Trends in dolphin abundance estimated from fisheries data: A cautionary note

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ABSTRACT

The previously published index of relative abundance of the northeastern offshore stock of spotted dolphins, the species most affected by the purse-seine fishery for tunas in the eastern Pacific Ocean, shows a decreasing trend in the last two decades despite dramatic reductions in incidental mortality since the early 1970s. To better understand the behaviour of this index, the effects of changes in data quality and methods of searching on estimation of relative abundance using current methodologies have been studied here. Changes in data quality since the late 1980s have led to a dramatic reduction in the proportion of sightings that are reported on or near the trackline. The decreasing trend in the index in the late 1970s and through the 1980s is strongly influenced by the fit of the detection function to the high proportion of sightings near the trackline that was present in the data during that time period. If this excess of sightings near the trackline is spurious, then much of the decreasing trend in the index over this time period is likely spurious. In addition, part of the decrease in the index in the late 1980s to mid-1990s is probably due to changes in data-collection biases that result from a dramatic increase in the amount of searching that is currently being carried out using helicopters as compared to high-powered binoculars. The results suggest that trends in bias associated with changes in data quality and fishery operations may have contributed to a trend in the index on the order of 1.0-1.5% per year, or approximately 25-33% of the maximum growth rate of the northeastern stock of offshore spotted dolphin. The pervasive nature of these sources of bias, and their potential magnitude relative to the maximum growth rates of the dolphin species involved, make use of this index in population growth models ill-advised. Fishery-derived indices such as these may be most useful for comparing trends in relative abundance between species, when the sources of biases are unlikely to be species-specific.

KEYWORDS: ABUNDANCE ESTIMATION; FISHERIES; BIAS; DOLPHINS; BYCATCH; INCIDENTAL MORTALITY; TRENDS

INTRODUCTION

First brought to public attention over 30 years ago, the effect of the international purse-seine fishery for tunas on dolphin populations in the eastern Pacific Ocean is an issue of concern that continues to be controversial. The yellowfin tuna (*Thunnus albacares*), one of the most sought after tuna species, is found in association with several species of dolphins in the eastern Pacific Ocean, primarily the spotted dolphin (*Stenella attenuata*), and the spinner dolphin (*S. longirostris*) (Allen, 1985). Fishermen use this association to locate and capture the tunas. Incidental mortality of dolphins can occur when the dolphins are encircled with the tunas in the purse-seine net. Since the late 1970s, management of marine mammal bycatch associated with this fishery has been the focus of national and international observer programmes, legislation and efforts by conservation organisations (Joseph, 1994; Hall, 1998; Gosliner, 1999). Attention has focused on reduction of bycatch, as well as estimation of abundance in order to determine sustainable levels of bycatch.

Despite these efforts, measures of population trajectories (Fig. 1) do not show the increasing trend that might be anticipated given estimates of population size relative to pre-fishery levels (DeMaster *et al.*, 1992; Wade, 1994). To monitor trends in abundance, data collected aboard tuna vessels by observers of the USA National Marine Fisheries Service (NMFS) and the Inter-American Tropical Tuna Commission (IATTC) have been used to estimate indices of relative abundance of dolphins (Buckland and Anganuzzi, 1988; Anganuzzi and Buckland, 1989; 1994; IATTC, 1991; 1992a; b; 1993; 1994; 1995; 1997; 1998; Anganuzzi *et al.*, 1993). Observers record sightings of marine mammals made by the vessel crew during the searching phase of the fishing operations when crew members search for dolphin herds in hopes of finding tunas. This index of relative abundance for the major species affected by the fishery (Fig. 1) does not show an increasing trend, despite dramatic reductions in incidental mortalities since the early 1970s (Lo and Smith, 1986; IWC, 1992, p.214-218; Wade, 1995; IATTC, 2000) to levels that have been considered sustainable since 1992 (i.e. below the Potential Biological Removal level as defined by Wade and Angliss, 1997).

Since the late 1980s, when the current methodology for estimating relative abundance indices from tuna vessel observer data was developed (Buckland and Anganuzzi, 1988; Anganuzzi and Buckland, 1989), there have been considerable changes in this fishery in terms of searching gear, policy regulating marine mammal bycatch and importation of tunas, and tuna marketing (Joseph, 1994; Hall, 1998) which may affect data collected by tuna vessel observers. For example, historically fishermen searched for tunas associated with dolphins primarily by 25× binoculars from the vessel, with binocular sightings accounting for the majority of sightings (Fig. 2). In the late 1980s, high-resolution radar use by the international fleet became common, and radar and helicopters have since replaced binoculars as the main sighting methods. These changes in the predominant methods of searching were followed shortly by changes in national and international policy designed to reduce the levels of marine mammal bycatch, including the development of the markets for tunas not caught in association with dolphins and annual individual vessel dolphin mortality quotas (IATTC, 1994; Joseph, 1994). These policies are thought to have contributed to changes in fishing strategies that led to the further development of the tuna fishery associated with fish aggregating devices in the mid-1990s (Lennert-Cody and Hall, 2000).

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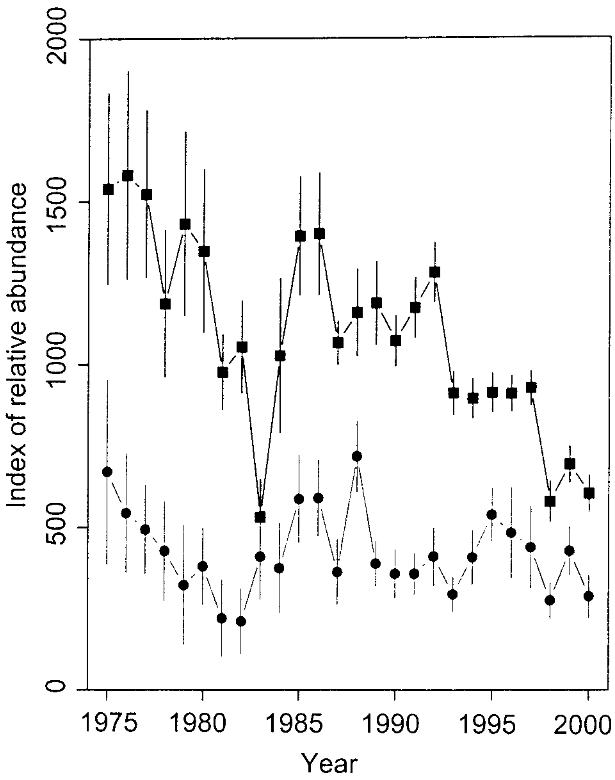

Fig. 1. Time series of point estimates of the index of relative abundance (number of animals, in thousands) of the northeastern stock of spotted dolphin (black line, squares) and the eastern stock of spinner dolphin (grey line, circles) (vertical bars indicate +/- one standard error), based on the methods of Buckland and Anganuzzi (1988) and Anganuzzi and Buckland (1989). See Table 1 for references.

The use of tuna vessel observer data has posed problems for estimation because of biases introduced through the opportunistic nature of the data collection (Buckland and Anganuzzi, 1988). However, in the absence of trends in these biases, estimation of trends in relative abundance from tuna vessel observer data is still statistically feasible (Buckland and Anganuzzi, 1988). One of the most serious problems has been the non-random distribution of search effort, which has been addressed by spatial stratification of the estimators (Buckland and Anganuzzi, 1988; Anganuzzi and Buckland, 1989). Further control of bias has been effected by deleting data of dubious quality, including: observer-initiated sightings, to avoid problems of vessel attraction; and entire cruises where there was evidence of inaccurate bearing measurements. Nonetheless, in light of the proposed use of the indices of relative abundance for fitting population dynamics models (Anonymous, 1999), a number of issues have been raised regarding the reliability of these indices to accurately capture trends in absolute abundance (IATTC, 1999; 2001; Perkins, 2000). Such issues include the effects of changes in fishery operations on sightings data collected by observers, the effects of changes in data quality, the lack of calibration of observer estimates of herd size and measurement errors. In addition, recent work indicates that abundance estimation methodologies for opportunistic data may need to take account of the effects on detectability of factors such as sighting cue (e.g. birds, splashes) and herd size (Marques, 2001).

This paper focuses on the effects of changes in data quality (bearing measurements) and methods of searching on trends in the indices of relative abundance as computed using current methodologies. The differences in the characteristics of sightings identified by different methods of searching ('sighting method') using data for the northeastern offshore stock of spotted dolphin are explored. The effect of these differences on the indices of relative abundance for the northeastern offshore stock of spotted dolphin, and to a limited extent, the eastern stock of spinner dolphin are also investigated. In view of the findings, the suitability of these indices for use in the management of dolphin populations is discussed.

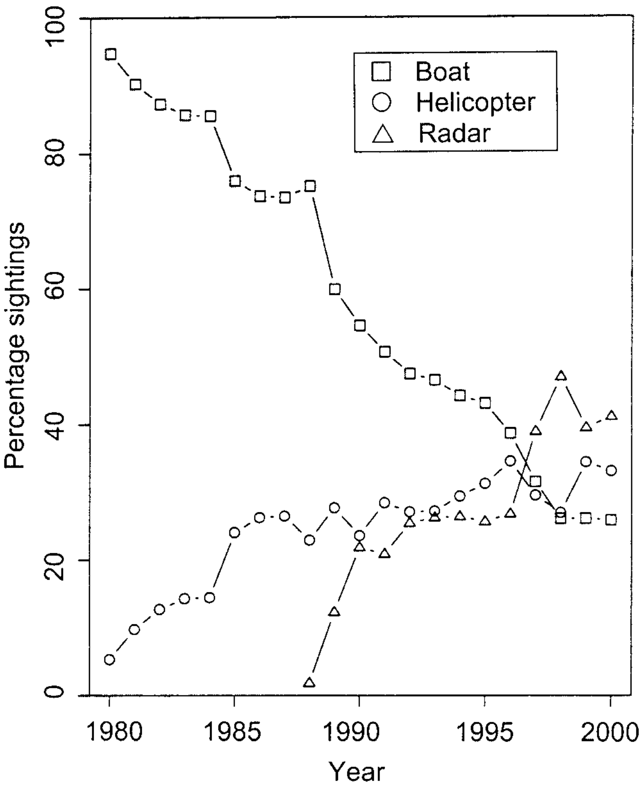

Fig. 2. Percentage of sightings by sighting method for 1980-2000 (IATTC data) within the northeastern spotted dolphin area (north of 5^0N and east of 120^0W). 'Boat' indicates binocular sightings made from any location on the vessel.

DATA AND METHODS

Data collection

Observers aboard tuna vessels collect data on marine mammal sightings made during the search for tunas. In this paper, only sightings originally detected by the crew are considered because herds originally detected by the observer may have been so close as to have already reacted to the vessel (Buckland and Anganuzzi, 1988). For crew-detected sightings, observers record radial distances and bearings to sightings, and make estimates of herd size. Radial distances and bearings are obtained from the vessels' high-resolution radar if available, or are estimated based on the travel time of the vessel to the sighting and the change in the vessels' course as it heads to the sighting. Whenever possible, observers are instructed to make their own assessment of radial distances and bearings, independent of the vessel crew. However, particularly in the case of sightings that do not lead to sets, the observer may have to rely on the vessel crew for such data. Observers make initial and best estimates of herd size; a best estimate is only possible when the herd is set upon and the observer is able to observe the herd for an extended period of time at close range. Measurement errors and counting errors undoubtedly occur, and there is evidence of rounding in the distance and bearing data. However, for the analyses presented here, these measurements were regarded as exact and no attempt was made to correct (or calibrate) the observer data. In all analyses, perpendicular distances (right angle distances to sightings from the trackline) were computed from the recorded radial distances and bearings.

Sighting characteristics

Differences in sightings characteristics by sighting method were explored using data collected by IATTC observers aboard vessels of the international purse-seine fleet with more than 363 metric tons fish-carrying capacity between 1980-2000. Sampling coverage by IATTC observers increased from an average of 12% of vessel trips prior to 1986 to more than 65% between 1992 and 2000 (IATTC, 1993; 1994; 1995; 1997; 1998; 1999; 2000; 2001; In press; Hall *et al.*, 1999). This analysis focused on sightings that involved offshore spotted dolphins within the northeastern offshore spotted dolphin area (north of 5°N and east of 120°W; Dizon *et al.*, 1994). Consistent with past treatment of these data (Buckland and Anganuzzi, 1988; Anganuzzi and Buckland, 1989), attention was restricted to sightings and effort (nautical miles searched) during light wind conditions (Beaufort scale ≤ 3) when the observer was on duty and the vessel was actively searching; for some parts of the analysis (see below), only sightings made within 5 n.miles perpendicular distance of the vessel were considered. Data for 1979 were excluded because it was not possible to determine the duty status of the observer for all trips. Finally, data for trips that made less than 5% of their sets on tunas associated with dolphins were excluded. In this way, it is hoped that trips during which serious effort was made to search for dolphin herds can be identified. Sightings made behind the vessel (bearings between 90°-270°) were excluded from analyses involving perpendicular distance.

For these data, differences in the characteristics of sightings made by different sighting methods were explored. The sighting method indicates the gear with which the herd of marine mammals was first detected. Three sighting methods were considered: (1) binoculars from any location on the vessel (hereafter referred to as 'boat' sightings); (2) helicopter; and (3) high-resolution radar (hereafter simply referred to as 'radar'). The empirical distribution of perpendicular distances, the proportion of sightings that led to sets and the average total herd size were computed for each sighting method, by year. Estimates of average total herd size by sighting method were based on the observers' initial estimates of the number of animals in the herd. Initial estimates were used to avoid biasing the comparison towards sightings that led to sets; however, similar results were obtained when the observers' best estimates were used. Estimates of the percentage of sightings that led to sets and the average herd size were made based on sightings within 5 n.miles perpendicular distance of the vessel.

To assess whether patterns seen in the relative percentage of sightings occurring near the trackline (see below) could be the result of rounding bearings to the nearest 5°, a random component of -2.5° to 2.5° was added to the recorded bearings for data from 1995-2000, and perpendicular distances were recomputed. The difference in the proportion of sightings within 0-0.5 n.miles and 0.5-1.0 n.miles of the trackline was taken as a measure of the presence of a deficit (or excess) of sightings near the trackline. This simulation was repeated 1,000 times for each sighting method to generate empirical distributions of perturbed perpendicular distances. If rounding of bearings was the sole cause of the observed patterns in distributions of sightings, both excesses and deficits of sightings near the trackline would be expected to occur when a random component is added to the bearing measurements.

Trends in the percentage of sightings that led to sets by sighting method, and differences in the overall percentage of sightings that led to sets between sighting methods, were tested by assuming a logistic model (e.g. Collett, 1991) for temporal trends in the probability that a sighting would lead to a set (p). It was assumed that the number of sightings that led to sets followed a binomial distribution and that the log of the odds ratio of p (i.e. $p/(1-p)$) varied linearly with year. For each year and each sighting method, p was estimated as the number of sightings that led to sets divided by the total number of sightings. Trends in the proportion of sightings that led to sets over time for a given sighting method, and differences in the overall proportion of sightings that led to sets by sighting method, were assessed by testing the significance of estimated slopes, and differences in estimated intercept terms, respectively.

Differences in average total herd size by sighting method were investigated by fitting an analysis of covariance model for average total herd size using weighted least squares, with year as the covariate and weights equal to the inverse of the variance of average total herd size. Assumptions were made for a constant slope between sighting methods but sighting method-specific intercept terms (i.e. a sighting method effect). Differences in the overall average total herd size between sighting methods were assessed by testing for the significance of a sighting method effect.

Index of relative abundance

The effects of changes over time in sightings characteristics on indices of relative abundance were explored using data collected by observers from the NMFS and the IATTC. With some exceptions, data used previously to estimate indices of relative abundance (Buckland and Anganuzzi, 1988) have been used herein. Because of problems with sample size, the period 1975-76 (see comments in Buckland and Anganuzzi, 1988) was not considered. Also excluded were data from trips that made less than 5% of their sets on tunas associated with dolphins. However, excluding these trips made little difference in the estimates because generally more than 75% of such trips were not included in previously published analyses, likely due to their very low sighting rate. A detailed discussion of data quality can be found in Buckland and Anganuzzi (1988).

To explore the effect of changes in the distribution of sightings near the trackline (see below) on estimated abundance of both northeastern offshore spotted dolphins and eastern spinner dolphins, the methods of Buckland and Anganuzzi (1988) and Anganuzzi and Buckland (1989) were modified by fitting a half-normal model to the perpendicular distance data rather than a hazard-rate model. The hazard-rate model exhibits greater flexibility than the half-normal model and thus is sensitive to the relative proportion of detections near the trackline, an undesirable property if changes are the result of a spurious process. Comparison of estimates of $f(0)$ and abundance obtained from the two different models provides a means of assessing the influence of trends in the relative proportion of sightings near the trackline on estimates of relative abundance. When the scale parameter of the half-normal model appeared to be going towards infinity (suggesting no fall-off in detectability over the width of the strip), the half-normal model was replaced by the uniform model (which assumes that all herds in the strip were detected). In contrast to previous methods (Buckland and Anganuzzi, 1988; Anganuzzi and Buckland, 1989), smearing of the sighting data was excluded from the estimation procedures to avoid arbitrary re-distribution of sightings near the trackline into perpendicular distance intervals where they may not belong. However, excluding smearing from the estimation procedures had little effect on the estimates of relative abundance when the half-normal model was used.

To explore differences in indices for the northeastern offshore spotted dolphin between different sighting methods, the sightings data were post-stratified according to the type of searching gear carried onboard the vessel. Given the limited information collected on activities of helicopters and radar, it is not possible to accurately estimate search effort associated with these sighting methods and thus abundance estimation must be done by categories of gear onboard vessels rather than by types of sighting method in use at the time of a given sighting. Four categories were used: (1) neither helicopter nor radar onboard; (2) helicopter onboard, but no radar; (3) no helicopter onboard, but radar onboard; and (4) both helicopter and radar onboard. These categories of searching gear were assumed to be homogeneous because detailed data on gear types (e.g. type of radar) are not available. Starting in 1979, observers recorded the presence of helicopters onboard vessels. Prior to 1979, data supplied by fishing captains (logbook records) on the presence/absence of helicopters onboard have been used. Unfortunately, these data were not available for all trips, limiting the sample size for post-stratification in these years. Data for the presence/absence of radar onboard were only available for IATTC-observed trips beginning in 1988 and NMFS trips beginning in late 1990. Under the assumption that, once installed, radar is unlikely to be removed, the presence/absence of radar onboard NMFS-observed trips between 1988 and late 1990 was estimated from IATTC data for the vessels' previous trips. Data on radar presence/absence prior to 1988 were not available and thus data in categories (3)-(4) are only present from 1988. Prior to 1988, categories (1)-(2) merely reflect whether or not there was a helicopter on board, in the absence of information on radar.

Differences in the indices of relative abundance by mode of search were investigated by comparing estimates of $f(0)$, encounter rate and average herd size, between modes of search. Rough comparisons of each of the components of relative abundance were done based on estimates of a 'mode-of-search' effect obtained from fitting an analysis of variance model by weighted least squares to the estimated quantities ($f(0)$, encounter rate or average school size), with weights equal to the inverse of the variance of the estimated quantity. Overall differences in the estimates of $f(0)$, encounter rate and average school size, were then assessed by testing for the significance of mode-of-search effects.

RESULTS AND DISCUSSION

Bearing data quality

Sighting characteristics: distribution of perpendicular distances

In contrast to an excess of sightings near the trackline in the early 1980s, a sighting deficit near the trackline developed in the 1990s for most sightings methods (Fig. 3). In the early 1980s, distributions of perpendicular distance often showed an excess of sightings within 0.5 n.miles of the trackline (Fig. 3; Buckland and Anganuzzi, 1988) due to the vessel turning towards the herd before the observer was aware of the sighting (Buckland and Anganuzzi, 1988). Since the late 1980s, distributions of perpendicular distance often show a deficit of sightings near the trackline, with the deficit usually extending the furthest off the trackline for helicopter sightings (Fig. 3). Simulations suggest that the sighting deficit near the trackline is not entirely the result of rounding error. If rounding were the sole cause, the simulations would be expected to yield both positive and negative differences (i.e. excesses and deficits of sightings near the trackline). For binocular sightings from the bridge, this was not found to be the case; simulated differences ranged from -0.037 to 0.048. However, simulations for binocular sightings from the crow's nest (simulation range: -0.045 to -0.023), helicopter sightings (simulation range: -0.017 to -0.002) and radar sightings (simulation range: -0.021 to -0.002), yield no excesses of sightings near the trackline, suggesting that other mechanisms, in addition to rounding, contributed to the observed deficit.

Both observer and crew biases against reporting bearings of exactly 0° may be the main factors contributing to the sighting deficit near the trackline. First, in 1986 the IATTC began including in their observer training specific instructions for the estimation of bearings of sightings near the trackline. Thus, increased focus during observer training on bearing estimation since the late 1980s may have led to a tendency of observers not to record bearings of 0° even if the observer believed the bearing to be exactly 0°. Second, based on conversations with crew members, there appears to be a tendency of crew members to round bearings that are close to 0° away from 0°. Information exchanged between crew members may be one of the observers' main sources of bearing and distance data, and thus data recorded by the observer may exhibit a bias against reporting bearings of 0° because of a crew bias against reporting bearings of 0°. This bias may have only become apparent following changes in observer training. Finally, search patterns, particularly those of the helicopter, may systematically avoid the area directly ahead of the vessel, and thus it may be that herds originally near (or on) the trackline are only detected once they have moved away. Changes in binocular search from predominantly on the bridge to the crow's nest in the late 1980s may contribute to the deficit as the binocular search from the bridge may have been more often directed ahead of the vessel. Vessel avoidance by dolphin herds could also contribute to the sighting deficit near the trackline but is difficult to separate from other potential causes.

Effect on the index of relative abundance: half-normal model

These temporal trends in the relative percentages of sightings near the trackline introduce bias in estimates of the probability of detection that changes over time. To remove the influence of these sightings on the estimates of $f(0)$[1], cruises with an average sighting angle of less than 20° were excluded from previous analyses (Buckland and Anganuzzi, 1988). However, even after applying this criterion, excess sightings near the trackline still exist and can exert influence on the fit of the hazard-rate model to the distribution of perpendicular distances, inflating the estimate of $f(0)$. With the development of a deficit in sightings near the trackline in the 1990s, the tendency for inflated estimates of $f(0)$ is diminished or even reversed, imparting a temporal trend in bias to the estimates of $f(0)$. As an illustration of this effect,

[1] $f(0)$ is the probability density function of perpendicular distances of detected herds from the trackline, evaluated at zero perpendicular distance (e.g. Buckland *et al.*, 1993).

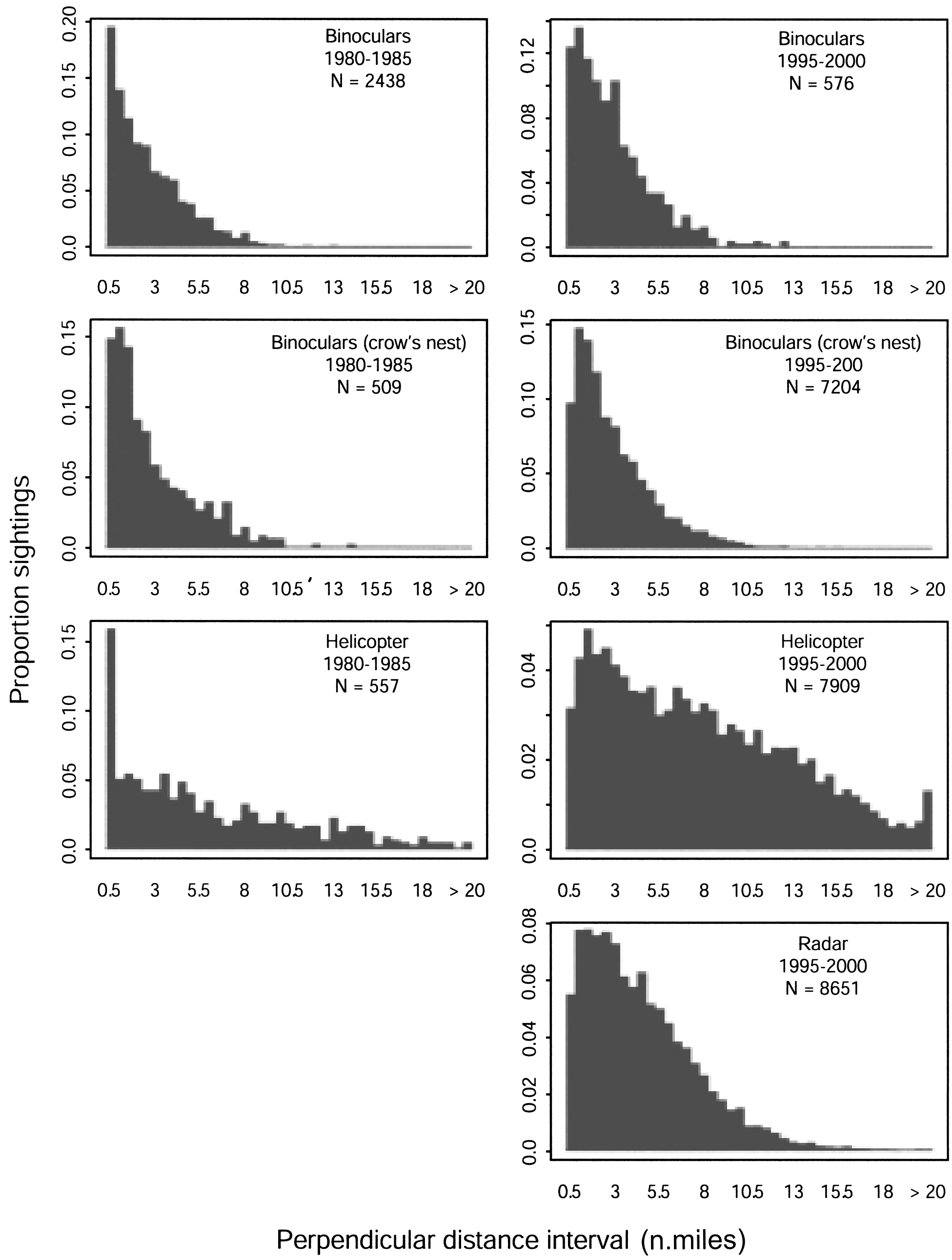

Fig. 3. Empirical distributions of perpendicular distance for 1980-1985 and 1995-2000 by sighting method. Perpendicular distance data were binned into 0.5 n.miles bins. 'N' indicates the number of sightings.

the time series of estimates of $f(0)$ based on the half-normal model shows less of a trend in $f(0)$ from 1977 through the early 1990s as compared to that based on the hazard-rate model; the two models give similar estimates of $f(0)$ since about 1993 (Fig. 4). The decreasing trend in $f(0)$ between about 1986-1993 (corresponding to an increasing trend in the effective width of search) for both the half-normal and hazard-rate models may reflect the development of high-resolution radar use in this fishery which likely began around 1986.

Comparison of estimates of relative abundance based on the hazard-rate model and the half-normal model (Fig. 4), shows that the overall decreasing trend in the index from 1977 through approximately 1992 is at least partially dependent on the treatment of the spike in the distribution of perpendicular distances near the trackline (Fig. 3). If the spike is spurious, then much of the decrease over this time period may also be spurious. For example, the average of estimates based on the hazard-rate model from 1989-1991 shows a decrease of 17% compared to the 1977-1979 average, however the average of estimates based on the half-normal model from 1989-1991 shows a decrease of 6% as compared to 1977-1979 (Table 1). A similar but smaller effect was seen for the eastern stock of spinner dolphin (Table 1).

Fishery-introduced bias

Sighting characteristics: percentage of sightings leading to sets, average herd size

Helicopter sightings were the more likely to lead to sets and involve larger herds of dolphins than other sighting methods. On average, 76% of helicopter sightings, 71% of radar sightings and 61% of boat sightings led to sets (Fig. 5). A maximum difference of 30% was found, occurring between helicopter and boat sightings in 2000. Results of fitting the

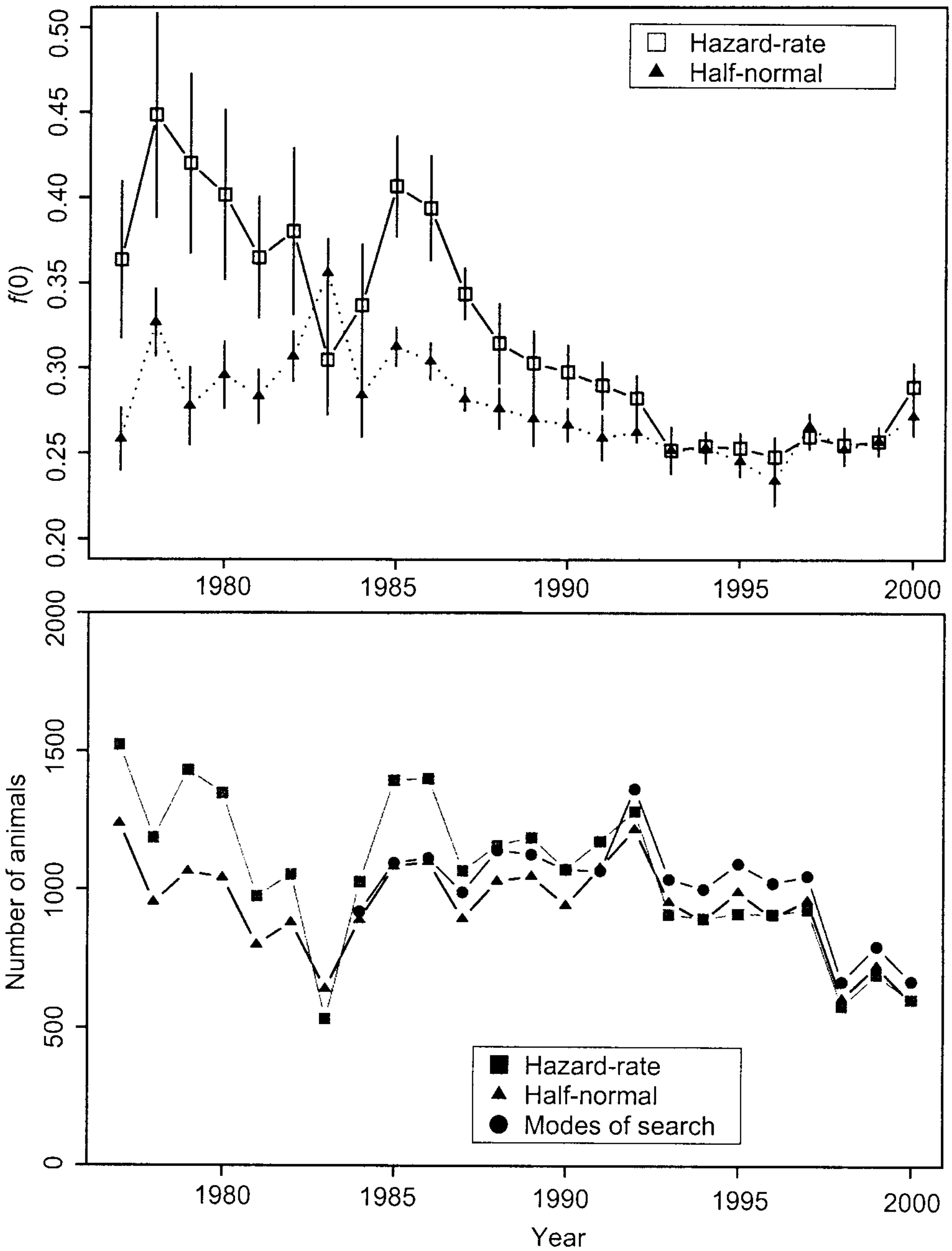

Fig. 4. Top panel: Estimates of $f(0)$ for the northeastern stock of spotted dolphin computed using the hazard-rate model (open squares; estimates based on methods of Buckland and Anganuzzi (1988) and Anganuzzi and Buckland (1989)), and the half-normal model (filled triangles). Vertical bars indicate plus/minus one bootstrap standard error. Bottom panel: Estimates of indices of relative abundance for the northeastern stock of spotted dolphin using the hazard-rate model (grey squares) and the half-normal model (black triangles) (Table 1). The 'Modes of search' index (grey circles; Table 1) is based on a weighted average of indices by mode of search (Table 2) (see text for details).

linear logistic model for p suggest a significant increase over time in the percentage of helicopter sightings leading to sets (p-value < 0.01; $t = 3.86$, 19df), but no significant trend with time for either boat sightings (p-value = 0.09) or radar sightings (p-value = 0.25). Pooling across sighting methods, the percentage of sightings that led to sets increased from an average of 61% in the early 1980s to 67% in the last several years. In addition, there was a significant difference in the offset between the percentage of boat sightings leading to sets and the percentage of helicopter sightings leading to sets (comparison of intercept terms: $p < 0.01$; $t = 4.05$, 19df). Although the average total herd size for boat sightings and radar sightings were similar, results of fitting the analysis of covariance model for total average herd size suggest that the average total herd size for helicopter sightings was significantly greater than that for boat sightings (p-value < 0.01; $t = 4.08$, 39df) (Fig. 6).

Differences in the percentage of sightings that led to sets and in average total herd size, by sighting method, suggest that the data made available by the crew to the observer varies by sighting method. Average herd size has been shown to be positively correlated with catch per set of yellowfin tuna (Hall *et al.*, 1999), the dominant species of tuna caught in association with dolphins (IATTC, 2000). Both the greater percentage of sightings that led to sets and the larger herd size for helicopter sightings are consistent with a tendency of crew aboard the helicopter to selectively report dolphin herds that are associated with tunas, an

Table 1

Estimates of indices of relative abundance for northeastern offshore spotted dolphins and eastern spinner dolphins, in thousands of animals, for the hazard-rate model (published time series based on methods of Buckland and Anganuzzi, 1988, and Anganuzzi and Buckland, 1989: see Annual Reports of the IATTC 1991-1998; Anganuzzi, Buckland and Cattanach, 1993; Anganuzzi and Buckland, 1994; eastern spinner estimates based on the hazard-rate model for 1977-1987 represent minor revisions to those in Anganuzzi and Buckland, 1989; estimates for both species based on the hazard-rate model for 1997-2000 have not been previously published) and the half-normal model. Bootstrap standard errors shown in parentheses. Also shown for the northeastern stock of spotted dolphins is a weighted average index computed from indices based on different modes of search (Table 3). Rough standard errors for the 'Modes of search' index were computed by the delta method, assuming that the weights were known constants and estimates based on different modes of search were independent.

	Northeastern offshore spotted			Eastern spinner	
	Hazard-rate	Half-normal	Modes of search	Hazard-rate	Half-normal
1977	1,523 (257)	1,238 (275)		494 (137)	360 (115)
1978	1,187 (227)	953 (161)		428 (153)	261 (98)
1979	1,432 (282)	1,064 (182)		323 (184)	288 (146)
1980	1,348 (252)	1,042 (155)		381 (117)	289 (72)
1981	976 (117)	800 (98)		222 (120)	271 (82)
1982	1,054 (143)	881 (99)		212 (102)	218 (57)
1983	532 (116)	641 (96)		410 (133)	367 (97)
1984	1,027 (238)	890 (199)	919 (199)	375 (139)	328 (102)
1985	1,394 (183)	1,082 (115)	1,096 (158)	587 (136)	503 (98)
1986	1,401 (188)	1,099 (104)	1,113 (173)	590 (118)	478 (75)
1987	1,067 (68)	894 (61)	989 (141)	363 (100)	328 (70)
1988	1,159 (135)	1,030 (90)	1,141 (146)	717 (110)	620 (100)
1989	1,188 (129)	1,048 (99)	1,127 (162)	389 (71)	337 (67)
1990	1,072 (79)	943 (69)	1,072 (153)	358 (76)	302 (75)
1991	1,174 (94)	1,078 (94)	1,067 (188)	358 (65)	307 (75)
1992	1,282 (92)	1,217 (78)	1,364 (218)	410 (91)	456 (105)
1993	911 (68)	954 (94)	1,037 (176)	295 (54)	271 (60)
1994	895 (63)	888 (78)	1,001 (171)	408 (85)	335 (65)
1995	913 (61)	990 (88)	1,092 (178)	538 (83)	506 (93)
1996	910 (56)	900 (86)	1,023 (171)	483 (139)	428 (152)
1997	927 (54)	959 (58)	1,048 (164)	439 (127)	423 (122)
1998	579 (63)	606 (65)	668 (122)	275 (56)	304 (45)
1999	693 (57)	724 (62)	795 (141)	427 (75)	399 (61)
2000	603 (57)	593 (57)	670 (117)	288 (68)	308 (64)

interpretation supported by interviews with observers and vessel crew. The increased percentage of radar sightings that led to sets compared to boat sightings may be due to the fact that the helicopter is apparently used to investigate radar sightings for the presence of tuna, and thus observers may not be made aware of all radar 'targets' that involved dolphins but no fish. The larger average herd size of helicopter sightings is unlikely to result primarily from an inability of helicopter crews to see smaller herds, especially since the mid-1980s with the advent of motion-stabilised binoculars, because more than half of the herds of 100 or fewer animals were reported at Beaufort 2-3 (for sightings in Beaufort conditions 0-3).

We believe that the selective reporting of sightings by helicopter crew to the observer probably results in a loss of sightings data. The increased success rate of helicopter sightings might be interpreted to reflect the fact that helicopters, which generally operate the furthest from the vessel, find the larger herds with tuna before they are able to be seen by the crew searching with binoculars. However, the average percentage of sightings that led to sets for vessels without helicopters between 1980 and 1990 was 67%, compared to 73% for helicopter sightings over the same time period. Neither this difference, nor the overall increase in the percentage of sightings that led to sets since the early 1980s noted above would be expected if all sightings not reported by the helicopter were detected and reported by other sighting methods. Moreover, because of the limited spatial overlap that occurs between the modes of search (Figs. 3, 7), it is not certain that sightings which go unreported by the helicopter (or radar) crew will be seen and reported by the crew searching with binoculars. Herd movement, particularly avoidance of both the helicopter and the vessel, may increase the likelihood that later detection, if it occurs, is further off the trackline. Changes in crew searching behaviour in response to detections made far from the vessel may compound this problem. For example, there has been an increase in the amount of search that occurs 'post-detection' (after the initial sighting of a herd to be set upon, but before the set) from an average of about 1% of the effort prior to 1989 to an average of over 4.5% since 1990. Post-detection search likely occurs when sightings are made too far from the vessel to initiate the chase and set phases of the fishing operations immediately after the initial sighting. Encounter rates associated with post-detection search are about an order of magnitude less than 'pre-detection' encounter rates, suggesting that post-detection search may be conducted with less intensity. Thus, we believe that selective reporting of sightings probably results in some data loss. The increasing trend in the percentage of sightings that were made by helicopters (Fig. 2), combined with differences in crew reporting to the observer, will introduce bias into the estimates of relative abundance if relative abundance indices from different search methods are not comparable.

Effect on the index: modes of search

Comparison of estimates of $f(0)$ and encounter rate between modes of search show patterns that are consistent with selective reporting of sightings by the crew in the presence of a helicopter beginning in the mid-1980s (Fig. 8). Estimates

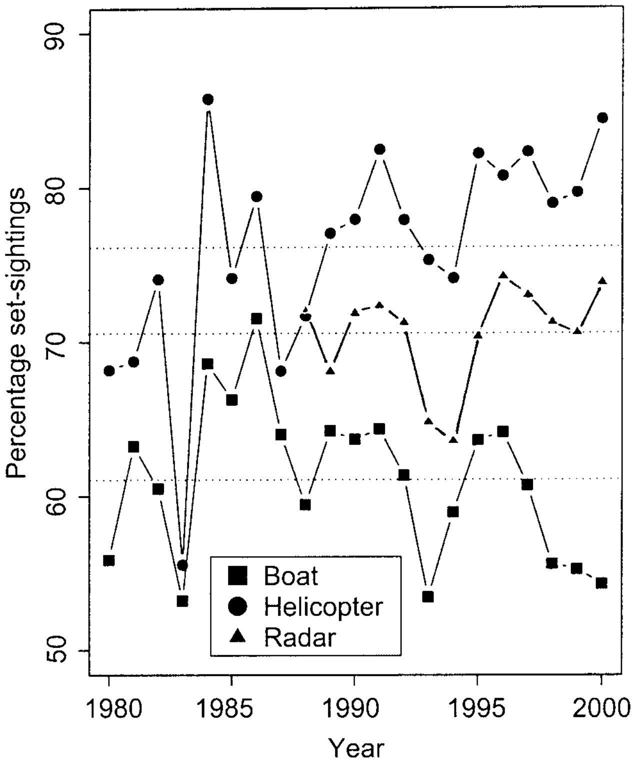

Fig. 5. Percentage of sightings that led to sets, by sighting method, for 1980-2000. Dashed lines indicate the overall average percentage, by sighting method. Data are for sightings made within 5 n.miles perpendicular distance of the vessel; similar patterns occur when percentages are based on all sightings.

of $f(0)$ based on data of vessels with helicopters were generally smaller than those of vessels without helicopters between 1984-1990 (one-tailed t-test, $p = 0.021$), yet the encounter rates were generally less over the same time period (one-tailed t-test, $p = 0.016$). Although there may be several factors contributing to the differences in encounter rates, in the absence of changes in true abundance, this pattern would be consistent with an increased level of selective reporting by the crew on vessels with helicopters as compared to vessels without helicopters. (Current methodology assumes that detection on the trackline is certain.) Similarly, estimates of $f(0)$ based on data of vessels with both radar and helicopter were generally smaller than those based on data of vessels with radar but no helicopter between 1989-1998 (one-tailed t-test, $p = 0.002$), and estimates of encounter rate were sometimes but not consistently less over the same time period (one-tailed t-test, $p = 0.164$). However, sizes of herds encountered by vessels with radar but no helicopter were on average smaller than those encountered by vessels with both radar and helicopter (one-tailed t-test, $p < 0.01$) (Fig. 8), even within the same sub-area (Table 2). This difference in herd size may result because crew aboard helicopters actively seek (and selectively report) larger herds. The difference in herd size, and the fact that since 1992, the search effort for vessels with radar but no helicopter largely occurred coastally (Fig. 9), outside of the main offshore area of the fishery on tunas associated with dolphins (Watters, 1999), may suggest differences in fishing strategies between the two modes of search.

Differences in $f(0)$, encounter rate and school size by mode of search lead to some differences in the indices (Fig. 10, Table 3). The index for vessels without helicopter is larger in general than that for vessels with helicopters prior to 1990. However, despite the high degree of variability in the index of vessels without helicopters, both modes of search suggest an increase in relative abundance in the mid-1980s. The lower abundance and greater rate of decrease in the index based on data of vessels with only radar in the 1990s as compared to that based on data of vessels with both radar and helicopter probably reflects differences in fishing strategies and selective reporting between these two modes of search.

To obtain a rough estimate of the magnitude of the effects on the index of changes in data quality and selective reporting in the last decade, a weighted average index was computed from the indices for modes of search. The index based on data of vessels with radar but no helicopter was excluded because of differences in fishing strategies and

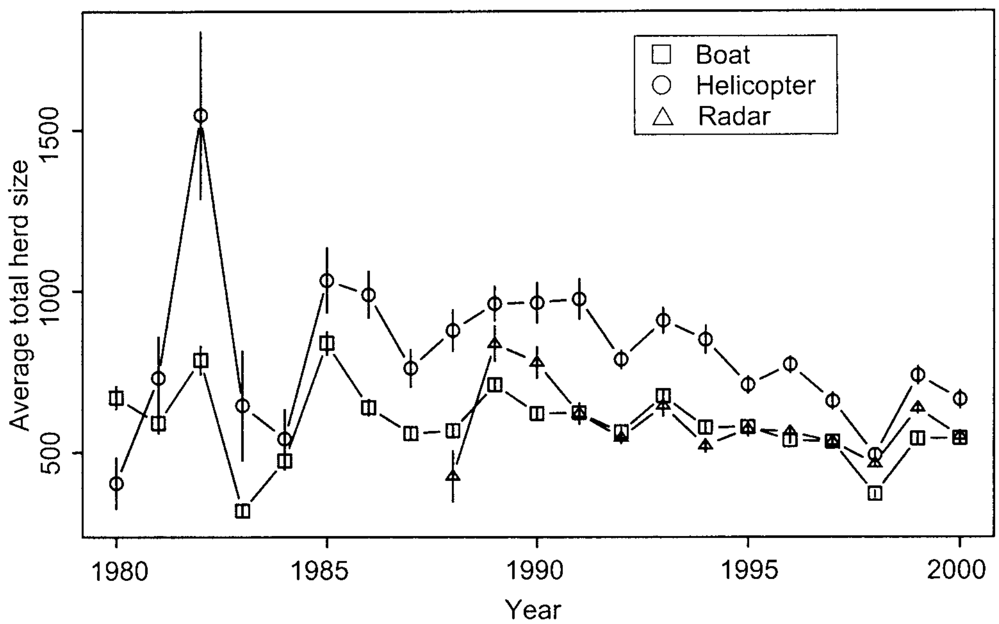

Fig. 6. Average total herd size, by sighting method, for 1980-2000. Vertical bars indicate plus/minus one standard error. Data are for sightings made within 5 n.miles perpendicular distance of the vessel; similar patterns occur when percentages are based on all sightings.

selective reporting as compared to vessels with helicopters, as noted above. Data prior to 1984 were also excluded because of issues relating to selective reporting, and data quality is likely poor. It was assumed that the average difference between the other three indices reflects an increase in selective reporting in the presence of a helicopter, which is assumed to be free temporal trends. A selective reporting correction factor was computed as the ratio of the sum of estimates from 1984-1990 for no helicopter and no radar divided by the sum of estimates from 1984-1990 for helicopter and no radar (Table 3), with an approximate standard error obtained by the delta method (e.g. Rice, 1988). The two time series of indices for vessels with helicopters were thus adjusted upwards by multiplying by a correction factor of 1.09 (SE = 0.157). (This correction factor is applied in spite of the fact that it is not significantly different from 1.0 because comparison of estimates of $f(0)$ and encounter rate between modes of search suggest the presence of selective reporting.) A weighted average index (Table 1; Fig. 4) was computed as a weighted average of the indices for the three modes of search (no helicopter, no radar; adjusted helicopter, no radar; adjusted helicopter, radar), with weights equal to the inverse of the squared coefficient of variation.

Comparison of the weighted average index to the previously published index (Fig. 4; Table 1) shows that the majority of the decline in the previously published index between the late 1980s to early 1990s, and the mid-1900s,

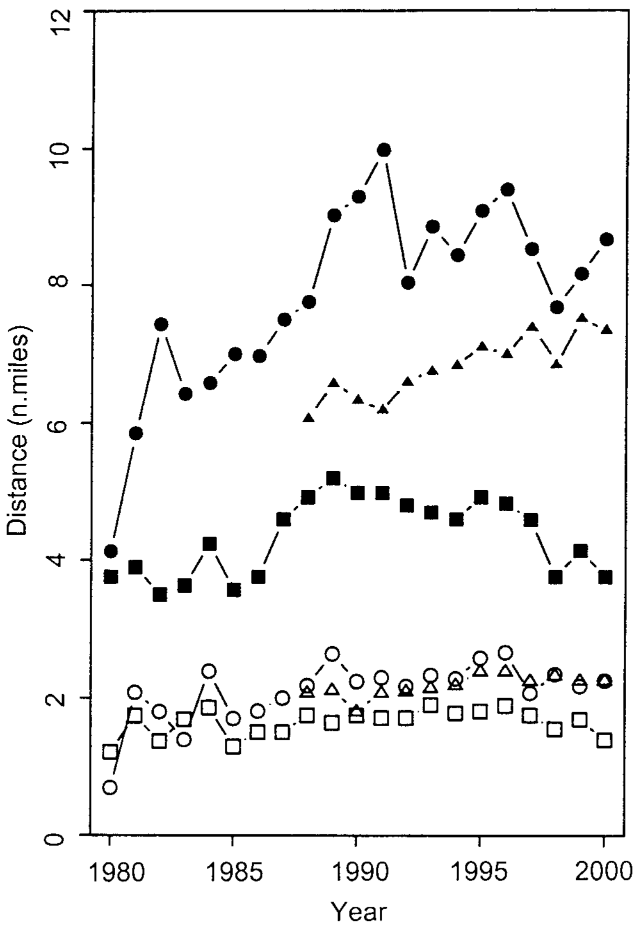

Fig. 7. Median distance of sightings ahead of the vessel (filled plot symbols) and median perpendicular distance to sightings (open plot symbols) for sightings made within 5 n.miles of the vessel, by sighting method. Similar patterns for distance ahead occur when all sightings are included. Squares: ‘boat’; circles: helicopter; and triangles: radar.

may be attributable to changes in data quality (captured by use of the hazard-rate model versus half-normal model) and the presence of fishery-introduced bias. For example, the average of previously published estimates from 1993-1997 shows a decrease of ~20% compared to the 1987-1991 average. By contrast, the average of weighted average estimates from 1993-1997 shows a decrease of ~4% as compared to that for 1987-1991 (Table 1). An El Niño effect on the index of relative abundance of northeastern offshore spotted dolphins in 1998 is consistent with the response of the indices to the 1982-1983 El Niño event (Figs 1, 4, 10), but the continued low level of the index through 2000 suggests that other processes are also at work. While we are unable to exclude the occurrence of a dramatic decrease in true abundance, the effects of selective reporting, coupled with apparent changes in fishing strategies noted above, lead us to suspect that such factors may play a role in the latest decrease as well.

IMPLICATIONS FOR MANAGEMENT

The identification of trends in bias associated with changes in data quality and fishery operations raises concerns about the use of this index for population management purposes, particularly in view of their recent use as input to population dynamics models (Anonymous, 1999). Because these indices span several decades, they are potentially an important tool for population management. However, their utility depends on establishing reasonable expectations of their ability to show trends in population change in the face of uncontrollable trends in bias. To address this issue, the potential use of relative abundance indices is categorised as follows: (1) as data inputs to population dynamics models; (2) as indicators of overall population stability; and (3) as indicators of overall population stability, and fisheries interactions, by way of comparison among species. The index in the context of each of these uses is discussed below.

Population dynamics models

As with many observer programmes, there is limited control over sighting data quality because observers may be dependent on vessel crew to obtain essential data such as distances and bearings. While we believe that major issues of bearing data quality have already been identified, rounding of bearings (and distances) still occurs and may be for all practical purposes unavoidable. Perhaps more importantly, there is probably no clear model for correcting the past bearing measurements to resolve the issue of excessive sightings near the trackline which occurred from the late 1970s through the 1980s. A half-normal model has been used for the detection function to study the effect of changes in the distribution of sightings near the trackline on the trend in the index of relative abundance because it is robust to excess sightings near the trackline. Identification of factors associated with excess sightings near the trackline (perhaps small herd size and large radial distance) might provide a less arbitrary means for screening and eliminating the effects of bearing data of dubious quality. However, because of uncertainty regarding the exact mechanisms leading to excesses and deficits of sightings near the trackline, it is unlikely that these issues will ever be completely resolved.

Correcting trends in bias due to changes in fishery operations presents a more difficult problem. Because of the evolution of helicopter and radar use in the last decade, observers appear to be further distanced from the search process, and sightings data made available to observers may

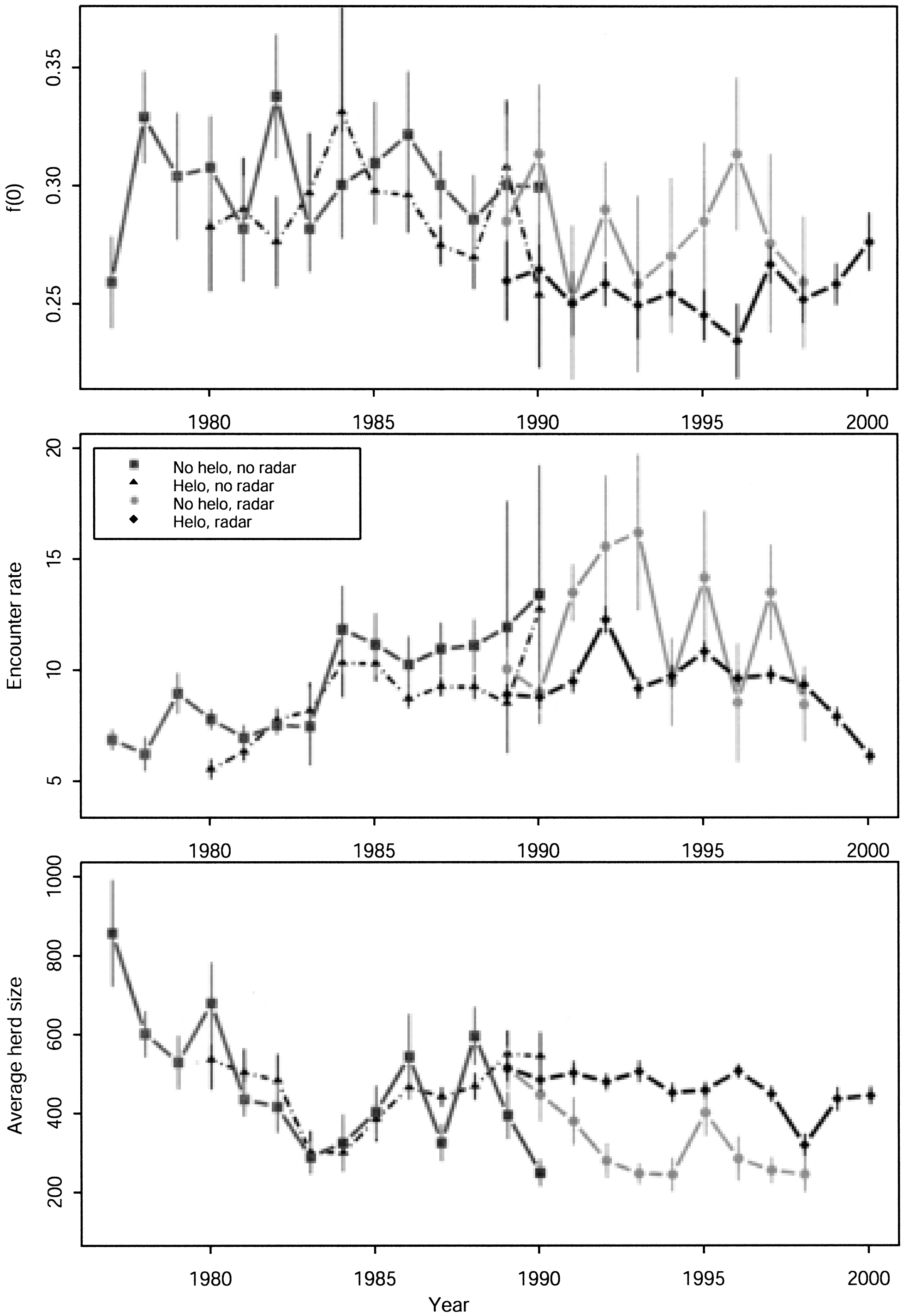

Fig. 8. Estimates of *f*(0) (top panel), encounter rate (middle panel) and average herd size (bottom panel) by mode of search for the northeastern stock of spotted dolphin (relative abundance shown in Fig. 10 and Table 2). Vertical bars indicate +/- one bootstrap standard error. 'Helo' = helicopter.

increasingly be for herds that were associated with sufficient fish to initiate a set. An increase in the percentage of 'search' that occurs post-detection (after the initial sighting, but before the set) since 1989 suggests more sightings are now being made at distances from the vessel where the observer probably has no ability to make an independent initial assessment of the sighting characteristics. Decreases in the percentage of binocular sightings leading to sets in the last several years (Fig. 5), combined with a decrease in the distance of binocular search ahead of the vessel (Fig. 7), suggest that further changes in fishing strategies and searching methods may be occurring. Further compounding these problems is the fact that new gear types, such as radar, are typically in use by the fishery some time before documentation of their use becomes part of data collection procedures. Thus, there is reason to believe that sources of fishery-introduced biases will continue to evolve. Because of the opportunistic nature of the data and the status of observer-fishermen relations, it seems likely that little can be done to address these changes in the near future, without incurring the great expense of designed surveys. Moreover, solutions to problems with historical data may remain elusive. The assumption of no trend in selective reporting made above is probably not valid, particularly in view of the increasing percentage of sightings that were initiated by helicopter and radar (Fig. 2), the greater percentage of

Table 2

Average total herd size (number of animals) by mode of search for herds involving offshore spotted dolphins. Shown are data for two areas and years 1989-1998 where there were at least 30 sightings. Standard errors (SE) and number of sightings (*n*) shown in parentheses. Overall, differences between average total herd size by mode of search were significant (mode of search effect estimated by weighted least squares): $p=0.01$ for sub-area shown in (1) below, and $p<0.01$ for sub-area shown in (2) below.

	Radar, helicopter	Radar, no helicopter
(1) Area: 80°-90°W and 5°-10°N		
1992	621 (SE = 37; *n* = 226)	597 (SE = 41; *n* = 231)
1993	754 (SE = 48; *n* = 243)	503 (SE = 42; *n* = 173)
1995	740 (SE = 40; *n* = 427)	535 (SE = 50; *n* = 141)
1996	653 (SE = 24; *n* = 672)	352 (SE = 28; *n* = 79)
(2) Area: 110°-120°W and 15°-25°N		
1991	329 (SE = 40; *n* = 35)	219 (SE = 33; *n* = 70)
1995	325 (SE = 26; *n* = 147)	160 (SE = 28; *n* = 40)
1996	316 (SE = 14; *n* = 301)	207 (SE = 33; *n* = 48)
1997	254 (SE = 13; *n* = 386)	154 (SE = 19; *n* = 67)
1998	262 (SE = 11; *n* = 605)	181 (SE = 26; *n* = 57)

helicopter sightings that led to sets (Fig. 5) and the increase in the overall sighting success rate. The presence of selective reporting would suggest that the estimates of $f(0)$ are not only conditional on detection, but also on the presence of sufficient fish to warrant further investigation. Annually, the effect of selective reporting on $f(0)$ might be explicitly addressed by using an estimate of the probability density function of the presence of sufficient fish associated with detected herds of given herd sizes to obtain an unconditional estimate of $f(0)$. However, it is unclear how this correction might be made in the 1990s, when data of vessels without helicopters and radar are too few to allow analysis by mode of search. Thus, we believe that trends in fishery-introduced biases are probably an inevitable shortcoming of opportunistic data.

For marine mammal species, these persistent problems raise questions about the wisdom of using such indices for fitting population dynamics models. The maximum growth rate for spotted dolphins in the eastern Pacific Ocean has been estimated to be 3.8% per year (Wade, 1994). From comparison of the index based on the half-normal model to that based on the hazard-rate model, we infer that changes in data quality rather than changes in real abundance were

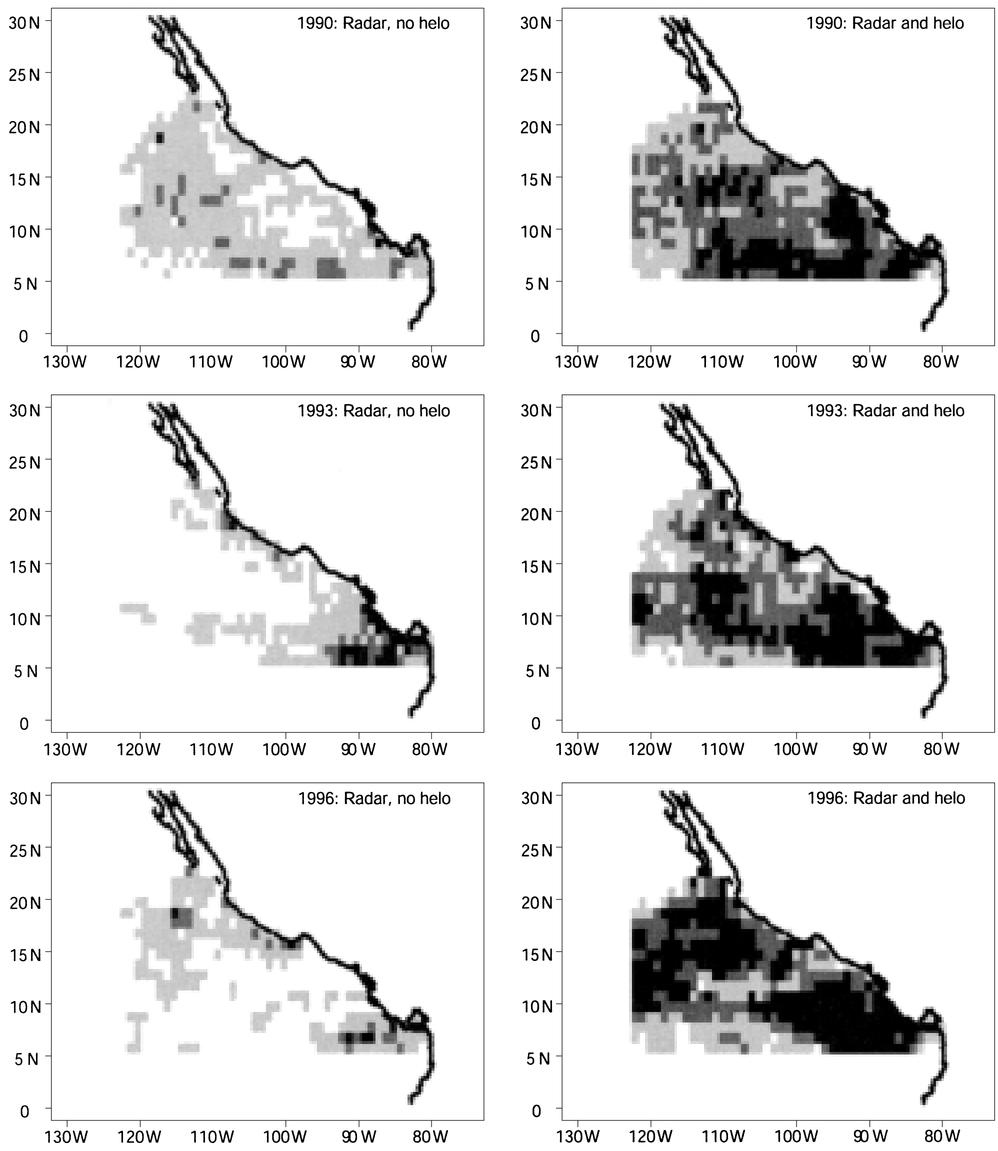

Fig. 9. Spatial distribution of searching effort (n.miles searched), by 1° square, for 'No helicopter, radar' and 'Helicopter, radar' modes of search in 1990, 1993 and 1996. Greyscale: ≤150 n.miles (light grey); >150 n.miles and ≤400 n.miles (intermediate grey), >400 n.miles (dark grey). 'Helo' = helicopter.

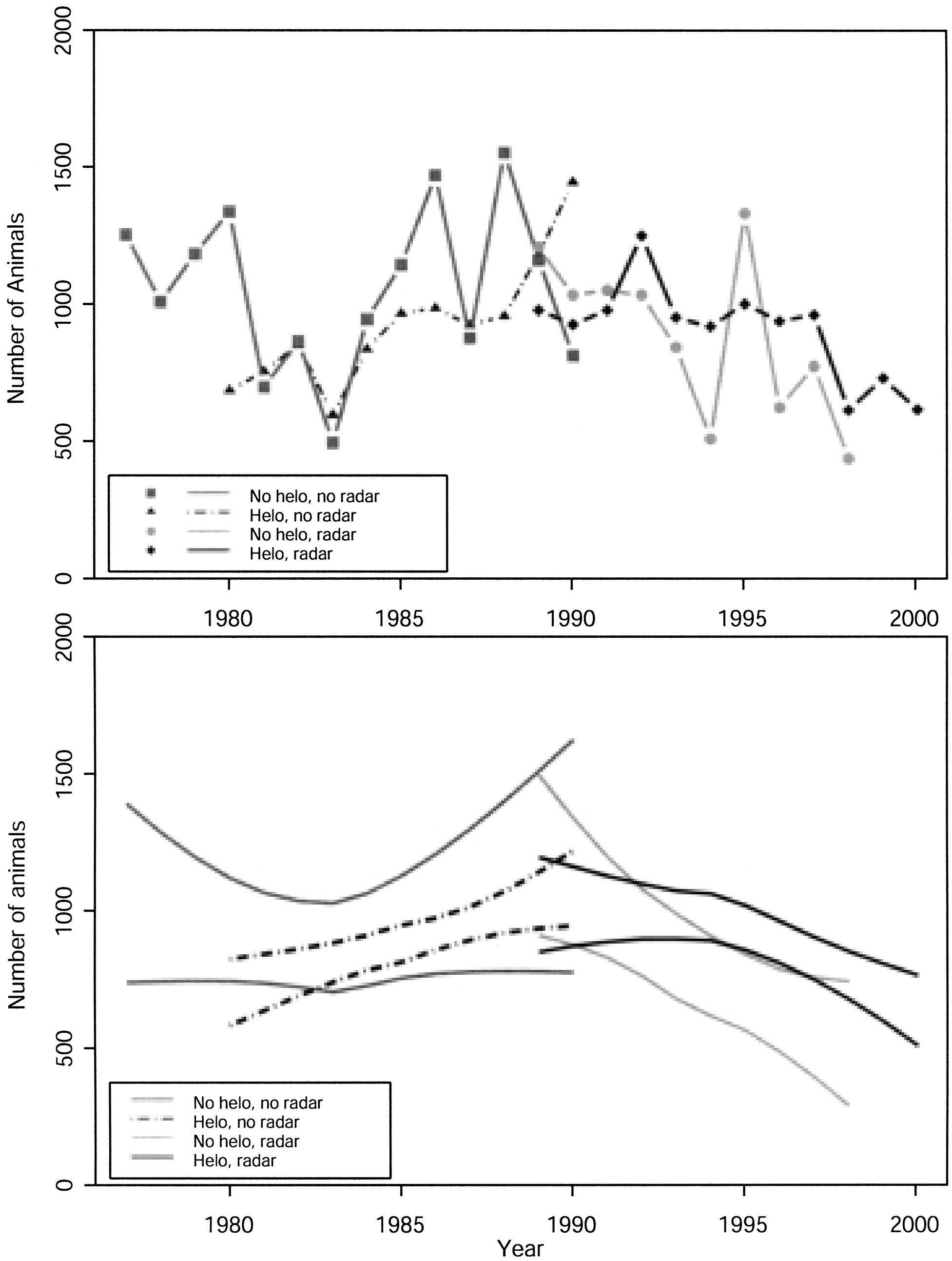

Fig. 10. Estimates of the index of relative abundance (thousands of animals) for the northeastern stock of spotted dolphin by mode of search. Top panel: point estimates (Table 2); bottom panel: approximate pointwise 95% confidence bands computed from a smooth of the time series shown in the top panel (smooth based on a locally-weighted moving line with a smoothing parameter of 1.0 (Cleveland, 1979) and additional weights equal to the inverse of the variance of relative abundance). 'Helo' = helicopter.

responsible for an approximate decrease of 11% over 15 years, or a rate of roughly 0.7% per year. In addition, from the overall increase in the percentage of sightings that led to sets, we infer that selective reporting minimally contributed to a change of approximately 6% over 21 years or roughly 0.3% per year (this assumes no effect on herd size or detection near the trackline). Alternatively, from comparison of the hazard-rate model to the 'Modes of search' index, we infer that changes in data quality and fishery-introduced biases were responsible for a change of approximately 16% over 11 years, or about 1.5% per year. Thus, conservatively, issues of data quality and fishery-introduced biases may have contributed to a trend in the index at a rate of approximately 1.0-1.5% per year, or about one quarter to one third of the maximum estimated growth rate. If the maximum growth rate is not being achieved, perhaps due to long-term changes in oceanography (e.g. Ebbesmeyer *et al.*, 1991; Wolter and Timlin, 1998; Miller and Schneider, 2000) that may affect carrying capacity, trends in bias and growth rates may be of similar magnitude. In such cases, trends in the index (or lack thereof) may reflect the confounding of trends in biases and changes in population size. Thus, we believe the use of these indices as input to population dynamics models to be ill-advised.

Overall stability

In view of the aforementioned trends in biases, we are left with an apparently stable, albeit biased, index of relative abundance for both the northeastern stock of offshore spotted dolphin and the eastern stock of spinner dolphin.

Table 3

Estimates of indices of relative abundance for northeastern offshore spotted dolphins, in thousands of animals, by mode of search for years with at least 10 trips and 3 spatial strata. Bootstrap standard errors shown in parentheses. Dashed lines indicate inadequate sample sizes.

Year	No helicopter, no radar	Helicopter, no radar	No helicopter, radar	Helicopter, radar
1977	1,252 (270)	-	-	-
1978	1,008 (183)	-	-	-
1979	1,182 (239)	-	-	-
1980	1,336 (243)	684 (131)	-	-
1981	696 (128)	753 (114)	-	-
1982	863 (152)	848 (134)	-	-
1983	494 (160)	595 (174)	-	-
1984	943 (351)	834 (182)	-	-
1985	1,143 (206)	965 (164)	-	-
1986	1,470 (429)	984 (95)	-	-
1987	875 (154)	922 (63)	-	-
1988	1,552 (250)	955 (75)	-	-
1989	1,160 (647)	1,181 (226)	1,206 (247)	977 (113)
1990	811 (416)	1,444 (326)	1,032 (231)	924 (78)
1991	-	-	1,050 (262)	977 (99)
1992	-	-	1,031 (182)	1,249 (87)
1993	-	-	841 (281)	950 (86)
1994	-	-	508 (170)	917 (85)
1995	-	-	1,330 (421)	1,000 (77)
1996	-	-	622 (185)	937 (80)
1997	-	-	772 (208)	960 (60)
1998	-	-	436 (162)	612 (69)
1999	-	-	-	728 (75)
2000	-	-	-	614 (60)

Data quality problems mean that little confidence can be placed in trend estimates in the late 1970s and early 1980s. Since the early 1980s, however, the northeastern offshore stock of spotted dolphins appears to have been relatively stable (Fig. 4; Table 1). Indeed, the 'Modes of search' index for northeastern offshore spotted dolphins is remarkably stable between 1985-1997; only one estimate falls below 1,000, and only one exceeds 1,150. The standard deviation of these 13 estimates is just 95, compared with a mean standard error of the annual estimates of 169; had there been significant changes in abundance through this time period, the standard deviation would have been expected to exceed the mean of the standard errors. Similarly, since the early 1980s, it seems that the eastern stock of spinner dolphins has been more or less stable (Table 1). The apparent stability of the indices for these two stocks is consistent with published research vessel annual estimates of absolute abundance that have large standard errors, and seem even more variable than these standard errors would imply, but do not show any compelling evidence of change (up or down) since the early 1980s (Wade, 1994; Gerodette, 1999; 2000).

The stability of the index for these stocks may be an indication of changes in carrying capacity. Both stocks are presumed to have been well below historic abundance in the late 1970s, following high levels of mortality (DeMaster *et al.*, 1992; Wade, 1994). If trends in bias were no more than say 2% per year and, because of depletion, dolphin populations were achieving maximal growth rates, some indication of an increase in the index over the 1985-1997 period might be expected. The lack of an increase may indicate that carrying capacity is now below historic abundance or that carrying capacity, and hence abundance, has always fluctuated, perhaps cyclically, and that carrying capacity is currently relatively low for environmental or other reasons. Because spotted and spinner dolphins have potential rates of recovery that are slow, fluctuating or cyclically-varying carrying capacity may reduce this potential rate to the point that a 1-2% bias in trend will mask it entirely, resulting in an appearance of stability.

Inter-species comparisons

Indices derived from fisheries data may be most useful in helping to understand differences in trends among species because it may be easier to verify that changes in data quality and fishery-introduced biases are similar among species than to verify that such trends in biases have been adequately addressed in data analysis. We have yet to verify whether issues of bearing data quality and selective reporting similarly affect sightings of northeastern offshore spotted dolphins and eastern spinner dolphins. However, this seems a more tractable task than verifying that these issues, particularly selectively reporting, have been corrected. Long-term trends differ between the indices for northeastern offshore spotted dolphins and eastern spinner dolphins, in part because of the decrease in the indices for northeastern offshore spotted dolphin in the last three years beginning with the 1997-1998 El Niño (Table 1; Fig. 1). The decrease in the index for northeastern offshore spotted dolphins during the recent strong El Niño-La Niña period, and a similar decrease during the 1982-1983 El Niño (Table 1; Fig. 1) raises the question of whether the stock 'boundaries' for spotted dolphins have remained constant over time. The eastern stock of spinner dolphins is distinguishable morphologically, and it is perhaps unsurprising therefore that it is possible to estimate long-term temporal trends with greater consistency than for a stock that is defined purely by whether the animals occur within a geographic area. Changes in oceanographic climate have been hypothesised to lead to movement outside of stock boundaries for other species (Forney, 1999). Whether strong El Niño events cause offshore stocks of spotted dolphin to shift their distribution, or whether it merely causes a change in behaviour that makes them less accessible to the tuna fleets, is unclear. Decreases in the index during El Niño periods for northeastern offshore spotted dolphins largely result because herd sizes of reported sightings are smaller during El Niño events (Fig. 8; Anganuzzi and Buckland, 1994). The cause of these changes in herd size is not known. However, such environmentally correlated events may provide useful data on environmental controls of dolphin-tuna associations.

SUMMARY

This paper has focused on the effects of changes in data quality and fishery-introduced biases on the applicability of data collected by observers aboard tuna vessels for estimation of relative abundance indices. For comparison to previously published indices, a half-normal model has been used to explore sensitivity of the indices to long-term changes in the relative proportion of sightings near the trackline. In addition, estimates of relative abundance by different modes of search have been computed to explore sensitivity of the indices to fishery-introduced biases such as selective reporting of sighting data by vessel crew. The results suggest that a significant percentage of the long-term decreasing trend in the previously published index of relative abundance for northeastern spotted dolphins may be due to changes in data quality and fishery-introduced biases in the last two decades. It is concluded that because of the magnitude of these biases, and their inherent presence in such opportunistic data, the use of fishery-based indices as input to population dynamics models for slow growing species is problematic and unlikely to produce sound

guidance for management purposes. On the other hand, fishery-derived indices may be useful for understanding differences between species, both in terms of fishery interactions and in terms of episodic oceanographic events such as El Niño. Over an extended period, such indices may also give a rough guideline of the state of a stock. For example, it seems unlikely that either of the stocks examined here are increasing at rates that might be expected if they had been well below carrying capacity through the 1980s. In spite of the pervasive nature of the aforementioned sources of bias, future research on the use of these indices must include efforts to develop more theoretically rigorous solutions to known problems, including better modelling of the detection function in the presence of biases in bearing measurements and rounding, and corrections for selective reporting by vessel crew that are not dependent on the assumption of no trend in reporting rates.

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