 2). During the 1982 and 1983 surveys, estimates of bearing were recorded using a 360° graduated washer attached to the base of the binoculars, and the radial distances were measured using a graduated reticle enclosed in the right eyepiece of the binoculars (Holt 1983b).

⁶Au, D., W. Perryman, and W. Perrin. 1979. Dolphin distribution and the relationship to environmental features in the eastern tropical Pacific. Southwest Fisheries Center Status of Porpoise Stocks working paper SOPS/79/36. 59 p.

⁷Cologne, J., and R. Holt. 1984. Observer effects in shipboard sight surveys of dolphin abundance. Southwest Fish. Cent. Adm. Rep. No. LJ-84-30, 42 p. National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

1979



1980

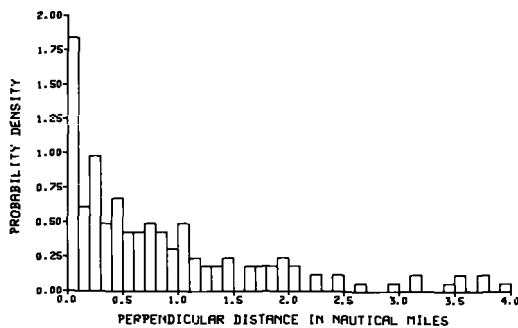
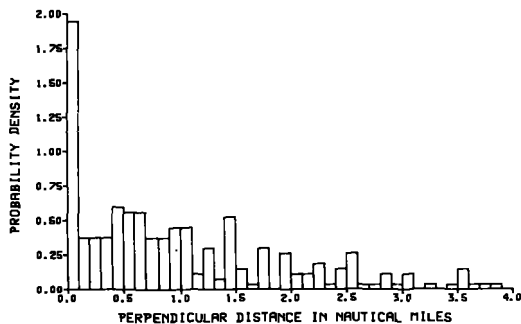
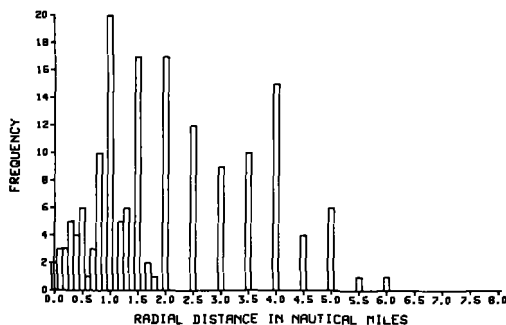
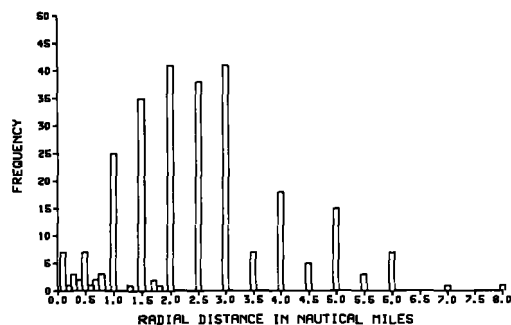
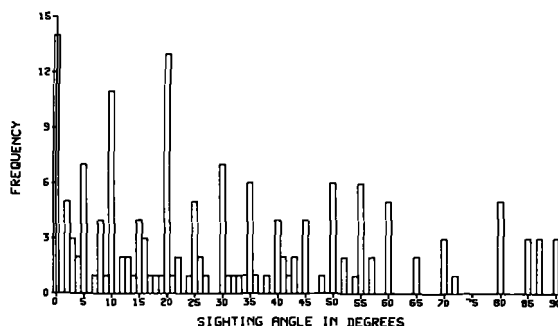


FIGURE 2.—Distribution of sighting angle, radial distance, and perpendicular distance from 1979, 1980.

With this system, the rounding to convenient values was not as evident (Fig. 2); however, measurements may still be inaccurate.

ANALYTICAL METHODS

Vessel data for area, sea state, sun glare, and observer performance strata were compared using rates of detection for all schools encountered within 2.13 km perpendicular distance of the ship (schools/1,000 km searched) and estimates of density of schools (schools/1,000 km²).

Similar comparisons of aerial data were completed using rates of detection for all schools encountered within 1.85 km perpendicular distance of the trackline, rates of detection for trackline schools, and estimates of school density.

Density estimates were made using line transect (LT) theory (Burnham et al. 1980). The basic equation (Seber 1973) is

$$D = \frac{n f(0)}{2L}$$

1982

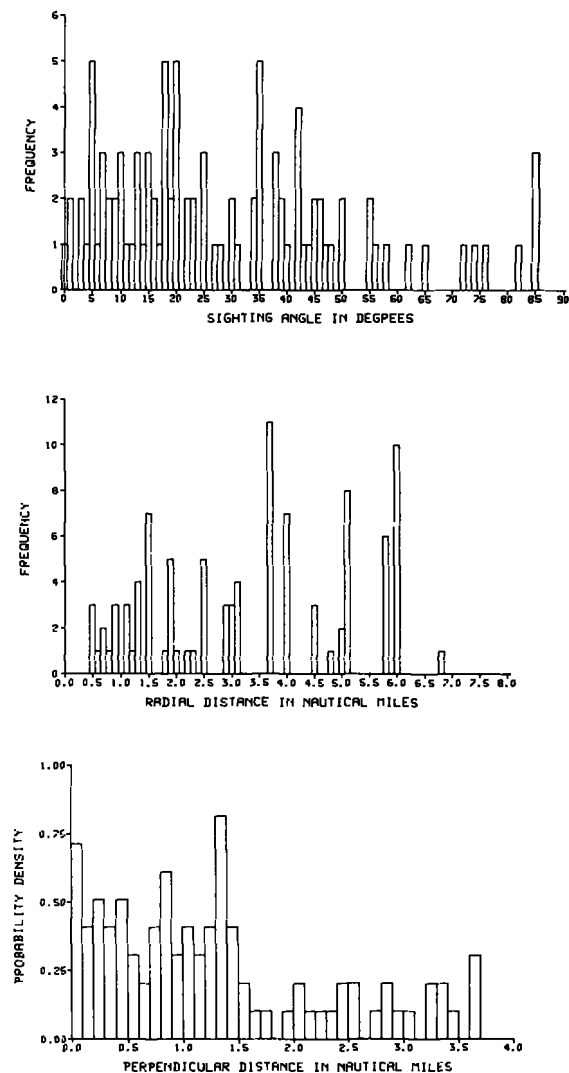


FIGURE 2.—Continued—and 1982 ship data.

where n is the number of schools sighted, D is the density of dolphin schools per km^2 , L is the total linear distance searched (km), and $f(0)$ is a probability density function (*pdf*) evaluated at perpendicular distance, $x = 0$. The Fourier series (FS) model (Crain et al. 1979) was used to estimate $f(0)$ based upon criteria developed by Burnham et al. (1979). Burnham et al. (1980) is recommended for a full presentation of the FS model and for variance estimation.

Several assumptions must be met for valid use of LT theory. I investigated three of them for this

study: 1) schools directly on the trackline are never missed, 2) schools do not move in response to the approaching ship or plane; and 3) no systematic measurement errors occur. All three assumptions have been made in analyzing previous aerial survey data (Holt and Powers 1982); however, field studies have subsequently been conducted to investigate the ability of observers to detect trackline schools (Holt 1983a), and whether or not dolphins avoid approaching ships (Au and Perryman 1982; Hewitt 1985). In addition, assumption 3 was not accepted because an inordinately large number of schools detected from the ships was recorded on the trackline.

Data Treatment

All species of dolphins encountered in the study area were included in the analyses. Of these, only schools with a mean minimum or mean best estimate of more than 14 animals were used because my field experience indicated that the probability that all animals in a school of at least this size would be submerged at one time, and hence undetectable, was very small. In addition, species affected by the fishery generally occur in schools with more than 14 animals.

During the first 18 of 20 flights of the 1979 aerial survey, two independent teams of three observers each searched for dolphin schools. Members of each team always searched for dolphins during the same time, alternating with the other team.

For aerial and 1979-83 ship data, observers recorded sea state conditions according to individual Beaufort, but during analyses, I grouped the data into 1) a "calm" sea state category: seas without whitecaps (Beaufort conditions 0-2) or 2) a "rough" sea category: seas with whitecaps (Beaufort conditions 3-5). Data for Beaufort conditions >5 were omitted from the analyses. The presence of whitecaps was important because animal splashes were used as sighting cues during calm conditions but could not be easily distinguished from whitecaps during rough conditions.

For aerial data and 1982-83 ship data, sun glare effects were investigated by classifying effort at various sun positions into "good" and "poor" categories depending on the amount of sun glare on the trackline (see Holt⁸ for method used

⁸Holt, R. 1984. Testing the validity of line transect theory to estimate density of dolphin schools. Southwest Fish. Cent. Adm. Rep. No. LJ-84-31, 56 p. National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

to record position of sun relative to the platform and for criteria used to define sun categories for aerial data). Criteria used for ship data were based upon observations recorded during a subsequent ship survey (Hohn⁹). Hohn found poor sun conditions on the trackline only when horizontal sun position was 12 and vertical position was 1, 2, or 3 or when clouds were accompanied by fog or rain. All other effort was defined as occurring during good conditions.

In order to apply the Fourier series (FS) model to aerial and ship data, I structured the data by 1) selecting appropriate interval widths for grouping the perpendicular sighting distributions (data cutpoints), 2) choosing a maximum observation distance perpendicular to the trackline (truncation point), 3) developing criteria to select the appropriate number of terms for the FS model, and 4) choosing the type of transformation to use in compensating for measurement error in the shipboard data.

Based on a subset of the ship data (Holt¹⁰), I used an interval width of 0.37 km (0.2 nmi) and truncated the perpendicular distance distributions at 3.7 km (2.0 nmi). Since perpendicular distance distributions for the ship data, and also to a lesser extent for aerial data, have very prominent modes or "spikes" at the origin, existing criteria to select the appropriate number of terms in the FS model were unsatisfactory. Therefore, I selected the model which provided the best visual fit to the distributions near the origin (Holt fn. 10). This technique was easily applied and was consistent among data sets. For use of the technique I assumed that the sizes of the spikes near the origins of the perpendicular distance distributions were indicative of relative density among the data sets. To minimize the effects of recording errors, the data were smoothed using the technique "smearing" (Butterworth 1982; Hammond 1984).

Based on previous investigations of aerial data (Holt and Powers 1982), I selected a truncation point of 1.94 km (1.05 nmi) and an interval width of 0.19 km (0.1 nmi) for the aerial data. I used the same technique as used for ship data to select the appropriate number of terms in the FS models;

⁹A. Hohn, Southwest Fisheries Center La Jolla Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038, pers. commun. January 1985.

¹⁰Holt, R. 1984. Estimation of density of dolphin schools in the eastern tropical Pacific Ocean using line transect methods. Southwest Fish. Cent. Adm. Rep. No. LJ-84-32, 72 p. National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

however, the aerial data were not smoothed because there was no evidence that the data contained estimation errors as did the ship data.

An estimate of density in the total area (\hat{D}_c) was calculated by combining the aerial inshore (\hat{D}_i) and ship offshore (\hat{D}_0) density estimates weighted by the relative sizes of the inshore (A_i) and offshore (A_0) areas as

$$\hat{D}_c = \frac{\hat{D}_i A_i + \hat{D}_0 A_0}{A_i + A_0}$$

The estimate of variance of \hat{D}_c is

$$\text{Var}(\hat{D}_c) = \frac{A_i^2 \text{Var}(\hat{D}_i) + A_0^2 \text{Var}(\hat{D}_0)}{(A_i + A_0)^2}$$

RESULTS

Factors Affecting Density Estimates

Aerial Data

Density estimates for the aerial data in the inshore area during calm seas or with minimal sun glare were more than twice the estimates for data taken during rough seas or poor sun conditions (Table 1). Differences in estimators were even greater for sea state and sun glare interaction effects. These differences may have occurred because observers failed to detect trackline schools during poor conditions or because sea state conditions were spatially confounded with distance from shore. Therefore, these differences may be reflecting a decreasing onshore-to-offshore density gradient. This was investigated by partitioning the inshore aerial data into "coastal" and "offshore" bands for each Beaufort sea state (Fig. 3) and sun glare condition (Fig. 4). Sufficient data were not available in each band to stratify detection rates by each sun and sea state interaction category.

Sea conditions during the aerial surveys were rougher offshore than nearshore. More searching was done in the coastal band during low Beaufort states, whereas more searching was done in the offshore band at higher Beaufort states (Fig. 3). The rates of detecting dolphin schools were higher at each corresponding Beaufort state in the coastal band than in the offshore band (Fig. 5). The rates of detecting trackline schools were generally higher in the coastal band; however, these rates were based upon very few

TABLE 1.—Estimates of school density made during all conditions and during calm and rough seas using aerial and ship data; estimates made during good and poor sun condition using aerial data. Estimates are made for data in the inshore, offshore and total areas. Estimates for all conditions were calculated using 1977 through 1983 data and estimates for sun and sea state conditions were calculated using 1979 through 1983 data. Estimates are also presented for data collected during an aerial experiment testing effects of sea state and sun glare.

Variable	Distance searched (km)	Number schools detected (n)	Density (\bar{D}) (schools/1,000 km ²)	SE (D)	CV (D)
Inshore area					
Aerial data					
all data	34,006	152	4.18	0.902	0.216
calm seas	8,920	70	8.48	2.198	0.259
rough seas	25,086	82	2.71	0.611	0.255
good sun	11,994	74	6.57	1.504	0.229
poor sun	22,012	78	2.87	0.505	0.176
calm-good	3,026	30	12.64	5.290	0.418
calm-poor	5,894	40	6.24	2.311	0.370
rough-good	8,967	44	4.29	1.202	0.280
rough-poor	16,118	38	1.78	0.460	0.258
Ship data					
all data	27,840	379	4.47	0.514	0.115
calm seas	8,008	170	7.32	1.259	0.172
rough seas	14,668	149	4.05	0.772	0.191
Offshore area					
Ship data					
all data	46,567	322	2.04	0.263	0.129
calm seas	4,623	72	4.91	1.414	0.288
rough seas	20,976	99	2.01	0.435	0.217
All areas					
Ship data					
all data	74,407	626	2.95	0.253	0.086
calm seas	12,631	242	6.53	0.991	0.152
rough seas	35,644	248	3.02	0.445	0.147
Holt (text fn. 10) aerial experiment					
calm-good	1,414	37	29.18	7.357	0.252
calm-poor	3,014	81	23.78	5.888	0.248
rough-good	1,886	42	39.42	8.193	0.208
rough-poor	5,467	103	20.16	4.513	0.224

schools (18 trackline schools in the coastal and 10 schools in the offshore band were detected). Lower offshore estimates for data recorded under the same Beaufort state were consistent with a decreasing onshore-offshore density gradient.

Within each band, sea state conditions were also spatially stratified because the lower Beaufort conditions occurred mostly in the nearshore and northern regions of each band (Fig. 3). Predictably, detection rates for all schools within each band declined as the Beaufort condition increased. Because of the large variability inherent in small sample sizes and spatial stratification of searching effort at the various Beaufort condi-

tions, comparisons of rates of detecting trackline schools did not yield consistent trends. For example, within both bands, the trackline detection rate for Beaufort 2 conditions was larger than for Beaufort 1 conditions. In the coastal band Beaufort 5 conditions had higher trackline detection rates than Beaufort 4 conditions and rates for Beaufort 4 were higher than rates for Beaufort 3 (Fig. 5).

Searching effort for aerial data during good and poor sun conditions was also confounded with distance from shore (Fig. 4) and thus with sea conditions. Most good sun conditions (78%) occurred in the coastal band, whereas 59% of all poor sun

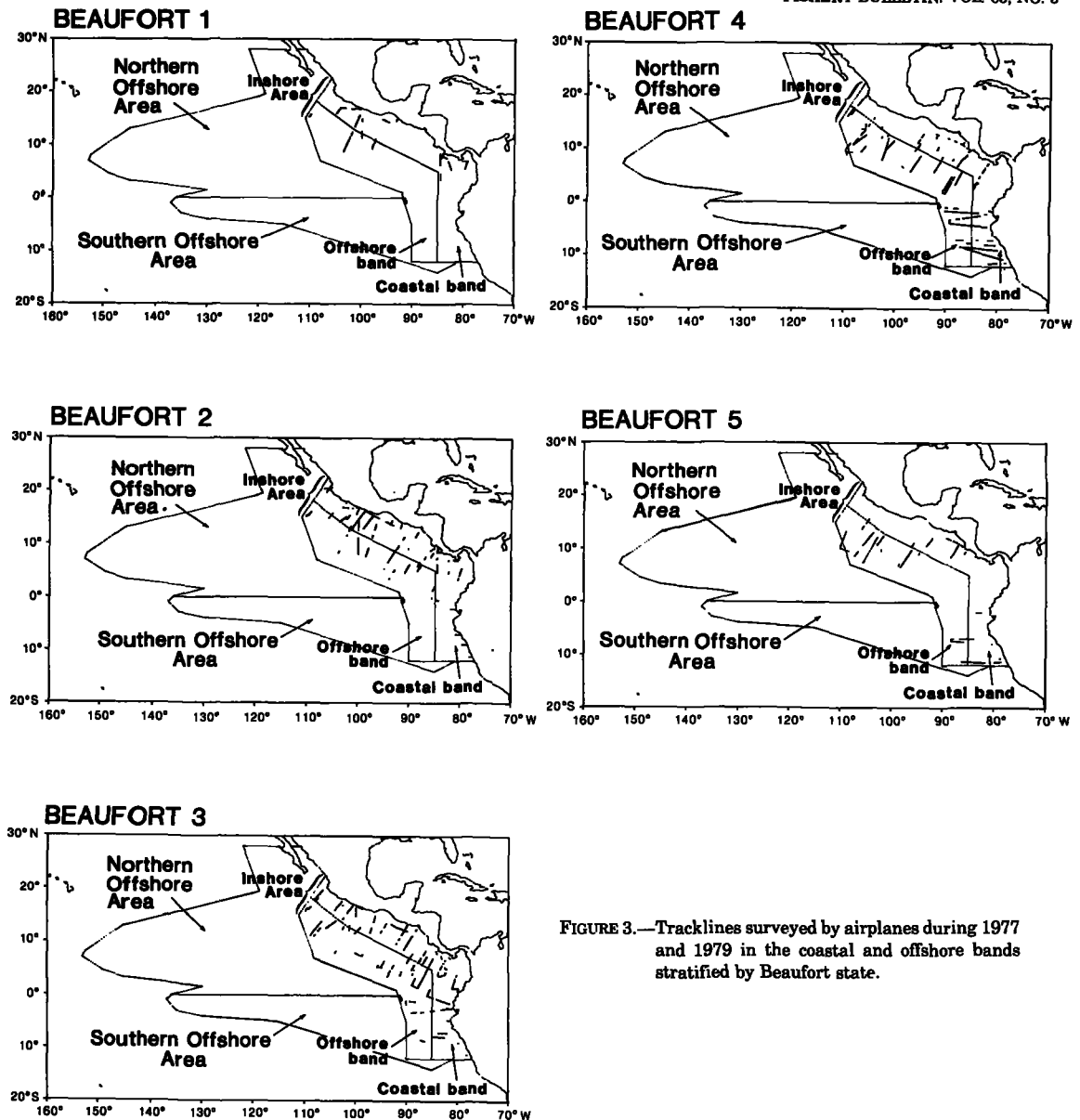


FIGURE 3.—Tracklines surveyed by airplanes during 1977 and 1979 in the coastal and offshore bands stratified by Beaufort state.

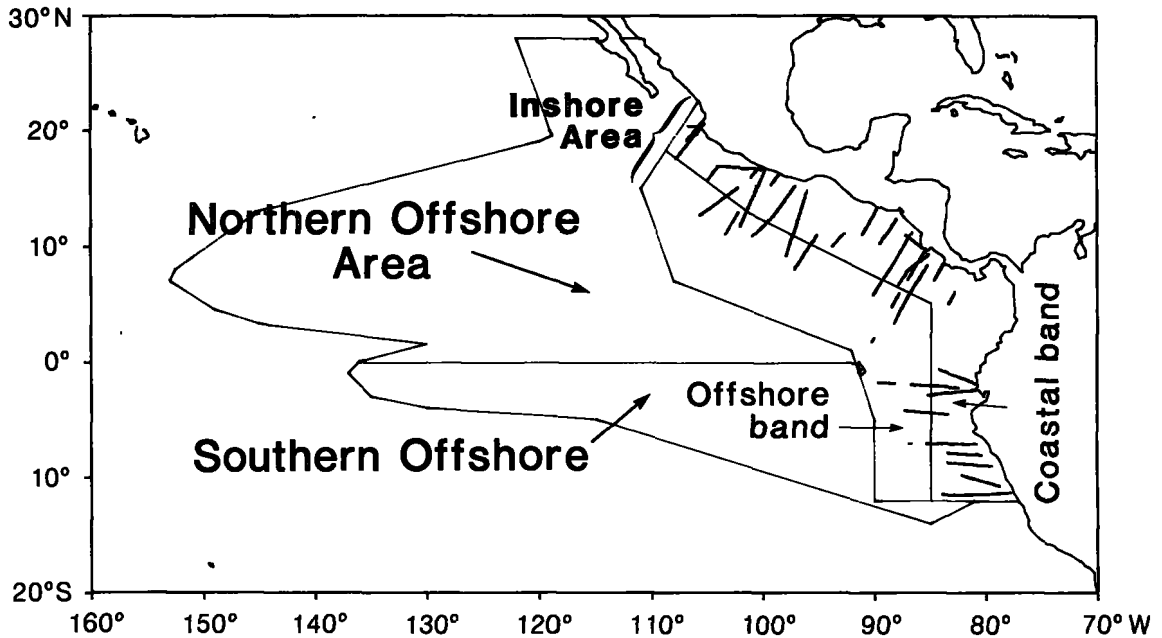
conditions occurred in the offshore band. This was because the general searching pattern was to begin searching on the westward, outbound leg in the morning, and then to turn the aircraft near noon and reach shore in late afternoon or night. Thus the sun was directly overhead or in front of the plane in the offshore reaches of the track and behind the plane in the nearshore areas.

Detection rates during good and poor sun conditions were higher in the coastal band than in the offshore band (Fig. 5), which was consistent with

a hypothesized decreasing density gradient. Within the coastal band, detection rates during good sun conditions were greater than during poor sun conditions, but most of the poor sun data was gathered in the westward portion of the band (Fig. 4). In the offshore band, trackline detection rates during good and poor sun conditions were similar, but the rate during good sun conditions was based upon three sightings and only 8% of the effort.

Finally, I compared data collected by the ob-

A. GOOD SUN



B. POOR SUN

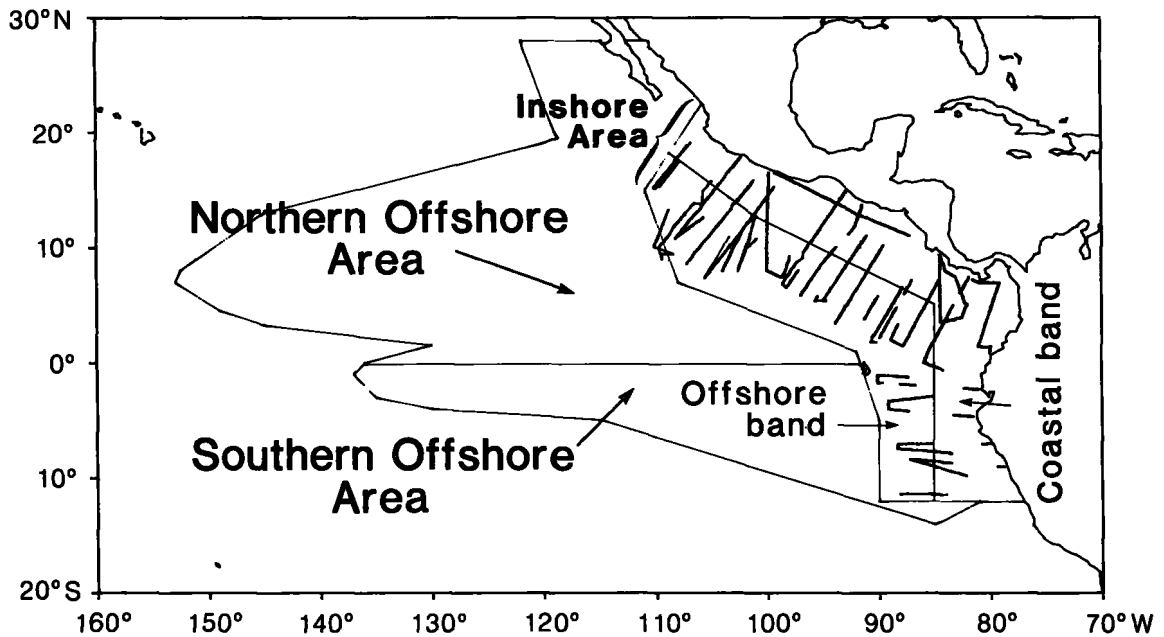


FIGURE 4.—Tracklines surveyed by airplanes during 1977 and 1979 during (A) good and (B) poor sun glare conditions in the coastal and offshore density bands.

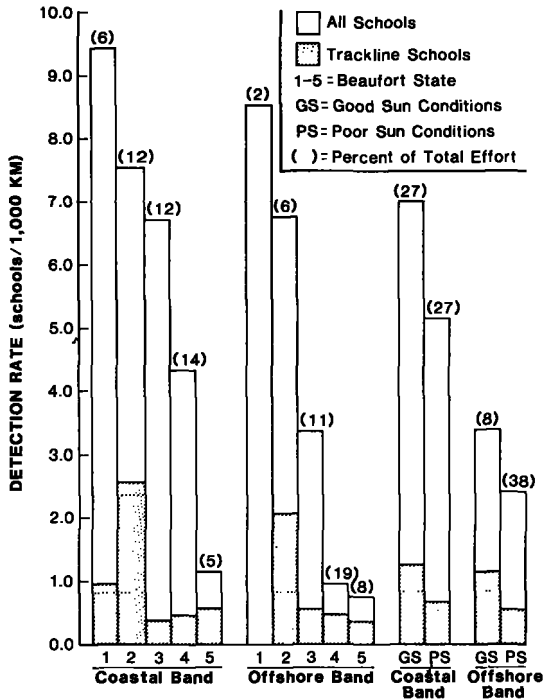


FIGURE 5.—School detection rates for aerial data in the coastal and offshore density bands for sea state and sun glare categories.

server teams to determine relative effects upon the density estimates. Team 1 and Team 2 searched approximately equal lengths of trackline (46% and 54% of the effort, respectively). No difference in performance of the two teams was evident: their rates of detecting schools, both on and off the trackline, and their estimates of school densities were approximately equal (Fig. 6).

Ship Data

The rates of detecting dolphins were greater during calm seas than during rough seas for the ship surveys from 1979 through 1983 (Fig. 7). The detection rate of dolphins during calm seas was more than twice the rate during rough seas in both the inshore and offshore areas. The ratio of calm sea to rough sea detection rates was larger in the offshore area than in the inshore area.

The offshore area was surveyed during rougher seas more than the inshore area (Fig. 8); seas were calm in the offshore area during only 17% of the effort as opposed to 35% for the inshore area surveys (Fig. 7). Dolphin density was lower offshore as indicated by lower offshore detection

rates than inshore rates during either calm or rough seas (Fig. 7). The inshore-to-offshore-area detection ratios were 1.5 during calm seas and 2.0 during rough seas.

Sun glare had little effect on the shipboard estimates during either year because poor sun conditions occurred only during 6% of the 1982 and 8%

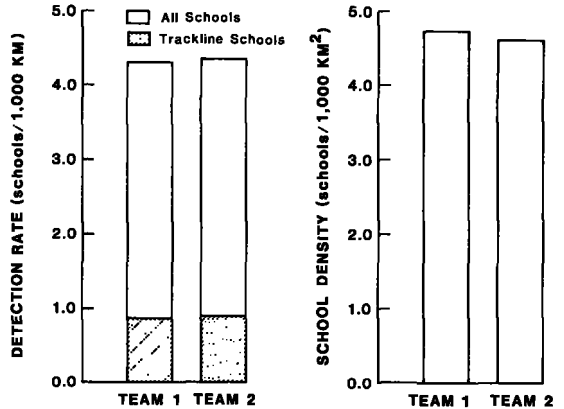


FIGURE 6.—School detection rates and density estimates for observer teams during the 1979 aerial survey.

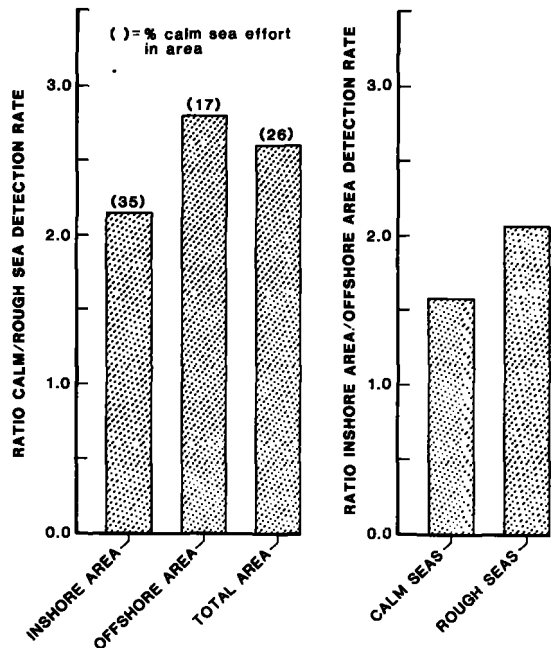
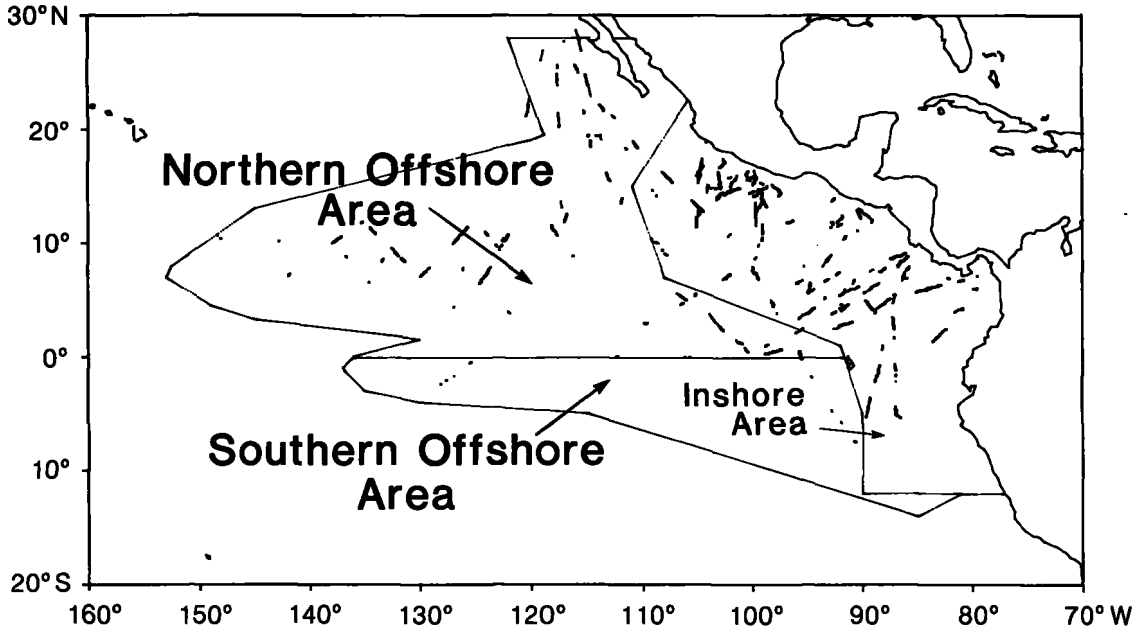


FIGURE 7.—Ratio of 1979-83 shipboard school detection rates for different sea states (calm sea versus rough sea) and area (inshore versus offshore). Detection rates computed with perpendicular distance data truncated at 2.1 km.

A. CALM SEAS



B. ROUGH SEAS

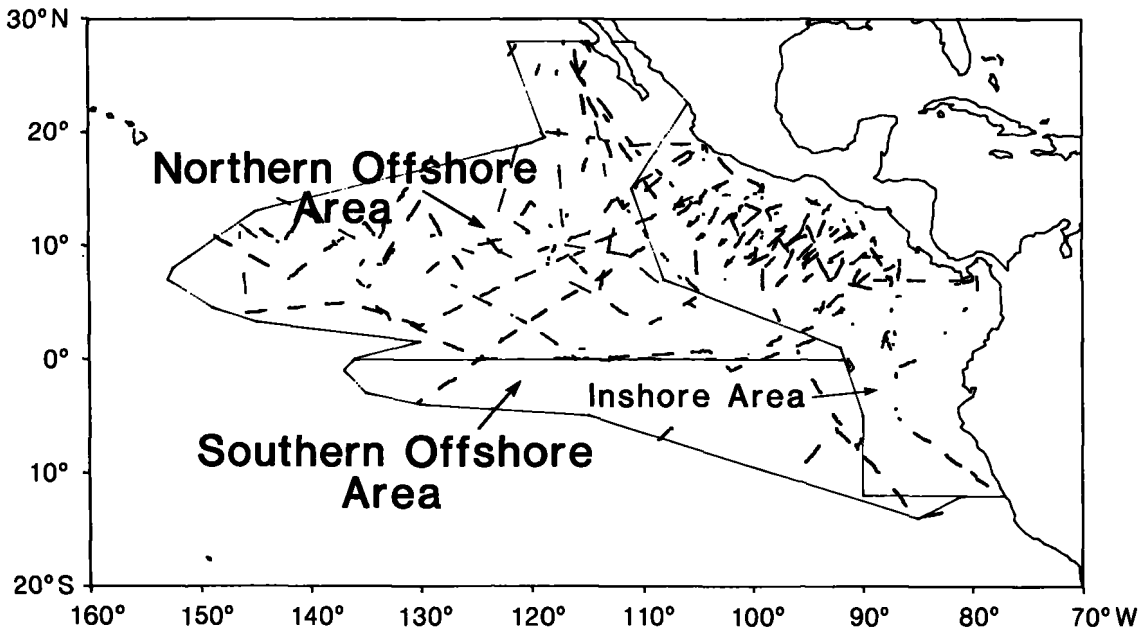


FIGURE 8.—Distribution of searching effort for the 1979-83 ship surveys during (A) calm and (B) rough conditions.

of the 1983 surveys. However, rates of detecting schools during good sun conditions were larger than during poor conditions (Fig. 9) and no schools were detected on the trackline during poor conditions.

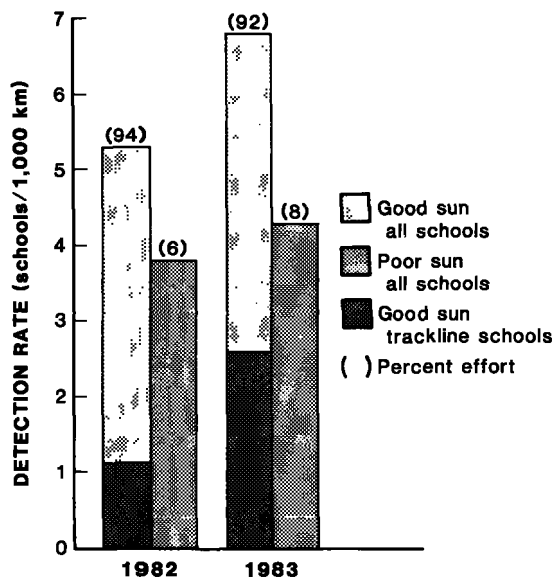


FIGURE 9.—School detection rates and relative density estimates during good and poor sun glare conditions for 1982 and 1983 ship data.

Density Estimates

Inshore Area

Aerial observers during the 1977 and 1979 surveys searched 34,006 km and detected 152 dolphin schools in the inshore area (Table 1). The estimate of school density using aerial data was 4.18 schools/1,000 km² with a standard error of 0.902.

From 1977 to 1983, shipboard observers searched 27,840 km in the inshore area and detected 297 schools (Table 2). Ship data yielded an estimate of density for the inshore area of 4.47 schools/1,000 km² with a standard error of 0.514 (Table 1). This was only slightly larger than the aerial inshore estimate.

Offshore Area

Observers aboard both vessels surveyed 46,567 km in the offshore area and detected 192 schools (Table 2). The estimate of density was 2.04 schools/1,000 km² with a standard error of 0.263 (Table 1).

Total Area

From 1977 to 1983, observers on both vessels searched 74,407 km in all areas and detected 489 schools (Table 2). The density estimate for all shipboard data was 2.95 schools/1,000 km² with a standard error of 0.253 (Table 1). The estimate of density using the aerial inshore estimate and the

TABLE 2.—School detection rates for 1977-83 ship data and for 1979-83 ship data stratified by sea state category in the inshore, offshore and total areas. Data were truncated at 2.13 km perpendicular distance.

Area/data source	Distance searched (km)	Percent (km) searched	Number schools detected	Percent schools detected	Detection rate (schools/1,000 km)	SE (detection rate)	Number days searched
Inshore area							
77-83 all data	27,840	100.0	297	100.0	10.67	0.82	173
79-83 calm seas	8,502	35.3	144	53.9	16.94	1.52	89
79-83 rough seas	15,609	64.7	123	46.1	7.88	0.92	124
Offshore area							
77-83 all data	46,567	100.0	192	100.0	4.12	0.50	251
79-83 calm seas	4,129	17.1	44	36.7	10.66	2.30	58
79-83 rough seas	20,015	82.9	76	63.3	3.80	0.56	134
Total area							
77-83 all data	74,407	100.0	489	100.0	6.57	0.47	417
79-83 calm seas	12,632	26.2	188	48.6	14.88	1.29	146
79-83 rough seas	35,624	73.8	199	51.4	5.59	0.54	256

ship offshore estimate was 2.71 schools/1,000 km² with a standard error of 0.334.

DISCUSSION

Onshore-Offshore Density Gradients

The onshore-to-offshore density gradient decreased based on aerial data in the inshore area and comparison of inshore and offshore density estimates. Offshore density estimates were only about one-half the inshore estimates (Table 1). Although sea state and sun glare conditions were confounded with distance from shore, comparisons of detection rates in the two inshore density bands for data stratified by Beaufort state or sun conditions indicated lower rates in the outer band (Fig. 5).

Fit of Fourier Series Model

Burnham et al. (1980) provided criteria for selecting the appropriate number of terms in the FS model. However, these criteria were not satisfactory for use with the aerial and ship perpendicular distance distributions, which had pronounced modes at the origin. Instead, I selected models which had the fewest terms but provided a good fit near the origin. This resulted in models with large numbers of terms. However, to the degree that the modes are representative of school density, my estimates of densities will be unbiased. Alternate statistical models need development which can fit data which lack a shoulder near the origin (i.e., data with pronounced modes at the origin). Buckland (1985) investigated several models but concluded that reliable estimation is not possible unless a shoulder exists.

Line Transect Assumptions

Aerial Data

Confounding of aerial sea state and sun condition data with distance from shore made it impossible to test the assumption that all trackline schools were detected during all viewing conditions. If viewing conditions had been homogeneous throughout the area, the density estimate calculated for calm sea and good sun conditions (12.64 schools/1,000 km²) could be used for the inshore area (Table 1). This estimate is over 7 times the rough sea and poor sun estimate (1.78 schools/1,000 km²). However, the calm seas and

good sun condition effort occurred mostly in the northern nearshore region of the inshore area (Fig. 3, 4) where density may be high.

Consequently, Holt (fn. 8) conducted an aerial experiment in a relatively small area to test sea state and sun effects upon LT density estimates. The results indicated that sun glare adversely affected estimates of school density. The density estimate was 39% larger during good sun conditions than during poor conditions. Although density estimates were larger for calm sea data than for rough sea data, the differences were not significant.

The aerial experimental data (Holt fn. 8) may be used to estimate maximum bias for sun and sea state effects. The adjusted density estimate (\hat{D}_A) is

$$\hat{D}_A = \sum_{i=1}^2 \sum_{j=1}^2 \hat{D}_{ij} P_{ij} \left(\frac{\hat{D}'_{11}}{\hat{D}'_{ij}} \right)$$

where \hat{D}_{ij} = Density estimate in survey area during *i*th sea state and *j*th sun condition,

P_{ij} = Proportion of effort in survey area with *i*th sea state and *j*th sun condition,

D'_{ij} = Experimental density estimate during *i*th sea state and *j*th sun condition determined from Holt (fn. 8).

In addition, *i* equal 1 denotes calm sea states and *i* equal 2 denotes rough sea states, and *j* equal 1 denotes good sun conditions and *j* equal 2 denotes poor sun conditions. An estimate of the sampling variance ($\text{Var}(\hat{D}_A)$) using the Taylor approximation method is

$$\begin{aligned} \text{Var}(\hat{D}_A) = & \sum_{i=1}^2 \sum_{j=1}^2 P_{ij}^2 \left[\left(\frac{\hat{D}_{ij}}{\hat{D}'_{ij}} \right)^2 \text{Var}(\hat{D}'_{11}) \right. \\ & + \left(\frac{D'_{11}}{D'_{ij}} \right)^2 \text{Var}(\hat{D}_{ij}) \\ & \left. + \left(\frac{\hat{D}_{ij} \hat{D}'_{11}}{(\hat{D}'_{ij})^2} \right)^2 \text{Var}(\hat{D}'_{ij}) \right]. \end{aligned}$$

The adjusted inshore density estimate is 4.51 schools/1,000 km² with a standard error of 1.107. This is an 8% increase over the unadjusted esti-

mate (Table 1). The adjusted combined estimate for the entire ETP was 2.81 schools/1,000 km² with a standard error of 0.152, a 4% increase from the unadjusted estimate.

Using the experimental results to adjust aerial estimates for sun glare (and possibly sea state), effects may be suspect because of differences in procedures followed and observational conditions encountered in the experiment and the surveys: 1) The wings on the aircraft used during the experiment were attached on the lower part of the fuselage, whereas wings on the 1977 and 1979 aircraft were attached to the upper part of the craft which allowed better lateral observation. 2) Procedures used to adjust for presence of sun glare during the surveys and the experiment differed. Observers during the surveys were instructed to stop searching if they believed conditions prevented their detecting trackline schools, but observers in the experiment searched during all conditions. 3) More rough seas were encountered during the surveys (74%) than in the experiment (62%). Also, more (46% as compared to 15%) of the surveys' total effort occurred at extreme Beaufort 4 and 5 conditions. Because of these uncertainties, I used the unadjusted density estimate to determine school densities.

Comparisons of the 1979 aerial observer teams' estimates did not indicate observers of either team missed dolphin schools on the trackline but both teams may have been equally affected by searching conditions. These results were consistent with results of the aerial experiment (Holt fn. 8) where comparisons of observer teams' performance also indicated no significant differences.

Ship Data

The density estimates calculated from calm sea data were larger than estimates calculated from rough sea data (Table 1). The difference was probably not due to missed trackline schools during rough seas. Schools on the trackline would probably be detected as the ship approached unless the schools avoided the approaching ship. In a ship-helicopter experiment Hewitt (1985) investigated the reaction of dolphins to survey vessels and found that dolphin schools only occasionally react to the approach of a vessel before they are detected by shipboard observers (1 of 12 schools).

The differences between calm and rough sea estimates may have resulted from actual differences in densities in areas surveyed during calm

and rough sea states (Fig. 8). Another possibility is that estimation errors resulted from observers detecting schools at greater radial distances during calm conditions (mean radial distance was 4.16 km) than during rough conditions (mean radial distance was 3.55 km). Estimation of sighting angles and distances of schools at greater distances from the ship may have been less accurate and may have increased the probability of schools being erroneously recorded near or on the trackline.

Although sun glare was not shown to affect the shipboard density estimates, Cologne and Holt (fn. 7) found that shipboard observers tended to avoid searching areas with sun glare. However, because of the relatively slow speed of the ship and the dolphins and because sun glare at any specific time is usually concentrated in a small region of the observers' field of view, all regions may be observed without glare.

The occurrence of errors in angle and distance estimations may have positively biased shipboard estimates. An inordinate proportion of dolphin schools (25% of all schools) was recorded as being on the trackline. Smearing the perpendicular distance distributions helped alleviate the bias but may not have eliminated it.

Comparison of Aerial and Ship Estimates

The estimates of dolphin densities in the inshore and the total areas using only ship data were slightly larger than estimates which used aerial inshore data (Table 1). This is logical because ship surveys were designed to overlap with aerial coverage in the inshore area and to provide systematic coverage of the offshore area. Therefore, they spent disproportionately more of their effort in the inshore area compared to its relative size and, within the inshore area, they spent disproportionately more effort in the northern nearshore region (Fig. 1), which has relatively high dolphin density. Although the inshore area represented 31% of the total area, 37% of the ship's effort was in the inshore area. In addition, 61% of the inshore effort was in the northern inshore region which represented approximately 44% of the inshore area. During the aerial surveys a systematic survey of the inshore area was conducted. Therefore, the best estimates of densities in the inshore and total areas are estimates calculated using the unadjusted aerial inshore data.

Comparisons with Previous Density Estimates

Density of ETP dolphin stocks have been estimated previously (SWFC 1976¹¹; Holt and Powers 1982). The methods I used to calculate estimates were similar to those used by Holt and Powers. Therefore, differences that they noted between their assessment in 1979 and the SWFC 1976 assessment are also applicable to comparisons between the SWFC 1976 assessment and this study. My estimates differ from the 1979 estimates in that mine include

- 1) schools where either the observers' "best" or "lowest" estimate of mean school size was more than 14 animals (the 1979 assessment included only schools with "best" estimates),
- 2) use of the 1977 aerial data in the inshore density estimate,
- 3) ship data collected in 1977, 1979, 1980, 1982, and 1983 (the 1979 assessment included only 1979 ship data),
- 4) investigation of aerial and ship data for effects of sun, sea state, and observer performance,
- 5) application of LT methods to ship data to calculate density estimates.

Density estimates calculated in this study were similar to those presented in the 1979 assessment (Holt and Powers 1982). My inshore and offshore estimates were 4.18 and 2.04 schools/1,000 km², respectively, with standard errors of 0.902 and 0.263. Holt and Power's estimates were 3.51 and 1.89 schools/1,000 km², respectively, with standard errors of 0.590 and 0.766.

CONCLUSIONS

LT methods were used on 1977 and 1979 aerial survey data to estimate dolphin density in the inshore area at 4.18 schools/1,000 km². LT methods applied to 1977-83 ship data yielded an estimate of offshore dolphin density of 2.04 schools/1,000 km². By weighting aerial inshore and ship offshore data by the respective size of the two areas, the total dolphin density was estimated at 2.71 schools/1,000 km².

¹¹SWFC (Southwest Fisheries Center). 1976. Report of the workshop on stock assessment of porpoises involved in the eastern tropical Pacific yellowfin tuna fishery. Southwest Fish. Cent. Adm. Rep. No. LJ-76-29, 60 p. National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038.

I investigated differences among densities at different visibility conditions for aerial data, but results were inconclusive owing to confounding of the factors with density gradient (area from shore). Adjusting the data for sea state and sun conditions increased the inshore aerial density estimate 8% and the total density estimate by 4%.

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