



Evaluating trends and biases in shipboard tuna vessel data used in the estimation of Dolphin abundance by Eric John Ward

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Biological Sciences

Montana State University

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Abstract:

Since the 1950s, several million dolphins have been reported killed by tuna vessels in the eastern tropical Pacific Ocean. In response to the Marine Mammal Protection Act, data has been collected on all stock of dolphins in the eastern tropical Pacific, including the stock most affected by the yellowfin fishery, the northeastern stock of offshore spotted dolphins (*Stenella attenuatd*). Data collected aboard tuna vessels does not conform to the assumptions necessary to analyze standard line transect data, but because of the volume of data available, tuna vessel data may be statistically corrected to examine relative trends in dolphin abundance. A third bias is that dolphin schools reported by tuna vessels are significantly larger than those reported by research vessels.

In this analysis, I attempted to quantify the impact each of the mentioned biases has on estimates of relative dolphin school size estimates from tuna vessel data. Search effort appeared to become more concentrated in areas of the eastern tropical Pacific with larger school sizes. Search technology also focused more effort on schools that were larger than average. Assuming both of these biases exhibited linear trends, I rescaled school sizes and abundance trajectories relative to the 1980 estimates. After removing the temporal and spatial variability that may affect estimates of dolphin schools reported by tuna vessels, I was able to conclude that schools reported by tuna vessels tend to be larger than those reported by research vessels (and this difference appears to have decreased over time). My final correction of tuna vessel data relied on research vessel data, which was only collected for half of the time series. While it does appear to reduce a small amount of bias in estimates calculated from tuna vessel data, I was not able to correct for all of the bias, due to the limitations of the research vessel data.

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by

Eric John Ward

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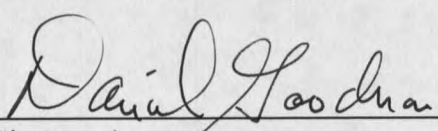
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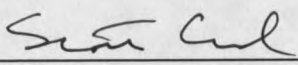
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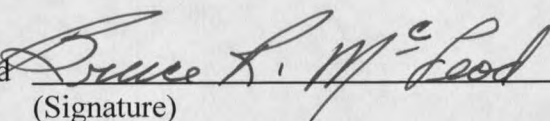
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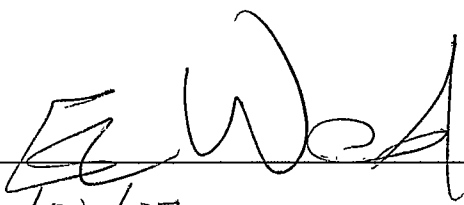

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ABSTRACT

Since the 1950s, several million dolphins have been reported killed by tuna vessels in the eastern tropical Pacific Ocean. In response to the Marine Mammal Protection Act, data has been collected on all stock of dolphins in the eastern tropical Pacific, including the stock most affected by the yellowfin fishery, the northeastern stock of offshore spotted dolphins (*Stenella attenuata*). Data collected aboard tuna vessels does not conform to the assumptions necessary to analyze standard line transect data, but because of the volume of data available, tuna vessel data may be statistically corrected to examine relative trends in dolphin abundance. A third bias is that dolphin schools reported by tuna vessels are significantly larger than those reported by research vessels.

In this analysis, I attempted to quantify the impact each of the mentioned biases has on estimates of relative dolphin school size estimates from tuna vessel data. Search effort appeared to become more concentrated in areas of the eastern tropical Pacific with larger school sizes. Search technology also focused more effort on schools that were larger than average. Assuming both of these biases exhibited linear trends, I rescaled school sizes and abundance trajectories relative to the 1980 estimates. After removing the temporal and spatial variability that may affect estimates of dolphin schools reported by tuna vessels, I was able to conclude that schools reported by tuna vessels tend to be larger than those reported by research vessels (and this difference appears to have decreased over time). My final correction of tuna vessel data relied on research vessel data, which was only collected for half of the time series. While it does appear to reduce a small amount of bias in estimates calculated from tuna vessel data, I was not able to correct for all of the bias, due to the limitations of the research vessel data.

INTRODUCTION

The tuna-dolphin issue in the eastern tropical Pacific Ocean (ETP) represents one of the best examples of the trade-off between conservation biology and commerce. Since the 1950s, the yellowfin tuna (*Thunnus albacares*) fishery in the ETP has been using purse-seine technology, and has become one of the most financially successful fisheries in the world. Schools of *T. albacares* are not usually visible from the surface, but since dolphins that associate with tuna are visible, fishermen can exploit the tuna-dolphin relationship to capture tuna. Ideally, dolphins are allowed to escape over the top of the purse-seine net after being encircled, but injuries and death do occur. The two species of dolphin with the closest ecological relationship to tuna, the spotted dolphin (*Stenella attenuata*) and the spinner dolphin (*S. longirostris*), have suffered large reported incidental mortality by the fishery. The northeastern stock of *S. attenuata* and the eastern stock of *S. longirostris* have been listed as depleted under the Marine Mammal Protection Act (MMPA) since 1993. Historically, the dolphin mortality incurred by the fishery has represented significant fractions of the northeastern stock of *S. attenuata* (Smith, 1983) and the stock is not showing clear signs of recovery (Wade et al., 2002). This analysis will focus on the northeastern stock of *S. attenuata*, which historically has been the stock with the highest reported mortality and has been involved in the largest proportion of sets on dolphins in the ETP (Archer et al., 2002; Gosliner, 1999).

Beginning in the late 1970s, the Inter-American Tropical Tuna Commission (IATTC) and National Marine Fisheries Service (NMFS) have collected independent data

on the northeastern stock of *S. attenuata*. Research surveys have been conducted by NMFS (Gerrodette et al., 1991; Gerrodette et al., 2002; Holt et al., 1987; Holt et al., 1989; Wade et al., 1992) in twelve years between 1979-2000. The research vessel surveys utilize standard line transect methods (Buckland et al., 1992; Buckland et al., 1993, Buckland et al., 2001). The IATTC has maintained a second data set, which is opportunistic data collected from tuna vessel observers, and is known to violate standard line transect methods and assumptions (Buckland et al. 1988). The tuna vessel observer data set has been collected in all years since 1974 and has been used to compute an index of relative abundance (Anganuzzi et al., 1991; Anganuzzi et al., 1993; Anganuzzi et al., 1994). Because of possible changes in data quality and variables relating to tuna vessel fishing technology (Lennert-Cody et al., 2001) the appropriate use of tuna vessel data as a complement to research vessel data has become uncertain.

History

During the 1960s and early 1970s, annual incidental dolphin mortality in the ETP was estimated to be several hundred thousand animals (Gosliner, 1999; Wade, 1995). In 1972, Congress passed the MMPA, prohibiting the future kills of marine mammals in U.S. waters, kills of marine mammals by U.S. citizens, and imported marine mammal products. The first important piece of the original MMPA legislation was the definition of the term "take," as the act or attempted act of harassing, hunting, capturing or killing marine mammals. Congress recognized the necessity of not destroying the ETP tuna fishery, and granted the fishery an exception to the MMPA. The taking of *S. attenuata*

was still allowed, with the ultimate goal of eventually approaching zero mortality. A second important piece of legislation in the MMPA was that the term "depleted" could be applied to any stock estimated to be at a level less than its calculated optimum sustainable population size (OSP, 60% of carrying capacity).

In an effort to monitor the annual number of dolphins killed by the fishery, NMFS started placing trained observers on some U.S. tuna vessels, starting in 1974. The IATTC began placing observers on non-U.S. vessels, starting in 1979. Some observers were placed on tuna vessels prior to 1974, but participation in those programs was voluntary (Gosliner, 1999). The initial responsibility of tuna vessel observers was to monitor the number of dolphins killed or injured during sets, but observers also collected information on dolphin school size, species composition of schools, and additional variables not relating to fishing behavior (e.g. Beaufort conditions, water temperature). By 1986, 100% of the countries fishing in the ETP were participating in the observer program (Gosliner, 1999); however, full observer coverage on all tuna vessels was not in place until 1995.

Over the course of the 1980s, several amendments were passed to the original MMPA. As fishing regulations in the ETP became stricter about setting on dolphins, many vessels that were registered in the U.S. became registered in foreign countries. Between 1980 and 2000, the number of U.S. vessels in the fleet dropped from approximately 100 vessels to less than 10, and U.S. vessels became outnumbered by non-U.S. vessels approximately 20:1 in 1995 (Gosliner, 1999). As a result of the change in fleet demographics, U.S. dolphin mortality dropped significantly, and incidental mortality by international vessels increased. In an effort to pressure non-U.S. vessels to achieve

mortality levels similar to U.S. vessels, the U.S. adopted an embargo against countries that did not practice dolphin-safe sets. This embargo was ultimately overturned with the International Dolphin Conservation Act (1992). The La Jolla Agreement was also signed in 1992 and was important for several reasons. First, an international quota on dolphin kills was passed for the first time, and was recognized by all countries fishing in the ETP. Second, the overall dolphin quota was shifted from a quota for the entire fleet to a by-vessel quota, or "dolphin mortality limit" (Gosliner, 1999). The goal of the new quota system was to reward captains and crews that achieved low mortality levels, rather than punish them when the fleet-wide quota was reached.

Line Transects

Ecological surveys for estimating wildlife abundance typically fall into one of two categories. The first method, capture-recapture, involves conducting multiple surveys on the same population, and estimating abundance by repeatedly capturing or marking individuals during each survey (Seber, 1982). The second method involves estimating abundance by conducting point transect or line transect surveys (Buckland et al., 1993). Line transect surveys have been conducted on dolphin stocks in the ETP for several reasons. First, the size of the northeastern stock area of *S. attenuata* is approximately 60% the size of the U.S. ($5.69 \cdot 10^6 \text{ km}^2$ versus $9.63 \cdot 10^6 \text{ km}^2$), requiring large-scale shipboard or aerial surveys. Second, because there are hundreds of thousands of dolphins in the region, the probability of an individual being sighted and re-sighted in a capture-recapture study is extremely small. Capture-recapture studies for marine mammals often

rely on large photographic databases for identification, and the number of *S. attenuata* individuals photographed in the ETP has been relatively small.

Several parameters need to be estimated for each object detected during line transect surveys. It is possible to estimate the perpendicular distance of an object from the survey trackline, but generally more accurate to estimate the radial distance from the point of detection to the object, and the sighting angle between the trackline and the detected object. After a transect or set of transects is complete, perpendicular distances are calculated from sighting angles and radial distances. The histogram of perpendicular distances is normalized and fit with a detection function (Buckland, 1985; Buckland, 1992a; Buckland, 1992b). For individual animals occurring in groups, such as dolphins, group size also needs to be estimated. Using the probability density function (p.d.f.) of detection distances evaluated at zero ($f(0)$) and the average group size, the standard line transect estimator can be applied (Burnham et al., 1980): $N_d = \frac{A \cdot n_s \cdot f(0) \cdot \bar{s}}{2L}$, where N_d represents the estimated number of animals, A is the size of the survey area, n_s is the number of groups detected over the entire survey, $f(0)$ is the p.d.f. of perpendicular distances evaluated at zero, $\bar{s}$ is the average group size, and L is the total length of trackline searched. The quantity $f(0)$ can also be written as $\frac{1}{w}$, where w is the effective strip half-width of the transect.

To obtain unbiased estimates of abundance from line transect surveys, several assumptions are required. Some of these assumptions are more robust than others, however all are applicable to both research vessel surveys and opportunistic tuna vessel

surveys. These assumptions are listed in order of decreasing importance (Buckland et al., 1988):

- 1) Within each region or stratum, either vessel search effort is randomly distributed or dolphin schools are randomly distributed;
- 2) Any movement of dolphin schools before detection is slow relative to the speed of the vessel;
- 3) All schools on the trackline are detected and identified with probability 1.0;
- 4) Sighting angles and distances are made without measurement error;
- 5) Sightings of schools are independent events;
- 6) School size is recorded without measurement error (and for mixed species schools the proportion of a given species is recorded without error);
- 7) The probability of detection for a given school is independent of its size, at least out to the boundary of the effective strip width.

Some of the above assumptions are violated in both research vessel data and the tuna vessel data. For example, it is impossible to assume that sighting angles and distances are recorded perfectly, as both are prone to human measurement error and rounding (Hammond et al., 1983). However, it is possible to assume that the errors on bearing and distance measurements are normally distributed, and do not exhibit directional trends that would contaminate the data (Kinzey et al., 2002). Because tuna vessel data are known to violate most of the above assumptions, *S. attenuata* abundance estimates derived from tuna vessel data cannot be used as indices of true abundance. The IATTC has relied on tuna vessel data for inference of relative abundance estimates. The time series of relative abundance is dependent on the assumption that any biases in tuna vessel data have

remained constant in time and have not exhibited a trend (Buckland et al., 1988). As *S. attenuata* abundance estimates have fluctuated since 1980, biases in the tuna vessel data must have remained proportionally constant over the time series. If biases have exhibited a temporal trend, inference of relative abundance will be impossible unless that trend in bias can be estimated and corrected. There also may be non-lethal biases present in the data that do not exhibit a temporal trend, but are problematic and should be corrected before final abundance estimates are calculated.

Current Status

Since 1992, incidental kills of the northeastern stock of *S. attenuata* have dropped significantly. Based on the advancements in fisheries technology, current estimates of reported incidental mortality for this stock are less than 1000 dolphins annually, having dropped from more than an estimated 300,000 dolphins annually (Gosliner, 1999; Wade, 1994). This represents a relatively insignificant fraction of the total stock size, however the population does not appear to be recovering to its pre-exploitation population size (Wade et al., 2002). The abundance trajectory calculated from the research vessel surveys (Figure 1; Gerrodette et al., 2002) does not show a clear trend since 1980, nor do the individual components of the line transect estimator calculated from research vessel data (Figures 2-4; Gerrodette et al., 2002). Average school size estimates do appear to be sensitive to strong El-Niño events (1983, 1998). In years with smaller average school size, there does appear to be a higher encounter rate of schools per nautical mile.

Figure 1. Abundance of the northeastern stock of *S. attenuata*, calculated from research vessel surveys (Gerrodette et al., 2002). Error bars indicate 1 standard error.

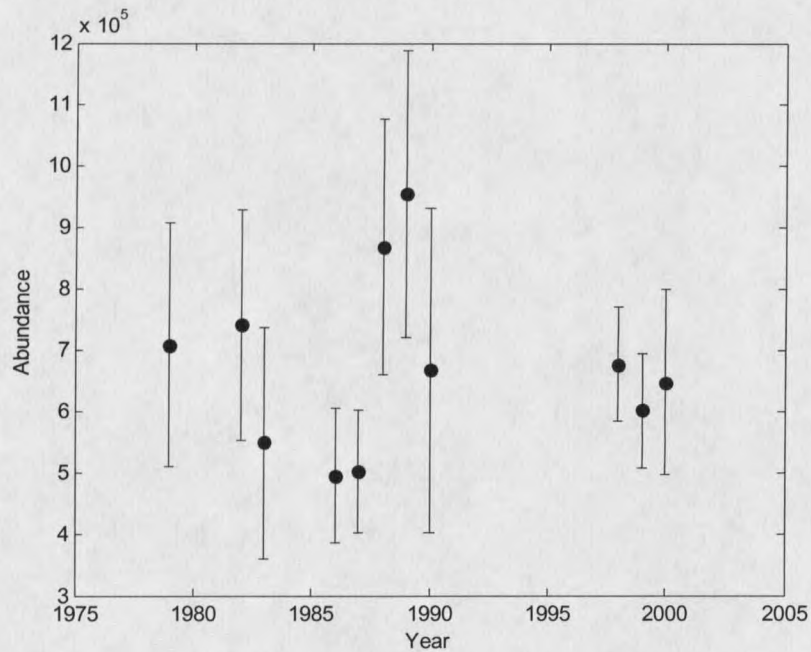


Figure 2. Estimates of $f(0)$ for the northeastern stock of *S. attenuata*, calculated from research vessel surveys (Gerrodette et al., 2002). Error bars indicate 1 standard error.

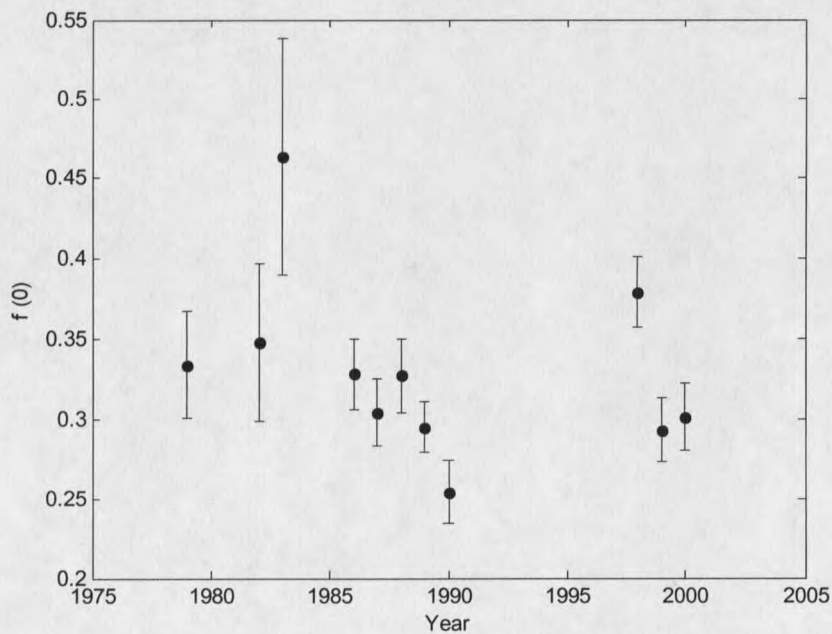


Figure 3. Estimates of average school size for the northeastern stock of *S. attenuata*, calculated from research vessel surveys (Gerrodette et al., 2002). Error bars indicate 1 standard error.

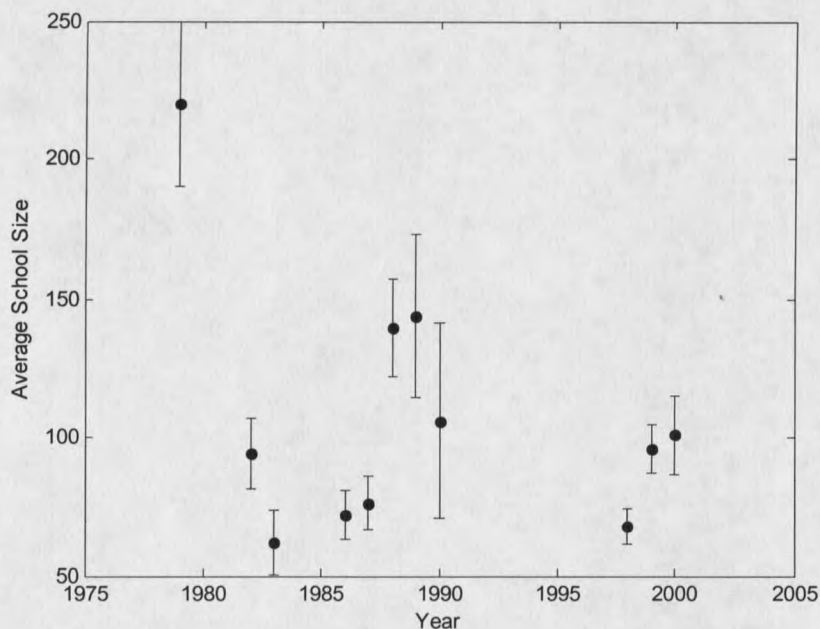
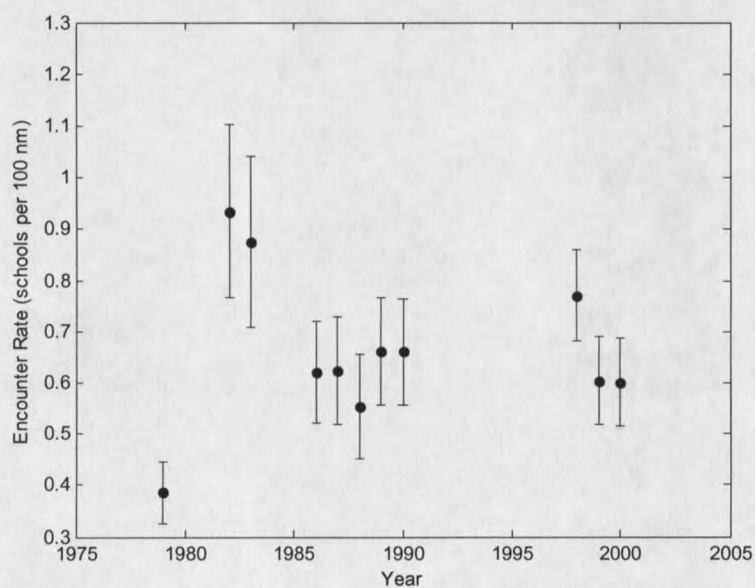


Figure 4. Estimates of encounter rate for the northeastern stock of *S. attenuata*, calculated from research vessel surveys (Gerrodette et al., 2002). Error bars indicate standard error.



There are several hypotheses for why the northeastern *S. attenuata* stock has not recovered. First, the population of *S. attenuata* may have shifted outside of the defined northeastern stock region, either because of environmental variables (Fiedler et al., 1994; Polacheck, 1987; Reilly et al., 1994) or in response to increased fishing in the stock region. Second, there may be indirect mortality involved in the fishing process, where animals are weakened or injured significantly during sets, but are not reported as killed. Third, the increased efficiency by the tuna fishery has caused some dolphin schools to be set on an average of eight times annually (Perkins et al., 1999). This increased efficiency may have detrimental effects on population fecundity, via increased stress levels (Curry, 1999). Since 1980, the estimated number of set on *S. attenuata* has increased (Figure 5; Archer et al., 2002), as has the estimated number of captured and chased *S. attenuata* individuals (Figure 6-7; Archer et al., 2002). The intensity of fishing activity appears to have decreased since the late 1980s, and appears to have been relatively constant since the early 1990s. Several types of fishing procedures not involving sets on dolphins have been explored (i.e. setting nets on logs or other floating debris), however all are less efficient at catching large yellowfin tuna than setting on schools of dolphins (United States, 1997). In 2001, NMFS used a chartered fishing vessel to measure the effects of stress on dolphins as a result of repeated chase and encirclement. In addition to blood and skin samples, information was collected on cow/calf separation and behavior between chases.

Figure 5. Estimated sets on the schools of *S. attenuata* in the northeastern stock region of the ETP (Archer et al., 2002).

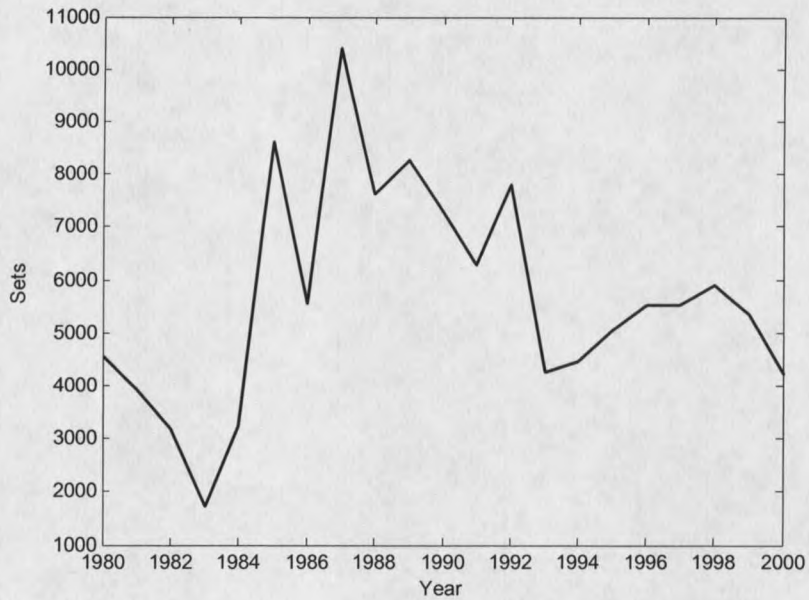


Figure 6. Estimated *S. attenuata* individuals captured in purse-seine nets in the northeastern stock region of the ETP (Archer et al., 2002).

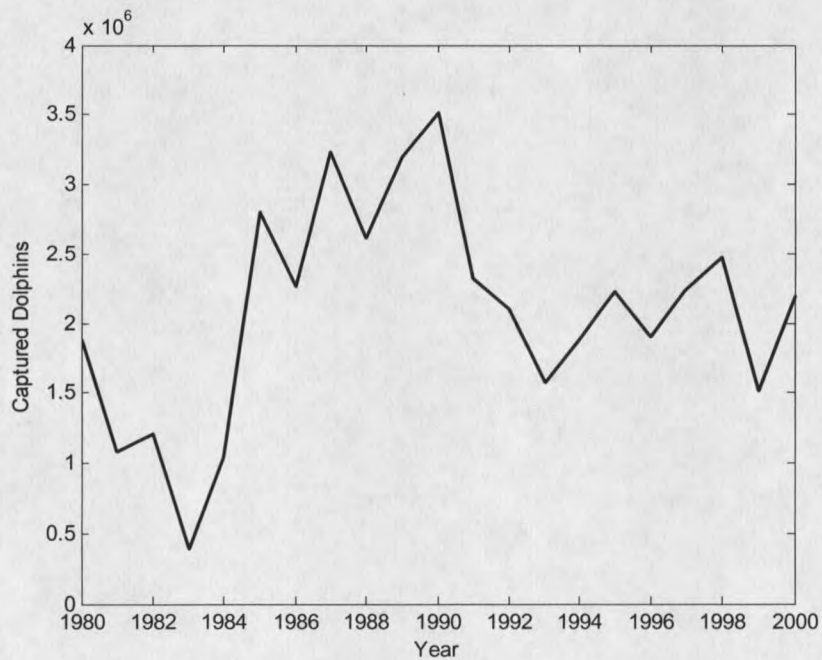
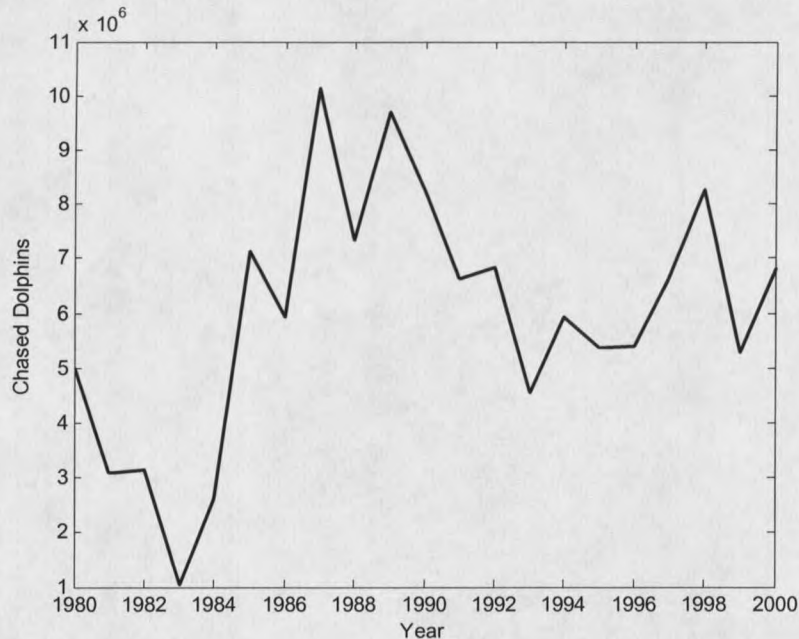


Figure 7. Estimated *S. attenuata* individuals chased during purse-seine fishing operations (captured and not captured) in the northeastern stock region of the ETP (Archer et al., 2002).



After conducting the chase and encirclement study, in addition to a 3 year population survey between 1998-2000, NMFS declared that purse-seine fishing operations were not detrimental to the recovery of the northeastern stock of *S. attenuata*, or any other depleted dolphin stock in the ETP (NMFS, 2002). An independent review panel reviewing NMFS' research suggested that portions of the tuna vessel data be used in addition to data collected from research vessel surveys, as data from research vessel surveys does not represent a continuous time series (Southwest Fisheries Science Center, 2002). If tuna vessel data and research vessel data are to be analyzed together to create a combined time series of abundance, time-varying biases cannot be present in the tuna vessel data.

Objectives

Of the three components associated with estimating dolphin abundance, the estimate of average school size has the largest vulnerability to bias, and will be the focus of this analysis. While all three of the line-transect components are affected by the non-random search process, search effort may be deliberately school size selective, and school size estimates are prone to observer error (encounter rate is only dependent on whether or not a school is observed and reported, and radar is often used to estimate the radial distance and bearing of each school detected by tuna vessels (Lennert-Cody et al., 2001), used to estimate $f(0)$).

There have been certain biases in the tuna vessel data set that represent a temporal trend and remain uncorrected for, such as the change in fishing technology and searching methods (Lennert-Cody et al., 2001). Related to this change is that there may be a trend in the distribution of tuna vessel search effort relative to the distribution of *S. attenuata* school sizes, as tuna vessels have become more skilled at finding large dolphin schools. According to basic line transect assumptions, the distribution of tuna vessel search effort should be random. Any departure from randomness should not exhibit a trend, because inference of the relative abundance estimates would be biased. A second uncorrected bias is that *S. attenuata* school sizes reported by tuna vessel observers have historically been larger than those reported by research vessels. It is unclear whether tuna vessels sample different spatial portions of the stock region, or whether observations made from tuna vessels tend to be overestimated. If there is a systematic over-reporting by tuna

vessel observers, any temporal trend in this bias would also prevent inference using the tuna vessel data index.

From a management standpoint, inference of tuna vessel data would not only supplement the existing research vessel data, but may be able to provide more insight on temporal and spatial variability on ETP dolphin populations. An absolute decision of whether or not *S. attenuata* abundance estimates from TVOD are reliable is beyond the scope of this project. The first objective of this analysis is to include a detailed description of the abundance estimation procedure currently used by the IATTC to estimate dolphin abundance from TVOD. A second objective is to attempt to quantify some known biases that exist in the TVOD, and to explore additional biases that may be subject to temporal trends. If biases in the TVOD are found to exhibit time-varying biases, I will attempt to correct for them. Any such correction depends on identifying the true model for the underlying bias (e.g. linear, quadratic, etc.).

Some biases in the TVOD have already been thoroughly examined (Lennert-Cody et al., 2001; Perkins, 2000). Other biases, such as the non-random distribution of search effort, have been evaluated (Anganuzzi, 1992), but the impact of the bias on TVOD estimates have not been quantified. Changes in search technology and tuna vessel fishing behavior have been examined (Lennert-Cody et al., 2001), but the impact of this bias on TVOD estimates has not been previously quantified. My goal is to quantify and correct for these biases, assuming that they have been varying linearly.

One bias that has not been examined in previous analyses is the disparity between dolphin schools reported by research vessel surveys, and dolphin schools reported by tuna vessels. The magnitude of the difference is quite large (tuna vessel observers often

observe schools 3-4 times the size of research vessel schools). I will attempt to determine the reason for the difference between the observation types, as well as whether the difference is affected by a time-varying trend. If the bias is found to prevent inference of *S. attenuata* abundance, I will attempt to correct for it. Corrected estimates will be compared to the original IATTC abundance estimates, as well as to NMFS estimates to determine whether the correction works as intended.

RELATIVE *S. ATTENUATA* ABUNDANCE CALCULATED FROM TUNA VESSEL
OBSERVER DATA AND INITIAL TRENDS, 1980-2000

Abstract

Tuna vessel observer data is opportunistic in nature, and does not conform to the standard assumptions of line transect theory. Some biases may be corrected for simply by removing sightings known to introduce bias. Other biases, such as the non-random distribution of tuna vessel search effort, are more complicated to remove. This analysis focuses on trends in the components of the line transect estimator, and possible trends in the tuna vessel data between 1980 and 2000. While encounter rate estimates appear to have the strongest linear association with abundance estimates, the residuals of $f(0)$ appear to have the strongest linear association with the residuals of abundance. The temporal trends explored here do not prevent inference of relative abundance, but do suggest a change in both search technology and data quality since 1980. These trends are consistent with known changes in fishing technology (Lennert-Cody et al., 2001).

Introduction

The Inter-American Tropical Tuna Commission (IATTC) has estimated trends in the abundance of the northeastern stock of the spotted dolphin *S. attenuata* using data collected aboard tuna vessels since the late 1970s. Data collected from observers on tuna vessels (tuna vessel observer data, TVOD) are known to violate several assumptions of traditional line transect theory (Burnham et al., 1980; Buckland et al., 1993), the most

obvious being the non-random spatial distribution of tuna vessel search effort. Larger dolphin schools tend to be associated with larger schools of tuna, meaning tuna vessel search effort may be more concentrated in regions of the eastern tropical Pacific (ETP) with larger school sizes. Simultaneously, regions of the ETP with small dolphin schools may receive little or no effort. In addition to the non-random distribution of search effort, tuna vessel captains communicate with one another, and are aware of regions associated with previous successes (Perkins, 2000; Polacheck, 1988). To correct for these biases, the IATTC has used an algorithm to initially filter the TVOD before applying a post-stratification routine (Anganuzzi et al., 1993) to the individual components of the line transect estimator (average school size, $f(0)$, encounter rate). The TVOD can still be used to estimate trends in relative *S. attenuata* abundance if the biases in the data have remained proportionally constant through time (Buckland et al. 1992).

The first stage of the IATTC's algorithm involves deleting entire cruises based on recorded sightings and effort data (Appendices). To concentrate the analyses on target species, cruises whose number of sightings is less than the minimum allowed number of target sightings (the default number is 5 sightings for the entire trip) are deleted. Cruises where the percent of bearing/distance pairs missing is greater than the tolerated percent (the default is 50%) are deleted to avoid biasing $f(0)$. The level of "dolphin-safeness" is found for each cruise by taking the total number of dolphin sets, divided by the total number of sets for that trip. Cruises with a proportion of "dolphin-safe" sets that is greater than the tolerated level (typically 0.05) are marked for deletion. Finally, it is possible to stratify the analysis by gear onboard (selecting cruises by the presence or

absence of radar or a helicopter, Appendices). Once these cruises are marked for deletion, they do not play a role in later calculations.

The second stage of the algorithm marks individual sightings and legs of effort for deletion based on the recorded variables. Sightings are deleted for a variety of reasons (Appendices) with the ultimate goal of removing sightings that have the potential to introduce bias (Anganuzzi et al., 1989; Buckland et al., 1988). In the late 1970s, observers would record the radial distance and bearing of the sighting after the vessel had already turned toward that sighting. To correct for this, sightings whose average bearing is less than the minimum tolerated bearing (0 degrees before 1977, 20 degrees after 1976) are deleted. Data from the effort files are subjected to similar constraints as the sightings data.

Although each tuna vessel only has one observer, three estimates of average school size may be made on the same school (an initial estimate by the observer through binoculars, an estimate by the crew through binoculars or from the helicopter, and a final estimate by the observer of schools that are set on). The adjustment terms for school size estimates lacking "set" estimates are calculated assuming linear relationships between observer estimates and "set" estimates and between crew estimates and "set" estimates. These adjustment factors are computed as follows (Buckland et al., 1988):

$$a_0 = \begin{cases} (\sum_{i=1}^{m_{bo}} n_{bi} / (\sum_{i=1}^{m_{bo}} n_{oi})), m_{bo} \geq 20 \\ 1.0, m_{bo} < 20 \end{cases}$$

$$a_c = \begin{cases} (\sum_{i=1}^{m_{bc}} n_{bi}) / (\sum_{i=1}^{m_{bc}} n_{ci}), m_{bc} \geq 20 \\ a_o \cdot (\sum_{i=1}^{m_{oc}} n_{oi}) / (\sum_{i=1}^{m_{oc}} n_{ci}), m_{bc} < 20, m_{oc} \geq 20 \\ 1.0, m_{bc} < 20, m_{oc} < 20 \end{cases}$$

In the above equations, a_o is the correction factor for the observer's estimate, a_c is the correction factor for the crew's estimate, m_{bo} is the number of sightings with both an observer's estimate and a "set" estimate, n_{bi} is the "set" estimate of school i , n_{oi} is the observer's estimate of school i , m_{bc} is the number of sightings with both a "set" estimate and a crew estimate, m_{oc} is the number of sightings with both an observer's estimate and a crew estimate, and n_{ci} is the crew's estimate for school i . The calculation for these adjustment terms is only done once for each year, across the entire stock region. The adjustment terms are then multiplied by the school sightings lacking "set" estimates to create corrected estimates (if an observer estimate is present a_o is used, and if only a crew estimate is present a_c is used).

To correct for the non-random distribution of search effort throughout spatial regions of the northeastern *S. attenuata* stock area, a post-stratification procedure is applied (Anganuzzi et al., 1989). Each component of the line transect estimator (average school size, $f(0)$, encounter rate) are stratified independently of one another. First, the stock region is divided into 1-degree by 1-degree squares, and within each square, the components of the line transect estimator are computed. The number of strata are calculated such that each stratum has approximately the same number of schools within 5 nm of the trackline. Once the number of strata are calculated, a smoothing process is

used to establish smoothed values for variables that correlate well with the original components of the line transect estimator (smoothed radial distance correlates with $f(0)$, smoothed average school size correlates with average school size, smoothed encounter rate correlates with encounter rate). It is important to note that the smoothed values are not meant to replace the original values in each 1-degree square, but only to assign regions of the stock area to particular strata. Smoothed values are calculated independently for each component by using an elliptical smoothing process. Only schools within 5 nm of the trackline are used to establish the smoothed average school size and smoothed encounter rate, but all schools are used to determine the smoothed radial distance. The distance between 1-degree squares is found using the equation $d = \sqrt{(I-i)^2 + (J-j)^2}$, where (I,J) is the center of the square in question, i is the distance in the longitudinal plane, and j is the distance in the latitudinal plane. The formulas used for smoothing the encounter rate are as follows (school size and $f(0)$ are similar):

$$e_i = \frac{\sum_j (w_{ij} n_j)}{\sum_j (w_{ij} f_j)}$$

n_j = number of schools detected in square j

f_j = total distance searched in square j

w_{ij} = weight for square i relative to square j , calculated as:

$$w_{ij} = \begin{cases} 1 - (d_{ij} / d), & d_{ij} < d \\ 0, & d_{ij} \geq d \end{cases}$$

d_{ij} = distance between centers of squares i and j

The weights decline linearly with distance, so the weights can be given by the equation

$1 - \sqrt{(I-i)^2 + (J-j)^2}$. The area of the elliptical region increases until it contains at

least 50 schools. The smoothing process is done for each 1-degree square in the stock area, regardless of whether a sighting (or search effort) occurred in that square. Areas outside the relevant stock area are not included in the smoothing process. When the smoothing process is complete, there are three 2-dimensional arrays of smoothed values, one for each of the components of stratification. Each array is sorted independently, and the limits of each stratum are established so that there are approximately the same number of schools in each stratum.

After the strata for each component are defined, $f(0)$ is estimated independently for each stratum, using only sightings within 5 nm of the trackline. Estimation of $f(0)$ is done by fitting either a half-normal or hazard-rate detection function. Regardless of the function chosen, sightings in each stratum are allocated to 10 bins (each bin with a width of 0.50 nm). The histogram of sightings is used to approximate the p.d.f. of perpendicular distances, which is then used to estimate $f(0)$. The areas of each stratum are computed by calculating the number of 1-degree squares in each stratum. Those areas are then used to weight the estimates of $f(0)$ for each stratum. The weighted estimates of $f(0)$ are summed, and the final estimate of $f(0)$ is found by dividing the summed area-weighted estimate by the total area of the stock region. To get the final estimate of encounter rate and school size, the respective components (the total number of schools and total track length for encounter rate estimation, the total number of dolphins and total number of schools for average school size estimation) are found in each stratum and weighted by stratum areas. The weighted stratum estimates are then added together and divided by the total area to get the final estimate of each component. With the final components calculated, the standard line transect abundance estimator

(Burnham et al., 1980): $N_d = \frac{n_s \cdot f(0) \cdot \bar{s} \cdot A}{2 \cdot L}$ is applied to calculate the overall estimate of relative dolphin abundance.

Methods

The post-stratification procedure implemented by the IATTC has been found to reduce some known biases in the TVOD (Anganuzzi et al., 1989; Anganuzzi, 1993). There are still some biases that have not been addressed by the algorithm, such as changes in fishing technology and searching behavior (Lennert-Cody et al., 2001). Additionally, the IATTC abundance estimation procedure may introduce biases into the abundance estimates. Inference of relative abundance based on the TVOD is dependent upon none of these biases exhibiting a temporal trend (Buckland et al., 1992).

As an initial exploration, time series plots of the three components of the line transect estimator (encounter rate, average school size, $f(0)$) and the IATTC's estimates of relative *S. attenuata* abundance were analyzed for linear trends. To examine each component's relationship to the relative abundance estimates, a correlation matrix was calculated, and the standardized values of each component were plotted with standardized abundance estimates. Simple linear regressions were performed independently on the standardized individual components and standardized abundance estimates, using only an intercept and the year as the predictor variable. The distributions of the residuals from the regressions were analyzed for a trend against the predictor variable, and the strengths of the linear relationships of the residuals across regressions were calculated with a correlation matrix.

To examine changes in data quality since 1980, sightings removed from the TVOD in each year for violating specific deletion criteria were examined for trends. As the number of sightings has changed annually, the proportion of total sightings deleted serves as a better index for each of the deletion criteria (Appendices). The total percent of sightings retained in the TVOD was also calculated using the IATTC abundance algorithm. Finally, the observer and crew correction factors used by the IATTC for sightings lacking “set” estimates were analyzed for a trend.

Results

Since 1980, there does not appear to be a clear linear trend in the relative abundance of the northeastern stock of *S. attenuata* calculated from the TVOD (Figure 8). Average school size estimates and encounter rate estimates also do not appear to exhibit linear trends between 1980 and 2000 (Figure 9, Figure 10). Estimates of $f(0)$ do exhibit a linear temporal trend (Figure 11), possibly because of changes in technology and search methods (Lennert-Cody et al., 2001). As helicopter use in the ETP tuna fleet has become standard for most vessels, more dolphin schools are detected away from the vessel, shifting the p.d.f. of detection distances away from the origin. As more weight is distributed in the tail of the p.d.f. of perpendicular distances, $f(0)$ would be expected to decrease.

Figure 8. Estimated relative abundance of the northeastern stock of *S. attenuata*, using the IATTC algorithm with a half-normal detection function (plus or minus 1 analytic standard error).

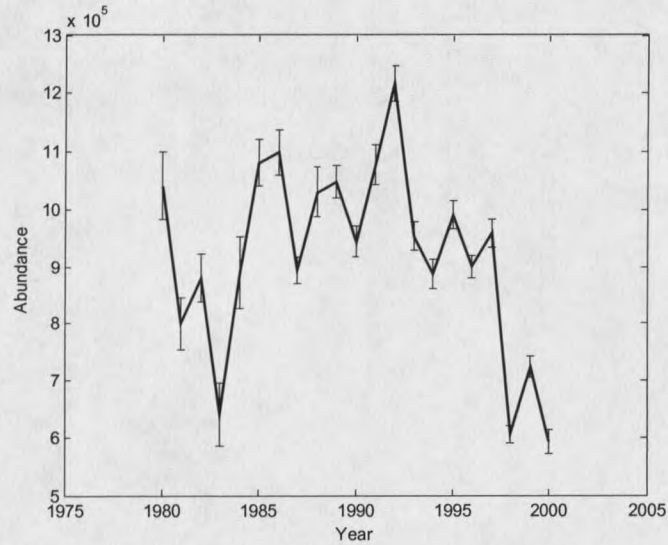


Figure 9. Annual estimates of *S. attenuata* encounter rate for the northeastern stock, as calculated using the IATTC algorithm (plus or minus 1 analytic standard error).

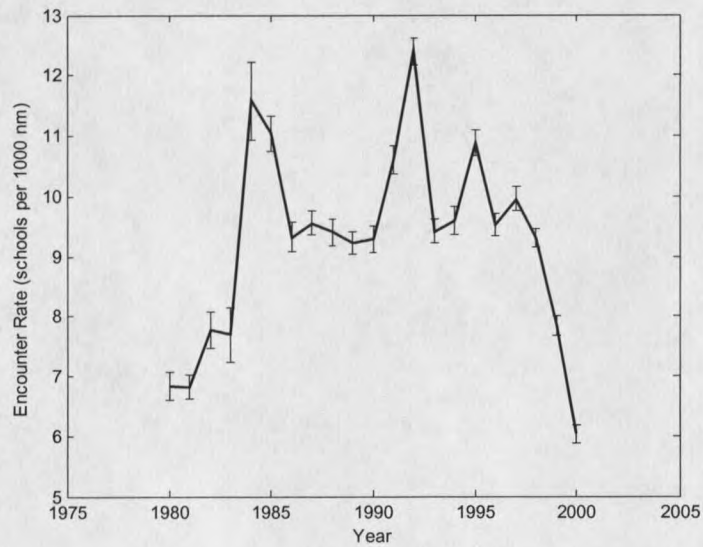


Figure 10. Estimates of *S. attenuata* average school size for the northeastern stock, calculated using the IATTC algorithm (plus or minus 1 analytic standard error).

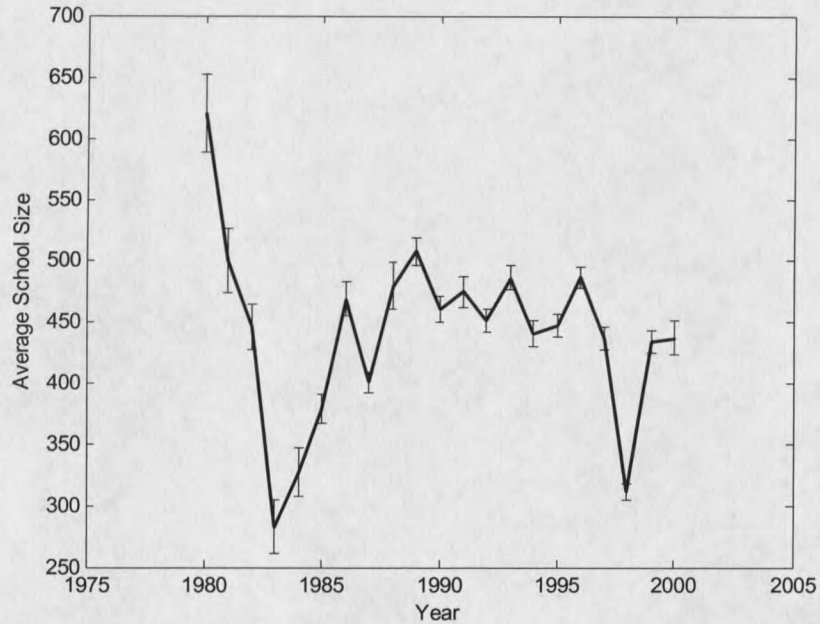


Figure 11. Annual estimates of $f(0)$ for *S. attenuata* schools in the northeastern stock region, as calculated by the IATTC algorithm (plus or minus 1 analytic standard error). A half-normal model was used as the detection function.

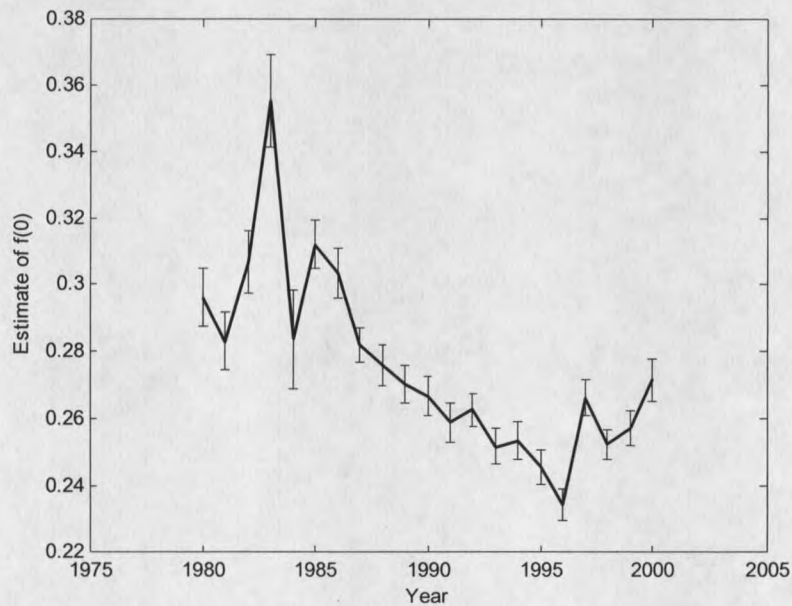
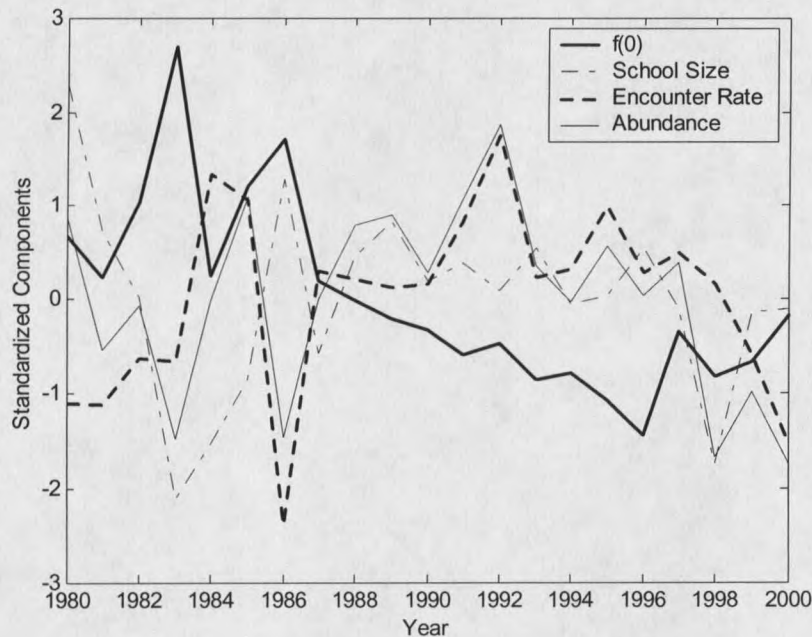


Figure 12. Standardized components of the line transect estimator and standardized abundance for the northeastern stock of *S. attenuata*, calculated with the IATTC algorithm. The half-normal model was used as the detection function.



Based on the correlation matrix and the plot of standardized estimates (Table 1, Figure 12), encounter rate appears to have the strongest linear association with abundance. This result is somewhat intuitive. According to standard line transect theory, regions with larger object densities and higher encounter rates should yield higher abundance estimates. Of the three components, $f(0)$ appears to have the smallest linear association with abundance. The residuals of the independent regressions show no clear linear trend, and the only possible problem is the presence of several outliers (Figures 13-16). The residuals for some of the regressions do seem to provide evidence for a quadratic trend (Figure 13, Figure 15, Figure 16). Of the three components of the line

transect estimator, the residuals of the regression of $f(0)$ against year had the highest correlation with the residuals of the regression of abundance against year (Table 2).

	Encounter Rate	$f(0)$	School Size	Abundance
Encounter Rate	1			
$f(0)$	-0.28472	1		
School Size	-0.25015	-0.29792	1	
Abundance	0.609951	-0.08914	0.50242	1

Table 1. Correlation matrix of the components of the line transect estimator and abundance. Estimates of each component were calculated from the IATTC algorithm using TVOD.

Figure 13. Residuals from the regression of standardized encounter rate against year. Year was used as an independent variable in the regression, and an intercept term was included.

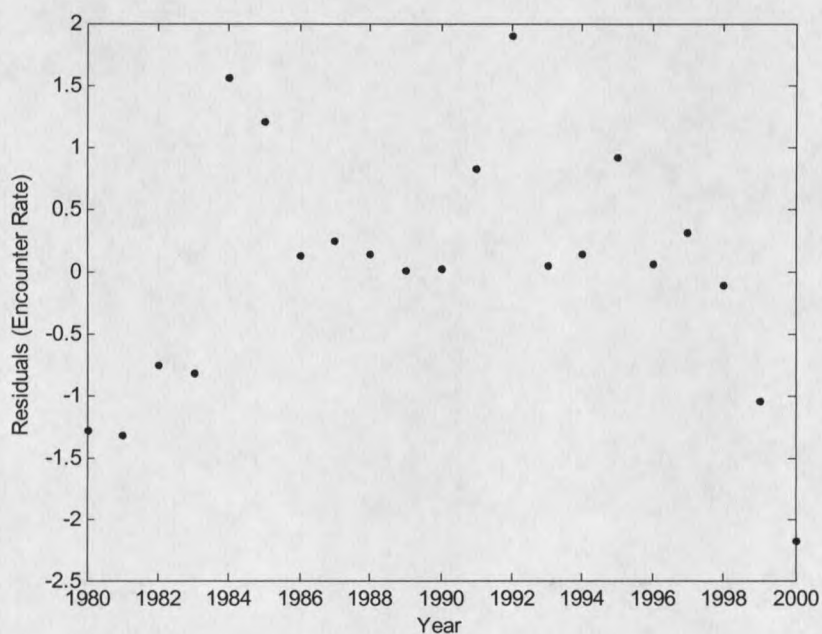


Figure 14. Residuals from the regression of standardized $f(0)$ against year. Year was used as an independent variable in the regression, and an intercept term was included.

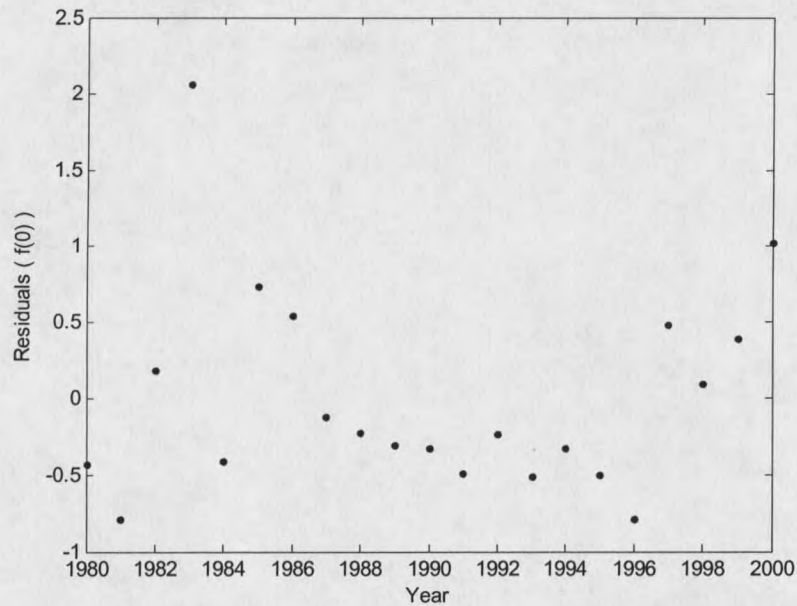


Figure 15. Residuals from the regression of standardized average school size against year. Year was used as an independent variable in the regression, and an intercept term was included.

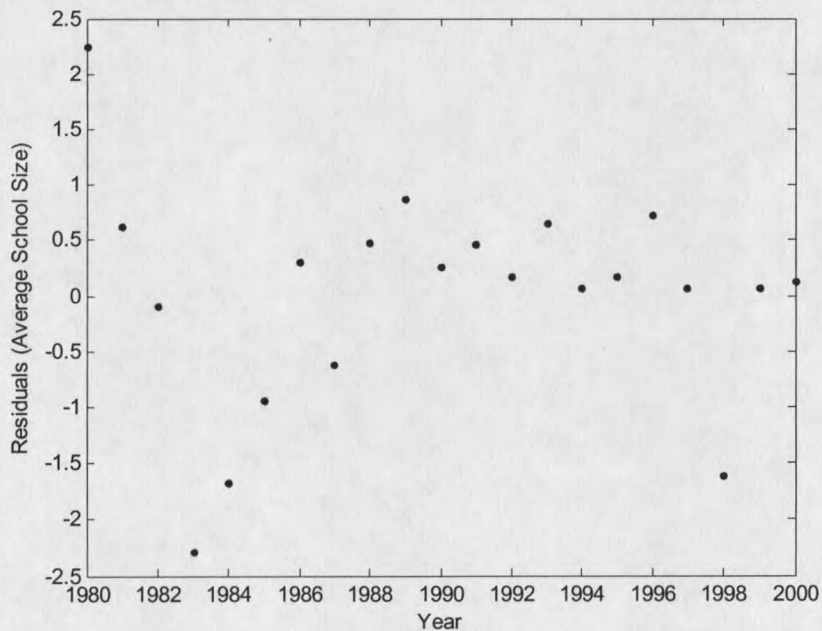
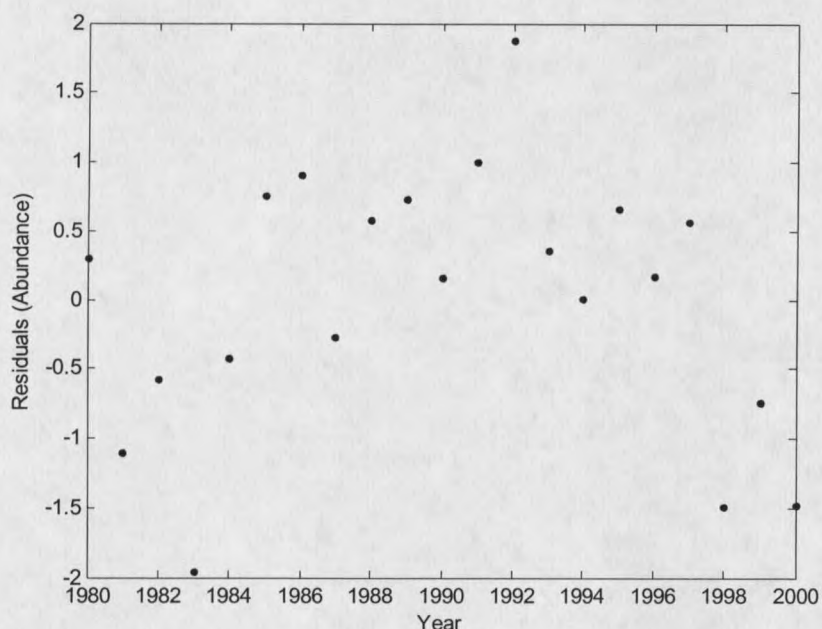


Figure 16. Residuals from the regression of standardized abundance estimates against year. Year was used as an independent variable in the regression, and an intercept term was included.



	Encounter Rate	f (0)	School Size	Abundance
Encounter Rate	1			
f (0)	0.101633	1		
School Size	0.60476	0.562433	1	
Abundance	0.472842	0.61556	0.322787	1

Table 2. Correlation matrix of regression residuals. Independent linear regressions were done on each of the components of the line transect estimator, in addition to abundance. The correlations between each set of residuals was then computed.

Of the deletion criteria examined (Appendices), those that exhibited the strongest linear trends were those sightings that were made first by the observer or sightings that were made by the observer and were too close to the vessel (Figures 17-18). Typically,

sightings are considered too close to the vessel if they are made within 1 nm. The proportion of sightings made while the observer was off-effort showed a decreasing trend (Figure 19). Overall, the percent of sightings retained annually has increased (Figure 20), but as many as a third of all collected sightings are deleted for specific reasons. Both the observer and crew correction factors for sightings lacking “set” estimates exhibit an increasing linear trend (Figures 21-22). The crew correction factor appears to have increased over the entire time series, however the observer correction only shows a linear trend after 1990. These multiplicative factors are less than 1.0 in most cases, indicating that both the observer and crew have a tendency to initially overestimate school size from a distance.

Figure 17. Percent of total *S. attenuata* sightings that were made by the observer and considered too close to the vessel. These sightings are deleted because they are assumed to have been already missed by the crew and observer, biasing radial distance estimates.

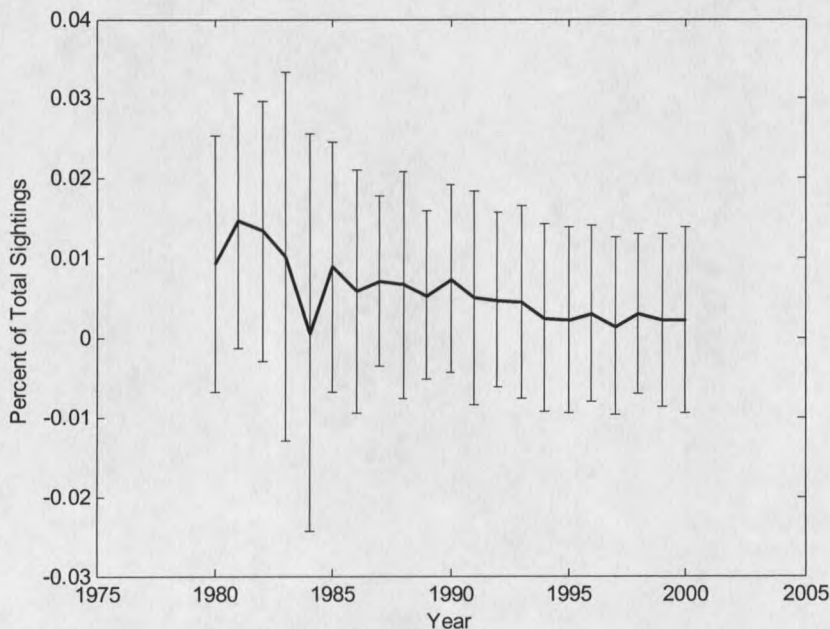


Figure 18. Percent of total *S. attenuata* sightings that were made first by the observer. These sightings are deleted because they are assumed to have been already missed by the crew and observer, biasing radial distance estimates.

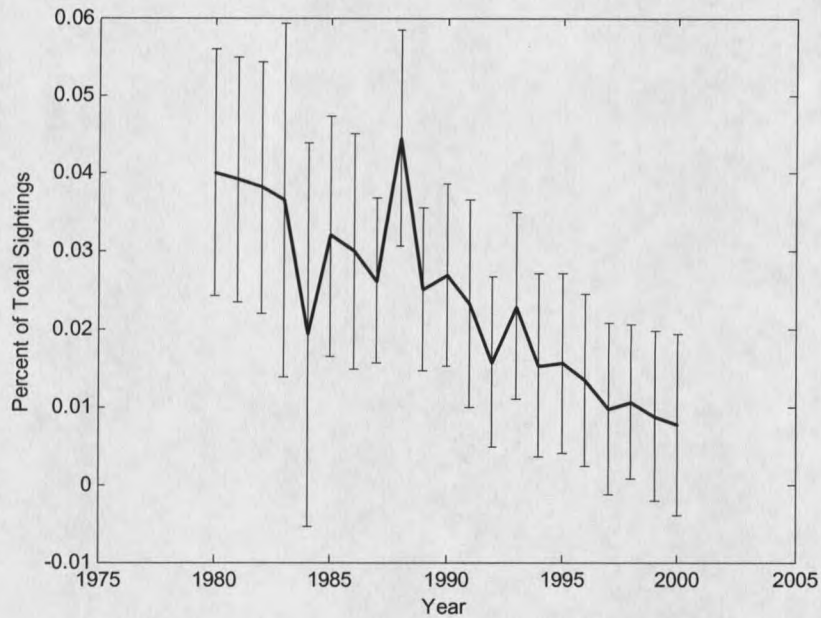


Figure 19. Percent of total *S. attenuata* sightings that were made while the observer was off-effort.

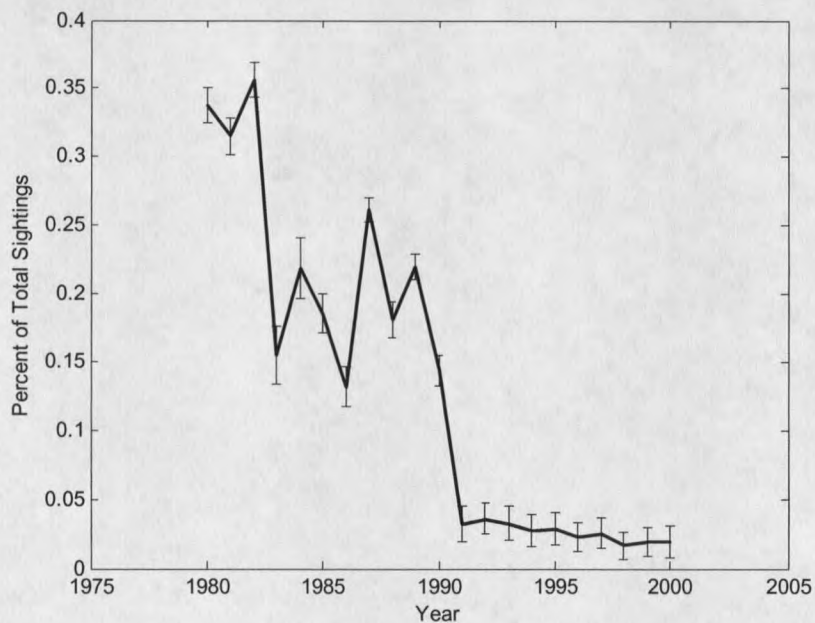


Figure 20. Percent of total *S. attenuata* sightings deleted. Those sightings not meeting the deletion criteria (Appendices) are not included in the IATTC's estimation of abundance.

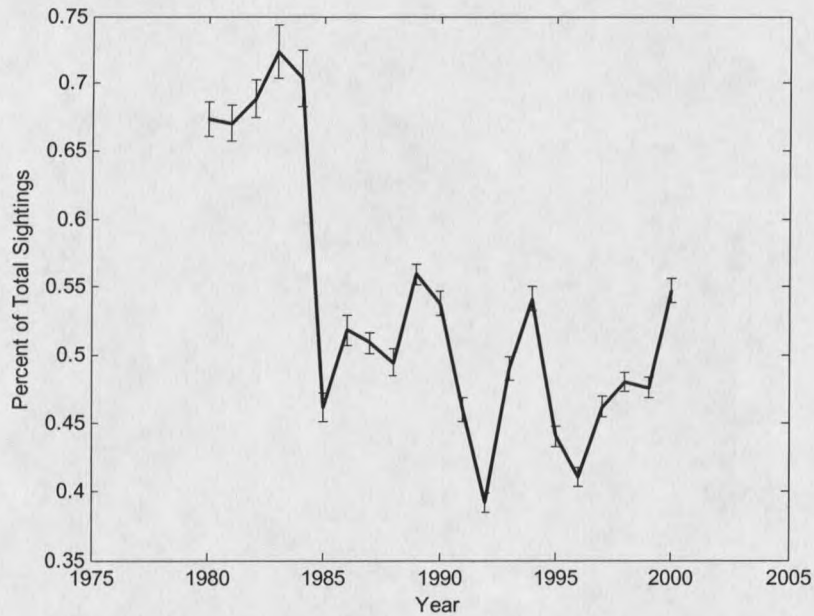


Figure 21. Observer correction factor used by the IATTC for *S. attenuata* sightings without "set" estimates.

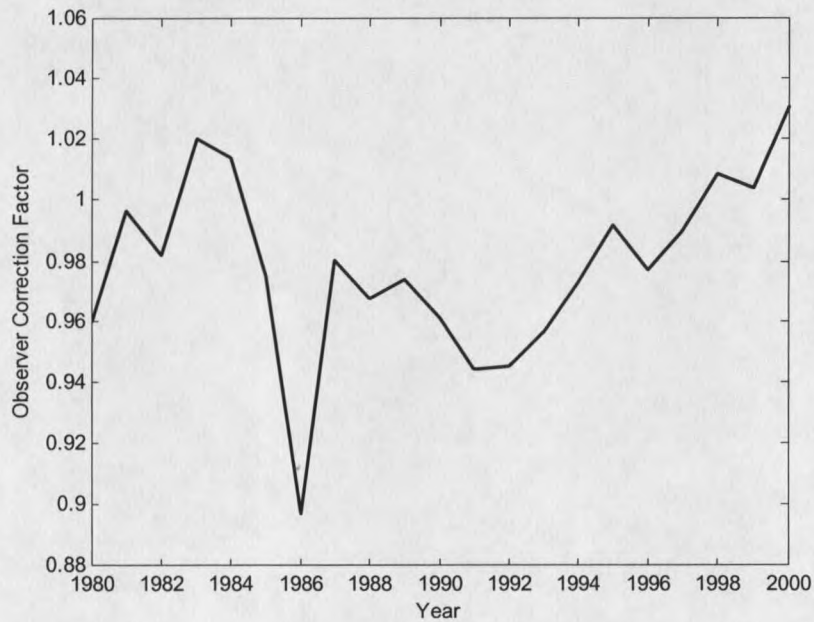
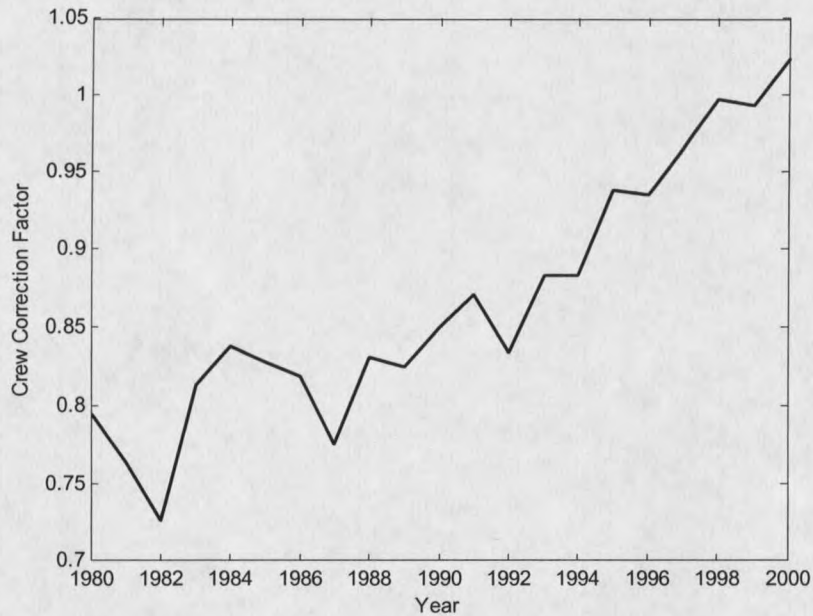


Figure 22. Crew correction factor used by the IATTC for *S. attenuata* sightings lacking both "set" estimates and observer estimates.



Discussion

Trends in the components of the line transect estimator and trends in the IATTC algorithm may provide insight as to whether there have been temporal trends in the biases associated with TVOD. Encounter rate estimates have the largest correlation with raw abundance, however the regression analysis showed that the residuals from the $f(0)$ regression were most closely tied to those from the regression of abundance estimates. The correlation between the regression residuals of $f(0)$ and abundance indicates that if a linear model is assumed, randomness in abundance estimates is most closely tied to the randomness in $f(0)$. The quadratic distribution of the residuals for the encounter rate estimates, average school size estimates, and abundance estimates indicates that the

original data should have been fit with quadratic regressions (concave-down). If the proportional bias in the TVOD index follows a quadratic form rather than a linear form, inference of population trends will still be problematic. Inference will also be difficult if linear corrections are applied to non-linear biases in the data, as new biases will be introduced as a result of fitting the wrong model.

The decreasing linear trend in estimates of $f(0)$ seemed to agree with trends in certain deletion criteria involving the observer. As fishing technology has changed since 1980 to involve bird radar and helicopters, we would expect more sightings to be made away from the trackline and not involve the observer. There also is a trend in the data quality since 1980, particularly when comparing the period 1980-1985 with the rest of the time series (Figure 20). These trends are in agreement with the changes in search technology since 1980 (Lennert-Cody et al., 2001). While these temporal trends are important, they are not necessarily lethal trends that would prevent inference of relative *S. attenuata* abundance.

In addition to changes in technology since 1980, full observer coverage was not in place in the international ETP tuna fleet until 1995. The year 1992 was also important as from a political perspective, as the La Jolla Agreement shifted the tolerated number of dolphins killed annually from a by-fleet quota to a by-vessel quota. Because the change in data quality and the response to political change are not directly quantifiable, the time series of TVOD prior to 1992 may contain biases that are impossible to correct for. If the relative abundance estimates between 1992 and 2000 are examined for a trend, there is a substantial decrease in *S. attenuata* abundance of approximately 50% in the TVOD (Figure 15), but not in the RVOD (Figure 8). Estimates of $f(0)$ and average school size

do not appear to exhibit a strong linear trend over this period, but estimates of encounter rate do exhibit a decreasing trend (Figure 9). Interestingly, TVOD estimates of average school size also appear to be affected by strong ENSO events (1983, 1998). If the 1992-2000 estimates are to be used in the same time series as the 1980-1991 estimates, it may be appropriate to assign them more weight because they appear to be more precise indices of *S. attenuata* abundance.

The biases associated with changes in technology and data quality since 1980 are difficult to correct for several reasons. First, it is not possible to accurately quantify the changes or associated biases. Second, such trends and biases are almost certainly non-linear, as technological evolution proceeds in rapid, unpredictable bursts, much like biological evolution (Jablonka, 2000). If the TVOD are to be corrected for these changes since 1980, several considerations need to be made. First, all data should be stratified by the gear onboard prior to analyses (e.g. by helicopter, radar, both radar and helicopter). This will reduce the overall sample of vessels for each year, however trends will be more consistent across years. The only problem with such a stratification is that comparisons between the early 1980s (when helicopter use was rare) and late 1990s (when helicopter use is common) cannot be made because the sample sizes will be too small in portions of the time series. A second approach would be for the tuna vessel observers and tuna vessel crews to collect more data on helicopter use and helicopter behavior. Currently, it is impossible to determine whether the helicopter was present during a TVOD sighting, whether the helicopter was broken, or whether the helicopter was grounded due to bad weather. Additionally, if GPS units were used to record the position of the helicopter, we

may be able to develop a better understanding of the effective strip width searched by tuna vessels.

SPATIAL AND TEMPORAL TRENDS IN TUNA VESSEL FISHING EFFORT
RELATIVE TO THE DISTRIBUTION OF DOLPHIN SCHOOL SIZES IN THE
EASTERN TROPICAL PACIFIC, 1980-2000

Abstract

Due to fluctuations in environmental variables, it is unrealistic to assume that the dolphin habitat in the eastern tropical Pacific is homogeneous. It is possible that in response to changing physical and biological oceanic conditions, there are seasonal or spatial gradients in dolphin school sizes. Since 1979, data collected aboard tuna vessels has been used as an index of dolphin abundance, and has been used to estimate relative trends. Tuna vessel search effort is non-random, and tends to be directed at larger dolphin schools. Changes in the spatial and temporal distribution of search effort relative to the spatial and temporal distribution of dolphin school sizes were examined and analyzed for a trend. Over the period 1980-2000, it appears that search effort has become more concentrated in geographic areas with larger average school sizes. Such a trend is expected, because of better searching methods (Lennert-Cody et al., 2001). However, this trend causes estimates of both average school size and abundance to be biased.

Introduction

To monitor the effect of incidental kills by the fishery on ETP dolphin populations, the National Marine Fisheries Service (NMFS) and the Inter-American Tropical Tuna Commission (IATTC) began placing scientific observers on tuna vessels,

starting in 1974 and 1979, respectively. Originally, the responsibility of scientific observers was to monitor the number of dolphins killed or injured during sets, but data on dolphin schools (including schools not set upon) were also collected. The record of all tuna vessel observer data (TVOD), have been used by the IATTC to estimate trends in relative abundance (Buckland et al., 1988). The TVOD data set cannot be used to estimate absolute abundance, because tuna vessel search effort is not randomly distributed in space. In addition to having prior knowledge of areas of fishing success in the region, tuna vessels may actively congregate in areas where success is currently high, and vessels communicate with one another (Perkins, 2000; Polacheck, 1988).

The inference of abundance estimates based on TVOD is only valid if biases in the data do not exhibit a temporal trend (Buckland et al., 1993). Prior to 1980, there is a declining trend in school size estimates, however these data have been judged to be unreliable (Lennert-Cody et al., 2001), and will not be used here. Since 1980, the overall search effort by the fishery has increased, and there have been significant changes in fishing technology and searching methods (Lennert-Cody et al., 2001). While average school size estimates calculated by the IATTC do not exhibit a trend (Figure 10), there does appear to be intra-annual spatial and temporal variation in *S. attenuata* school sizes (Figure 23, Figure 24). The most likely explanations for within-year fluctuations in dolphin school size are changes in habitat quality, and changes in environmental variables (Fiedler et al., 1994; Polacheck, 1987; Reilly et al., 1994). Since 1980, tuna vessel search effort may have become more or less concentrated in spatial or temporal strata that have larger average school sizes. If there has been a trend in the distribution of effort (Figure 25, Figure 26) relative to the distribution of recorded *S. attenuata* school

sizes, biases may be present. If these biases remain uncorrected and exhibit a trend, the uncertainty in the TVOD index of abundance will increase.

Figure 23. Average *S. attenuata* school size, calculated by calendar day, and pooled over 1980-2000. Only data used by the IATTC to estimate average school size was included.

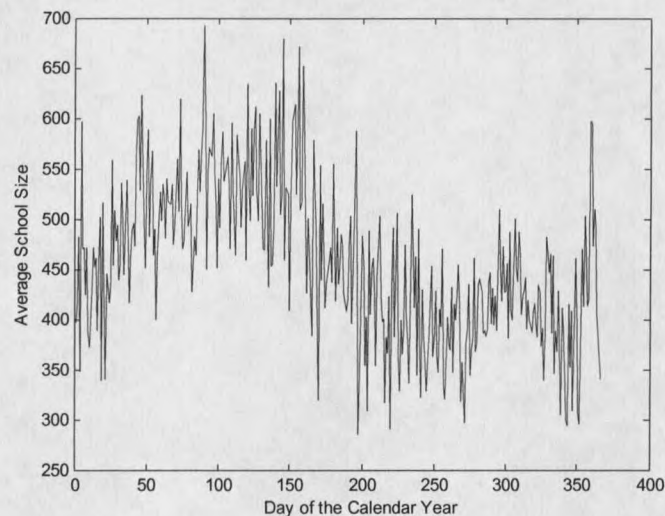


Figure 24. Cumulative average school sizes (1980-2000) for *S. attenuata*. Using only sightings retained for average school size estimation by the IATTC, average school size was calculated as the total number of dolphins observed and recorded in each 1-degree square, divided by the total number of schools observed and recorded in that square.

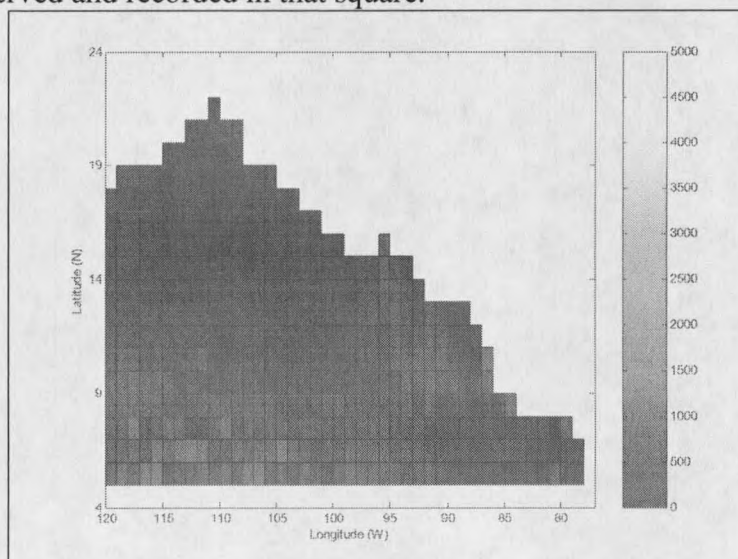


Figure 25. Nautical miles of search effort in the northeastern stock region of *S. attenuata*, accumulated over 1980-2000 for each calendar day. Only search effort included in the IATTC's abundance algorithm has been included.

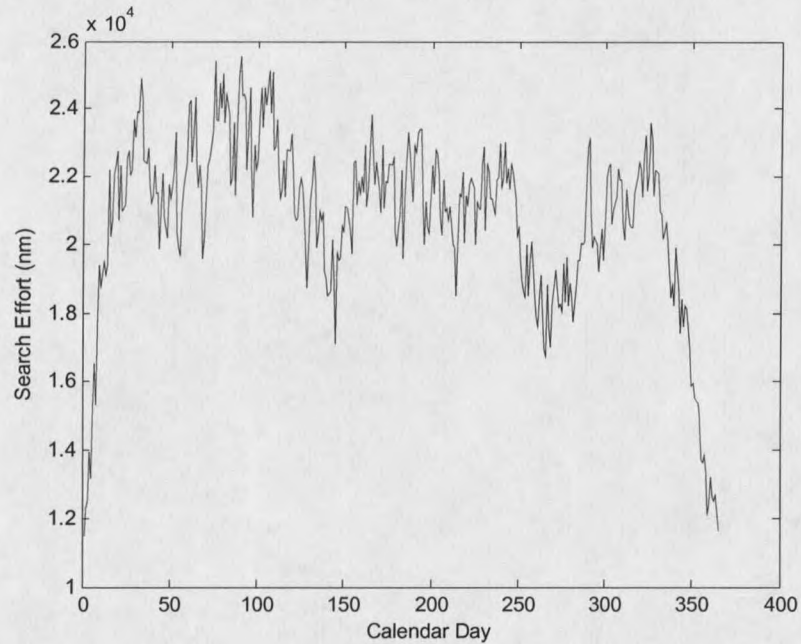
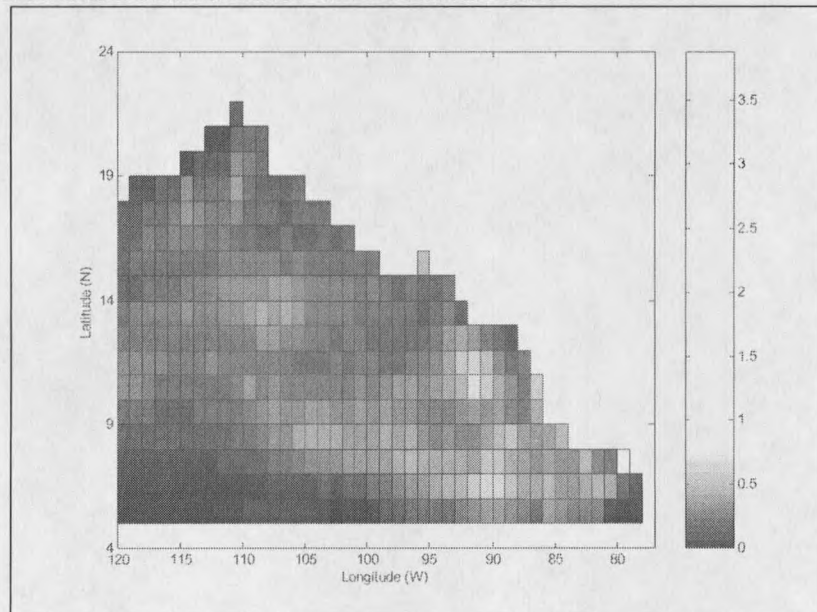


Figure 26. Total nautical miles of search effort ($\text{nm} \cdot 10^4$) in the northeastern stock area of *S. attenuata*, 1980-2000. Only legs of effort included in the IATTC's calculation of abundance have been included.



Methods

Almost all biological populations are heterogeneously distributed in space and time. Accurately surveying areas with standard line transect methods often requires the survey area to be divided into multiple strata, because survey effort and animal density are not constant across strata. As a simple example, consider two square regions in the ETP, each 100 nm on a side. Stratum 1 represents an area of larger average dolphin school sizes, while stratum 2 represents an area of smaller average school sizes. If survey effort is approximately equal between the two strata, and the number of schools observed is the same between strata, an unbiased estimator of the total overall average school size

is: $S_T = \frac{A_1 \cdot S_1 + A_2 \cdot S_2}{A_1 + A_2}$, where S_T is the total average school size, S_1 is the average

school size in stratum 1, S_2 is the average school size in stratum 2, A_1 is the area of stratum 1, and A_2 is the area of stratum 2. For this example, stratum areas are equal, meaning that the average of the stratum averages is an unbiased estimator of total average school size.

Problems will arise with the calculation of total average school size if search effort or the number of schools observed varies significantly between strata, and the estimates obtained in each stratum are given equal weight. If more effort was allocated to stratum 1 than stratum 2, or stratum 1 had a higher density of schools, we would expect to observe more schools in stratum 1. Total average school size estimates would be downwardly biased if the estimate was calculated as the average of the stratum averages (the opposite would be true if more effort was allocated to stratum 2, or more schools

were observed in stratum 2). An unbiased estimator of the raw average school size would be to divide the total number of dolphins seen in all strata by the total number of schools observed in all strata. The same result can be found by weighting the average school size estimates in each stratum by the proportion of total schools seen in that stratum.

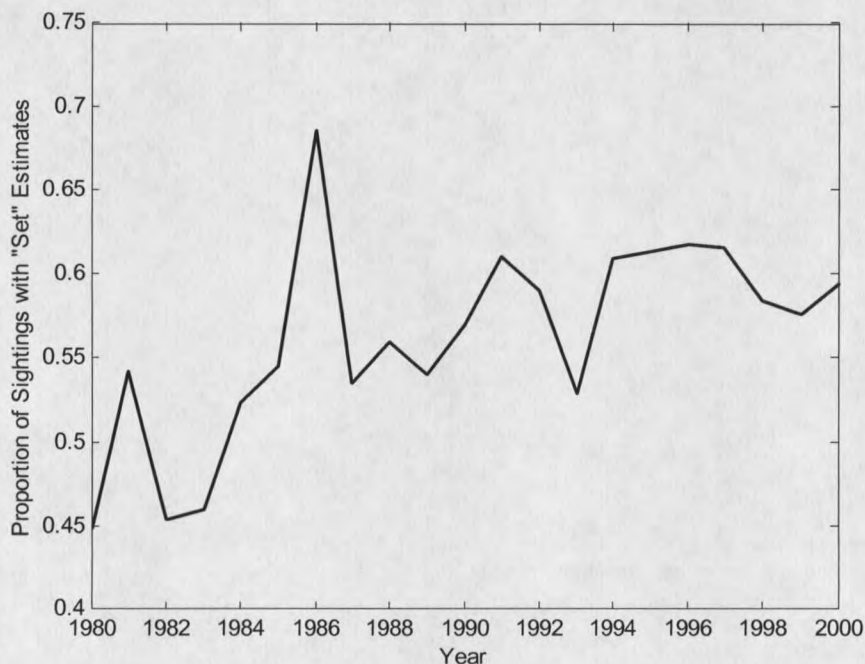
Assuming that search effort is correlated with the number of observed schools, it may be possible to use the proportion of survey effort in each stratum to weight the stratum school size estimates.

In the IATTC's calculation of abundance, strata are assigned so that there are approximately the same number of sightings in each stratum (Buckland et al. 1988). Average school size estimates are calculated independently for each stratum, and a final estimate is calculated as a weighted average, with weights being equal to the stratum areas. The sample in each stratum (at least 50 schools) is large enough so that small differences in the number of sightings between strata probably do not significantly affect calculation of average school size. To verify that the strata used to estimate average school size are not themselves subject to a trend, the mean and variance of the number of squares in each stratum were used to calculate the CV of squares per stratum for each year, and examined for a trend.

In the abundance estimation procedure implemented by the IATTC, not all sightings or legs of search effort are used to estimate abundance. Sightings and effort that are known to introduce bias are deleted before strata are defined (Appendices). In order for comparisons to be made to the *S. attenuata* school sizes calculated by the IATTC, only sightings and search effort that would normally be used to estimate *S. attenuata* average school sizes will be included in this analysis. For each school sighting

made by a tuna vessel, there may be up to three school size estimates made for the same school: initial observer estimates (sightings made through binoculars and at a distance), crew estimates (made from the vessel or a helicopter), and “set” estimates (sightings made by the same observer, but up close, of schools that are set upon). “Set” estimates are considered the most reliable, followed by crew estimates and observer estimates (Buckland et al., 1988). If “set” estimates are not present, a linear relationship between estimates is assumed, and bias in observer and crew estimates is corrected by multiplying each observation by a scaling factor (Buckland et al., 1988; Figures 21-22). All school sizes lacking “set” estimates were multiplied by the IATTC correction factors, calculated by year. On average, approximately 45% of all sightings needed correction (Figure 27).

Figure 27. Proportion of sightings with “set” estimates present. Only sightings used in the IATTC’s estimation of average school size for *S. attenuata* have been included.



Ideally, line transect effort should be randomly distributed in both space and time. To quantify the impact of the non-random distribution of search effort in time on *S. attenuata* school sizes, tuna vessel search effort, total observed schools, and total observed dolphins were binned by calendar days within each year. If tuna vessel search effort was random, we would expect it to be uniformly distributed over the stock region. The expected *S. attenuata* average school size under uniform random sampling was calculated for each year by taking the total number of dolphins divided by the total number of schools seen in that year (the raw average can also be found by separately assigning weights to the number of schools and dolphins for each day, with weights being equal across days, and dividing the sum of the weighted dolphins by the sum of the weighted schools). Average school size weighted by search effort was found by separately weighting the dolphins and schools on each calendar day by the effort for that day. The sum of the weighted dolphins was divided by the sum of the weighted schools to obtain a final estimate of average school size under temporal stratification.

To examine whether there has been a change in the spatial distribution of tuna vessel search effort, the stock area was divided into 1-degree by 1-degree squares following the stratification method used by the IATTC (Buckland et al., 1988). Search effort, observed schools, and observed dolphins were accumulated within each square, for each year. Estimates of average school size under uniform random sampling were calculated as before. Average school size estimates weighted by search effort were found by weighting the dolphins and schools in each square by the effort occurring in that square. Final estimates were found by summing the weighted dolphins and schools

across all squares in each year, and dividing the sum of the weighted dolphins by the sum of the weighted schools.

The ratio of average school size estimates under uniform random sampling to the school size estimates weighted by search effort was calculated as an index of changes in the distribution of effort relative to the distribution of *S. attenuata* school sizes. Values of the ratio greater than 1.0 indicate the fishery is focusing effort in periods of time or regions of space with smaller average school sizes. Value of the ratio less than 1.0 indicates that the fishery is directing search effort towards strata with larger average school sizes. Corrected school size estimates used by the IATTC were compared to the expected average school sizes under random sampling, and the average school size estimates weighted by search effort, to examine whether the algorithm has corrected biases that may be present.

To determine the rate of change, if any, in the ratios of school size estimates, a series of Bayesian regressions was performed using WinBUGS. Non-informative priors were assumed for all parameters. Parameters were checked for convergence by comparing the traces across multiple chains. The median was accumulated for each iteration, along with the 2.5% and 97.5% quantiles. For comparative purposes, standard least squares estimates were also calculated.

Results

After calculating the CVs for the number of squares per stratum in the IATTC's analysis, there does not appear to be any trend in the allocation of squares to strata over time. There do not appear to be major differences between average school size estimates

weighted by search effort, and average school size estimates calculated by the IATTC (Figures 10, 28). This indicates that although the IATTC's abundance algorithm does not weight school sizes by effort, the post-stratification procedure (Buckland et al. 1988) produces a similar result. A negative trend does appear to be present in some of the ratios of average school size estimates (Figures 29-30). As sampling becomes less random, either in space or time, we would expect the ratio of the weighted average school size estimates to the expected estimates under uniform random sampling to deviate further from 1.0. If the IATTC's post-stratification procedure is correcting this bias, the ratio of IATTC school size to the average school size estimate calculated under uniform random sampling would be expected to be close to 1.0 and exhibit no temporal trend.

Figure 28. Average school size estimates for *S. attenuata*, using spatial and temporal stratification. School size estimates have been weighted by search effort after stratification.

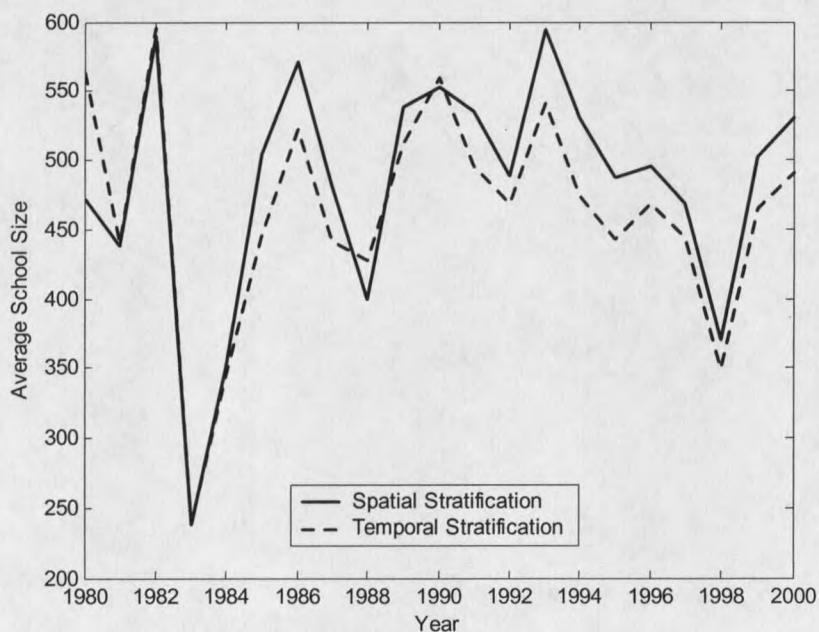


Figure 29. Ratio of average school size estimates used by the IATTC to average school size estimates weighted by search effort (solid line) and the ratio of the expected average school size estimates assuming uniform sampling to the average school size estimates weighted by search effort (dashed line). Weighted estimates were calculated by first stratifying the stock area into 1-degree squares within each year.

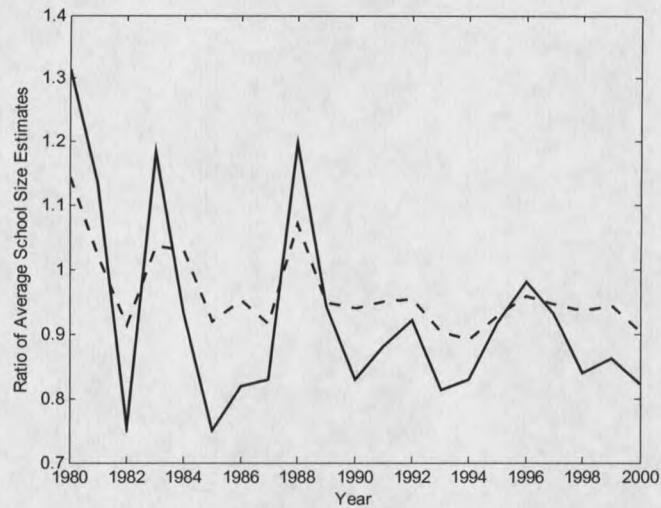
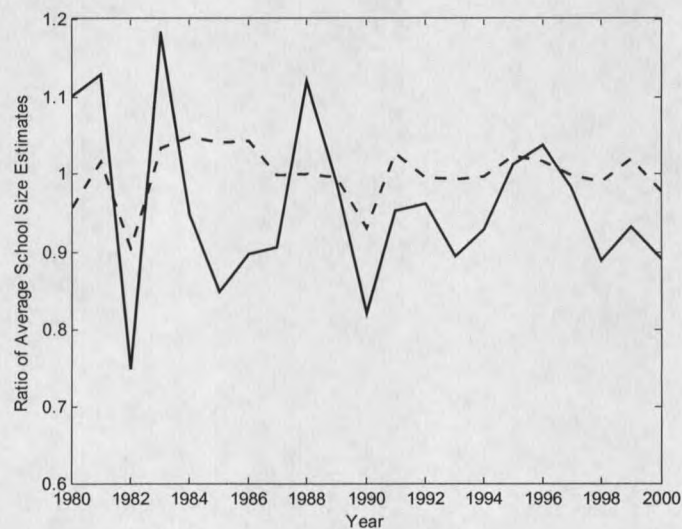


Figure 30. Ratio of average school size estimates used by the IATTC to average school size estimates weighted by search effort (solid line) and the ratio of the expected average school size estimates assuming uniform sampling to the average school size estimates weighted by search effort (dashed line). Weighted estimates were calculated by first stratifying the data by calendar days within each year.



For each Bayesian regression performed, posterior distributions of the slope parameter were used to determine the presence and direction of a trend. Based on the mean and variance of these distributions, there do appear to be significant negative trends in the ratio of IATTC school size estimates to spatially stratified school size estimates weighted by search effort ($\hat{b} = -0.01108, \sigma_b = 0.00533$), and in the ratio of global school size estimates to spatially stratified school size estimates weighted by search effort ($\hat{b} = -0.0058, \sigma_b = 0.002086$). The posterior distribution of the regression slope parameter is centered around negative values in both cases, and the 95% posterior intervals do not contain zero (Figures 31-32). There do not appear to be negative trends in the ratio of IATTC school size estimates to temporally stratified school size estimates weighted by search effort ($\hat{b} = -0.00399, \sigma_b = 0.00369$) or in the ratio of global school size estimates to temporally stratified estimates weighted by search effort ($\hat{b} = 8.52E - 04, \sigma_b = 0.00103$), as the 95% posterior intervals contain zero in both cases (Figures 31-32). A standard least squares regression analysis was also conducted, using the same time series of ratios as in the Bayesian regressions. The mean slope parameters were identical to the slope parameters calculated from the Bayesian regressions. Regressions involving spatially stratified school sizes were found to be statistically significant at a 0.05 level ($p = 0.0403$ for the ratio involving IATTC estimates, $p = 0.0074$ for the ratio involving global estimates), and regressions involving temporally stratified data were not found to be statistically significant ($p > 0.25$).

Figure 31. Posterior distributions of the slope parameter in a Bayesian regression, after 100,000 iterations. Ratios of school size estimates were used as the response variable, with “IATTC” = IATTC school size estimates, “Spatial” = spatially stratified school size estimates weighted by search effort, “Temporal” = temporally stratified school size estimates weighted by search effort, “Uniform” = global average school size estimates.

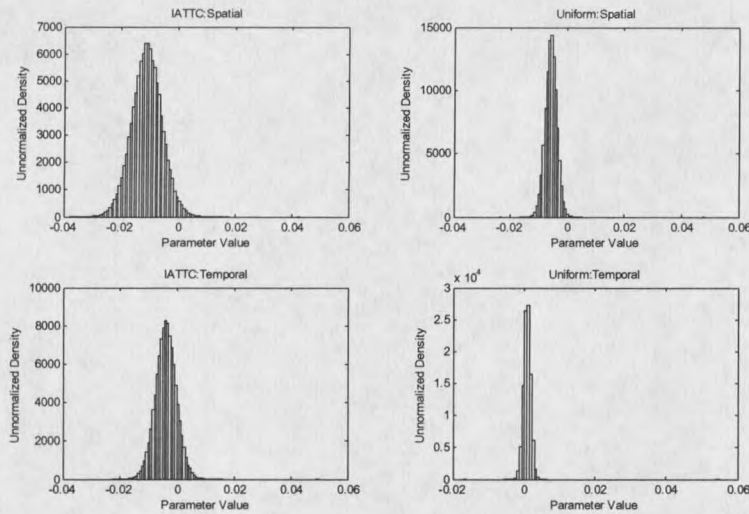
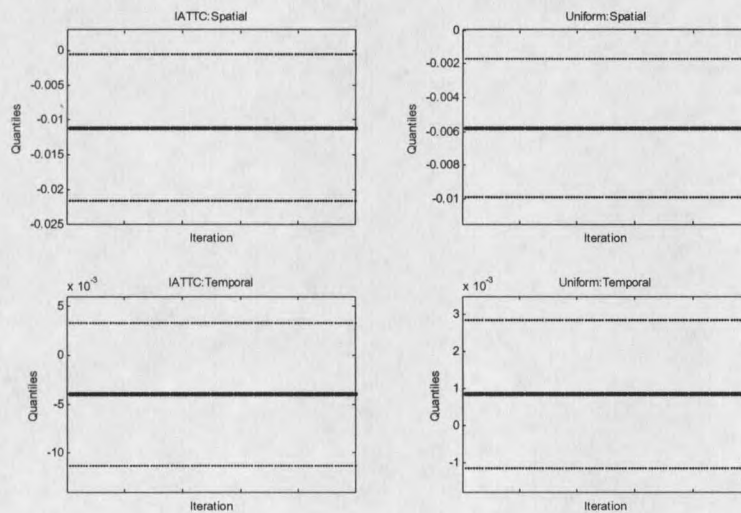
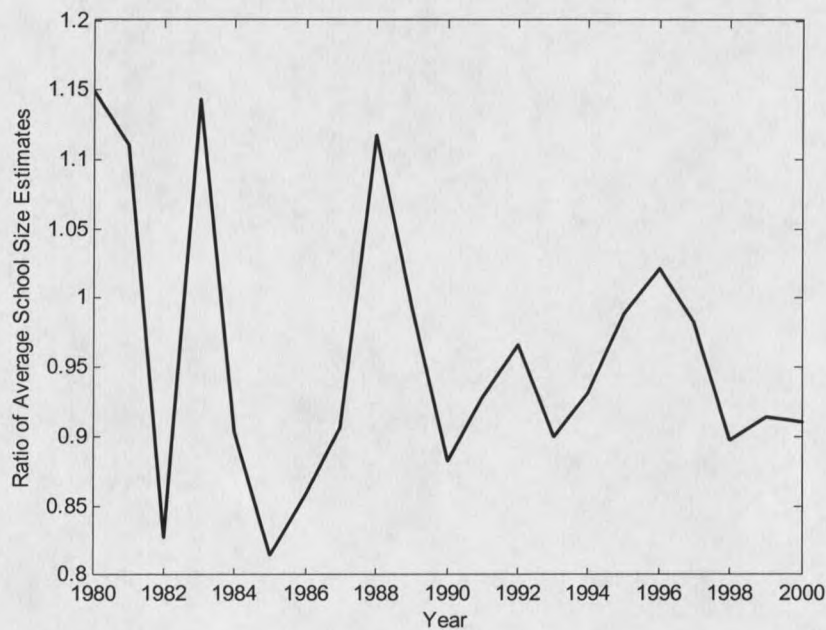


Figure 32. Quantiles for the posterior distributions (2.5%, 50%, 97.5%) of the slope parameter in the linear regression. Ratios of school size estimates were used as the response variable, with “IATTC” = IATTC school size estimates, “Spatial” = spatially stratified school size estimates weighted by search effort, “Temporal” = temporally stratified school size estimates weighted by search effort, “Uniform” = global average school size estimates.



There is not a significant trend in the ratio of average school sizes used by the IATTC to estimates under uniform random sampling (Figure 33) when the regression is performed under a standard least squares approach ($p = 0.1623$), and when the regression is performed in a Bayesian framework ($\hat{b} = -.004968$, $\sigma_b = 0.003631$, lower 2.5% = -0.01216, median = -0.004977, upper 97.5% = 0.002201).

Figure 33. Ratio of average school size estimates used by the IATTC to the expected average school size estimates assuming uniform random sampling.



Discussion

Since 1980, the within-year temporal distribution of tuna vessel search effort in the TVOD does not seem to exhibit a trend relative to the temporal distribution of *S. attenuata* school sizes. One explanation for this is that it may be difficult or impossible for fishermen to predict intra-annual temporal variation in dolphin school sizes. Between

1980-2000, tuna vessel search effort has become more concentrated in geographic regions with larger school sizes, possibly because fishing technology has become better at finding larger schools (Lennert-Cody et al., 2001). This trend is problematic for estimating abundance for several reasons. Most importantly, average school size estimates and abundance estimates have become more inflated over time, as the sample collected has become less representative of the actual population. Encounter rate estimates may be inflated as well, depending on whether there is a correlation between areas with large school sizes and areas with high school densities. There are several possible explanations as to why search effort has become less random. First, fishermen are known to return to areas of previous successes (typically, large tuna schools tend to be associated with larger dolphin schools, Buckland et al., 1988), and accumulate that learning over time. Second, tuna vessel captains communicate with one another, implying search effort from multiple vessels is not independent (Polacheck, 1988), and may become less random as more vessels enter an area. An alternative hypothesis is that the proportion of schools that are observed and recorded may have changed. It is known that not all observed schools are reported (Buckland et al., 1988), and there may be a size-dependent factor determining which schools are most likely to be reported.

The trend in the spatial distribution of search effort relative to the spatial distribution of *S. attenuata* school sizes violates the assumptions required for inference from the TVOD, particularly that biases in the data do not exhibit a temporal trend (Buckland et al., 1993; Perkins, 2000). The ratio of average school sizes weighted by search effort to average school sizes calculated by the IATTC algorithm does show a trend, indicating that the current implementation of the algorithm is not correcting for this

bias. Until the changes in technology and increased searching efficiency (Lennert-Cody et al., 2001) are corrected for, abundance and average school size estimates calculated from the TVOD index may be overestimated, and this overestimation may be subject to a temporal trend.

It may be possible to correct for the concentration of effort in spatial regions with larger average school sizes, assuming that the trend is linear. Such a correction would allow inference from TVOD estimates to remain viable. Based on the Bayesian regressions performed, it appears that the average school size estimates calculated by the IATTC have become inflated at a rate of approximately 1.108% per year. Using the available time series of IATTC average school sizes, the average school size estimates were rescaled for each year relative to the estimated average school size for 1980, based on estimated inflation rates. Although the rate of 1.108% may not appear significant, the 2000 estimates are inflated of a rate of approximately 20% relative to the 1980 estimates. New abundance trajectories were calculated from the IATTC data, based on the rescaled average school sizes, and original estimates of $f(0)$ and the encounter rate (Figure 34). This same trend can also be calculated relative to the 2000 average school size estimate (Figure 35). Regardless of which method is used to rescale estimates of average school size, there is a sharper declining trend in abundance, particularly over the period 1990-2000. The rescaled estimates indicate that either average school sizes have become overestimated in later years, relative to the 1980 estimates, or that average school sizes were underestimated in the earlier years, relative to the 2000 estimates.

Figure 34. Original abundance trajectory for *S. attenuata* calculated with the IATTC algorithm (solid line), and revised estimates accounting for the non-random distribution of search effort in regions with large school sizes (dashed line). Revised estimates are calculated relative to the 1980 estimates.

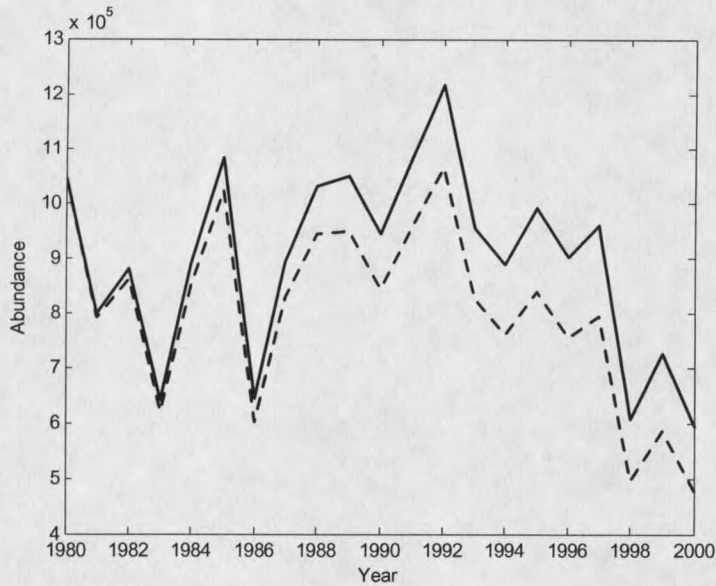
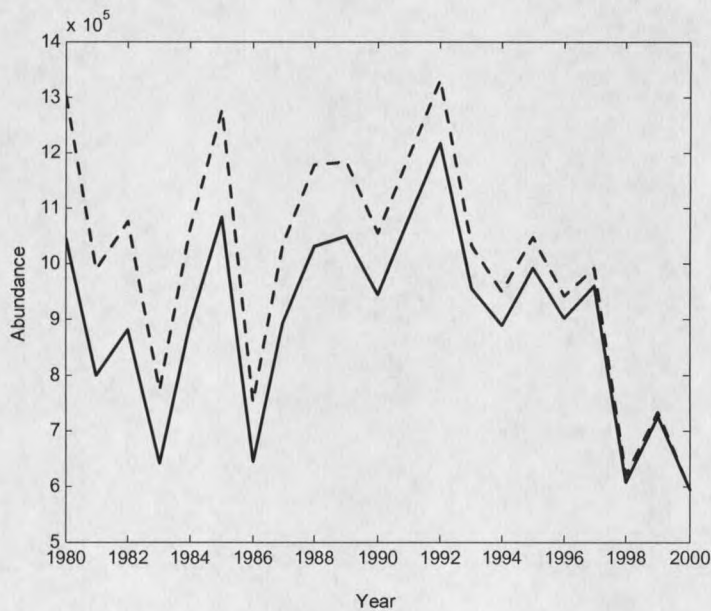


Figure 35. Original abundance trajectory for *S. attenuata* calculated with the IATTC algorithm (solid line), and revised estimates accounting for the non-random distribution of search effort in regions with large school sizes (dashed line). Revised estimates are calculated relative to the 2000 estimates.



Previous analyses have shown that the post-stratification procedure implemented by the IATTC does remove the majority of the biases associated with the non-random distribution of effort in simulated analyses (Edwards et al. 1989, Anganuzzi et al., 1993). One problem previously identified is that small-scale interactions between aggregations of dolphin schools and the specific post-stratification scheme implemented by the IATTC may produce unintentional biases (Edwards et al., 1989). As temporal and spatial patterns of dolphin aggregations are not fully understood in the ETP, it seems reasonable that potential biases in the post-stratification procedure also must be better understood before inference of TVOD is considered reliable.

Future work should incorporate complex models of tuna vessel fishing behavior in relation to the distribution of dolphin schools. For the most part, the IATTC's abundance estimation procedure has been applied to annual data. The temporal and spatial patterns in the distribution of dolphin school sizes seems to indicate that this information should also be incorporated into future analyses. The IATTC's algorithm needs sufficiently large sample sizes in each stratum to estimate $f(0)$, but it may be possible to analyze month long intervals of data separately to include information on temporal variability. Spatial variability may be included if the assignment of 1-degree squares to strata is not entirely random, but somehow weighted based on the location of each square within the ETP.

A COMPARISON OF FISHERY-DEPENDENT AND FISHERY-INDEPENDENT
OBSERVATIONS OF STENELLA ATTENUATA SCHOOL SIZES IN THE
EASTERN TROPICAL PACIFIC, 1980-2000

Abstract

Since 1979, two data sets have been used to estimate trends in the abundance of the northeastern stock of the spotted dolphin *S. attenuata* in the eastern tropical Pacific. Data collected aboard tuna vessels have been used to estimate relative abundance, while data collected aboard fishery-independent research vessels have been used to estimate actual abundance. One of the largest discrepancies between the two data sources is that tuna vessels tend to report dolphin schools that are 400%-500% larger than schools observed by research vessels. After comparing research vessel and tuna vessel observations overlapping in space and time, it appears that either measurement error or selective reporting of large schools is the most likely explanation for the disparity. The differences between research vessel and tuna vessel sightings have exhibited a temporal trend, possibly due to technological changes in the fleet since 1980. This trend makes inference of *S. attenuata* population abundance estimates from tuna vessel data suspect unless it is corrected.

Introduction

Historically, the stock of dolphins suffering the greatest number of incidental kills due to the fishing practices of the yellowfin tuna (*Thunnus albacares*) fishery in the

eastern tropical Pacific (ETP) has been the northeastern stock of the offshore spotted dolphin *S. attenuata* (Smith, 1983). Since the late 1950s when the association between dolphin and tuna began to be utilized, fishermen have used dolphins as a sighting cue to capture the associated tunas with purse-seine nets. To monitor incidental dolphin mortality caused by purse-seine sets on school of dolphins, trained observers were placed by the National Marine Fisheries Service (NMFS) on all U.S. vessels, beginning in 1974, and by the Inter-American Tropical Tuna Commission (IATTC) on all international vessels, starting in 1979. Since 1979, the IATTC has used tuna vessel observer data (TVOD) to estimate relative trends in *S. attenuata* abundance by line transect methods (Anganuzzi et al., 1989; Buckland et al., 1992). Fishery-independent research vessel cruises have been conducted by NMFS in some years to estimate actual *S. attenuata* abundance (Gerrodette et al., 1991; Gerrodette et al., 2002).

Each of the data sets used in estimating the status of the northeastern stock of *S. attenuata* has its strengths and limitations. The fishery independent data set (research vessel observer data, RVOD) is collected by NMFS during research vessel surveys, and is an unbiased source of data for estimating dolphin abundance using line transects. The weaknesses of the RVOD are that data has not been collected for all years, leaving gaps in abundance estimates (years since 1979 lacking cruises are 1981, '84-'85, '91-'97); and, the number of schools sighted in the RVOD is relatively small, because the research vessel search effort is much smaller than the search effort of the tuna fishery. The fishery dependent data set, the TVOD, constitutes a much larger sample than the RVOD in any year, and represents a longer continuous time series, but the TVOD are subject to significant biases (Lennert-Cody et al., 2001; Perkins, 2000). Some biases associated

with the departures from traditional line transect theory (Burnham et al., 1980) in collecting the TVOD have been addressed in previous analyses (Anganuzzi et al., 1989; Buckland et al., 1988; Marques 2001).

One of the most noticeable differences between the TVOD and RVOD is that *S. attenuata* school sizes reported by tuna vessels are much larger than those reported by research vessels. One possible explanation for this difference is that tuna vessels may concentrate effort in portions of the stock area, or periods of the calendar year, with larger, on average, school sizes. A second possibility is that tuna vessel observers have a tendency to overestimate dolphin school sizes. A third possible explanation for the difference between the research vessel and tuna vessel sightings is that there is selective reporting by tuna vessels (Buckland et al., 1988), and larger schools have a higher chance of being reported. If an estimate of absolute dolphin abundance were required, TVOD school size estimates would be required to be unbiased. TVOD are only used to estimate relative abundance, meaning that any bias in school size estimates must be consistent or proportionally constant across time (Buckland et al., 1992).

Currently, no quantitative comparison exists between TVOD estimates of northeastern *S. attenuata* school sizes and RVOD estimates. Dolphin schools are not marked, and because the movement of individuals between schools is fluid, no single documented school has been simultaneously recorded in both the TVOD and the RVOD data sets. If portions of the TVOD and RVOD data overlap in space and time, those sightings may provide insight as to whether the difference in *S. attenuata* school size estimates is a result of the non-random distribution of search effort.

Methods

In the TVOD data set, up to three school size estimates may be recorded for each sighting: an initial estimate made by the observer through binoculars and at a distance, an estimate made by the crew at a distance, and a final estimate made by the observer of schools that are set on. "Set" estimates are considered to be the most reliable (Buckland et al., 1988). It is known that both the observer and crew at a distance tend to overestimate school size relative to the "set" estimate. In the IATTC's estimation of relative dolphin abundance, sightings without "set" estimates are corrected using linear correction factors specific to each year, so that all sightings will be similarly scaled (Buckland et al., 1988). This approach does not allow for non-linear relationships that exist among observer estimates (Scott et al., 1985), and does not use both initial observer estimates and crew estimates as simultaneous predictors of "set" estimates. To avoid introducing new biases into the data with different predictive equations, the correction factors calculated by the IATTC were used to correct for sightings that lacked "set" estimates. Calculation of research vessel school sizes by NMFS is more complicated. For each school in the RVOD, there are at least 9 estimates of school size (three independent observers record a "low," "high," and "best" estimate of group size), in addition to aerial photographs for some schools. Observer estimates are calibrated to aerial photographs using a linear model that takes Beaufort and annual variability into account (Gerrodette et al., 2002b).

Following the methods of Buckland et al. 1988, TVOD and RVOD sightings with the potential for introducing bias were deleted from the analysis. Reasons for deletion included: the position coordinates of the sighting were outside of the northeastern stock region, no position coordinates were recorded, the observer was not on effort, the vessel was not actively searching for dolphins or tuna, the sighting was made in sea state conditions greater than Beaufort 3, or the sighting was made from a perpendicular distance of more than 5 nautical miles (nm) from the trackline. Sightings with a perpendicular distance greater than 5 nm are considered to be outside of the search area, and are not included in the IATTC's calculation of average school size. Sightings with a recorded radial distance of more than 5 nm were included for both data sets because TVOD sightings with a radial distance greater than 5 nm contribute to the IATTC's estimation of average school size. For dolphins occurring in mixed-species schools, only the estimated number of *S. attenuata* individuals were included as an estimate of school size.

To allow comparisons between the RVOD and TVOD estimates over the period 1980-2000, several assumptions were made. First, the true distribution of dolphin school sizes was assumed constant over a small period of time and region of space. Second, the reported school sizes within that region were assumed to be representative of the total research vessel and tuna vessel search effort. Defining the period of time and region of space to accumulate sightings was initially arbitrary. In the IATTC's stratification of the *S. attenuata* stock area, the stock area is stratified into 1-degree by 1-degree squares. Because of the curvature of the earth's surface, the length in nautical miles of 1-degree at the equator is not the same as the length of 1-degree at higher latitude. The latitude-

longitude coordinates of retained RVOD sightings were used to construct circles with radii of 30 nautical miles (~ 0.5 degrees at the equator in the ETP), unique to each RVOD sighting (the coordinates of the RVOD sightings being the centers of the circles). Within each of the circles, the distribution of school sizes was assumed to be relatively constant over a 29-day period, centered on the date of the RVOD sighting. That is, all TVOD sightings located in the defined spatial region, occurring either 2 weeks before or 2 weeks after the RVOD sighting were then stored for comparison and labeled as a “match.”

A standard bootstrap comparison of the TVOD and RVOD sightings had the potential to introducing bias, because not every TVOD sighting would be weighted equally. A modified bootstrap procedure was used to generate confidence intervals on the difference between RVOD and TVOD school sizes. Bootstrapped sample estimates were generated by iteratively sampling with replacement from the vector of RVOD sightings with known TVOD matches, and sampling with replacement from all TVOD sightings used in this analysis (Efron et al., 1993). To avoid introducing spatial or temporal biases, TVOD sightings in the replicate without “matches” in the sample of RVOD sightings were discarded. Sampled RVOD sightings without TVOD “matches” were also discarded. After one bootstrap was complete, the mean RVOD and TVOD school sizes were calculated. The difference between the two means and ratio of the two means were stored in separate histograms, and the process was repeated 10,000 times.

To analyze whether the difference in RVOD and TVOD school size estimates has changed over time, data were grouped into 3 intervals based on available research vessel data: 1980-1983, 1986-1990, 1998-2000. RVOD and TVOD school sizes within each interval were combined and bootstrapped as before to generate confidence intervals on

the mean difference and the ratio of the difference within each interval. This analysis was extended to include larger spatial regions and temporal periods, including spatial regions with a radius of 150 nautical miles, and temporal windows of 30 days before and 30 days after each RVOD sighting.

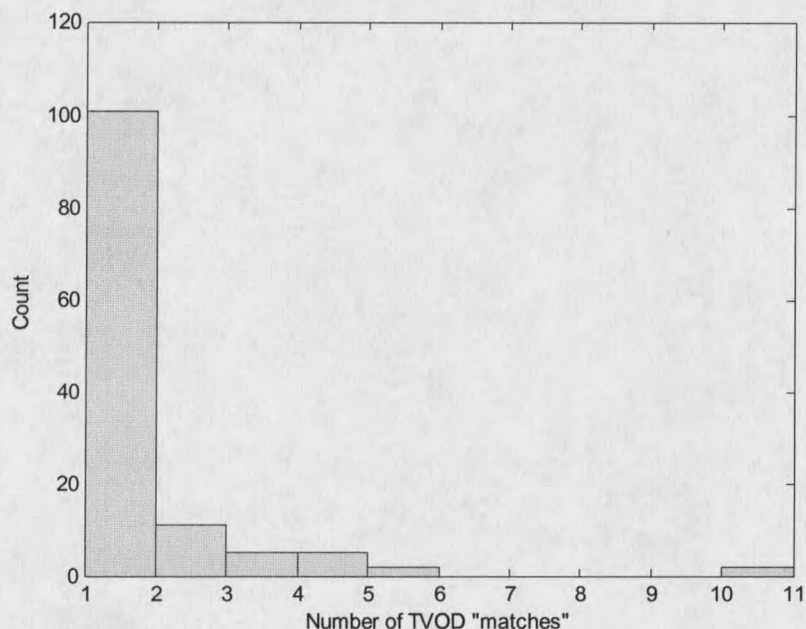
The bootstrapped procedure introduced in this analysis has the potential for creating new biases. RVOD sightings with a large number of TVOD “matches” have a higher chance of being included in the analysis. Similarly, TVOD sightings with fewer “matches” for the same RVOD sighting contribute more heavily to the TVOD average than TVOD sightings with fewer “matches.” As an alternative analysis, matched t-tests were conducted on the raw data to determine whether a difference between the means existed, and whether any detected difference was significant.

Results

In the smallest spatial and temporal region considered, the 126 RVOD sightings were matched against a total of 239 TVOD sightings. The number of TVOD “matches” for each RVOD sighting ranged from 1 to 10 (Figure 36; $\bar{x} = 1.89$, $\sigma^2 = 2.75$), with only a small percentage of the RVOD sightings between 1980-2000 having “matches” (Table 3). As the size of the spatial and temporal regions increased, the overall sample of RVOD sightings and TVOD sightings also increased (Table 4). When the temporal window was extended to 30 days, and the spatial region was extended to a circle with radius 150 nautical miles, just over half of all RVOD sightings had at least one “match.” Within each combination of space and time, there is a strong temporal component, particularly for the number of TVOD sightings. The increase in TVOD sightings can be

explained by increased fishing effort and increased observer coverage on tuna vessels between 1980 and 2000 (Gosliner, 1999).

Figure 36. Distribution of TVOD "matches" for all RVOD *S. attenuata* sightings, 1980-2000. The spatial region used to accumulate matches was a circle with radius 30 nautical miles. The temporal period used to accumulate matches was 14 days before or 14 days after each RVOD sighting.



Interval	30 nm, 14 days	30 nm, 30 days	150 nm, 14 days	150 nm, 30 days
1980-'83	0.1028 (0.0016)	0.1122 (0.0033)	0.3224 (0.0373)	0.3785 (0.0863)
1986-'90	0.1638 (0.0013)	0.2768 (0.0025)	0.5424 (0.0378)	0.6384 (0.0719)
1998-'00	0.1503 (0.0039)	0.2189 (0.0082)	0.6078 (0.0828)	0.6471 (0.1845)
Total	0.144 (0.0024)	0.216 (0.0048)	0.5109 (0.0549)	0.5771 (0.1177)

Table 3. Percent of total retained RVOD and TVOD sightings meeting the deletion criteria in each interval. Spatial regions included circles with radii of 30 or 150 nautical miles. Temporal windows included periods of either 14 or 30 days. The percent of total TVOD sightings is in parentheses.

Interval	30 nm, 14 days	30 nm, 30 days	150 nm, 14 days	150 nm, 30 days
1980-'83	22 (32)	24 (66)	69 (757)	81 (1752)
1986-'90	58 (56)	98 (106)	192 (1607)	226 (3053)
1998-'00	46 (151)	67 (317)	186 (3200)	198 (7132)

Table 4. Number of research vessel sightings in each interval with TVOD "matches." Spatial regions included circles with radii of 30 or 150 nautical miles. Temporal windows included periods of either 14 or 30 days. The number of TVOD "matches" is in parentheses.

The bootstrapped difference in RVOD and TVOD mean school sizes is approximately normal in all cases (Figure 37), from the results of the central limit theorem. Because the normal distribution is also symmetric, the bootstrapped confidence intervals are symmetric about the mean. The bootstrapped ratio comparing TVOD and RVOD school sizes can be considered a ratio of two normal random variables, which is not necessarily normal. The confidence intervals on the bootstrapped ratio of the TVOD to RVOD mean school sizes are not symmetric about the mean, due to the ratio not being normally distributed (Figure 38). The difference between the two samples may be analyzed with a standard paired t-test, however the distribution of the ratio cannot be analyzed with the paired t-test because the assumptions of normality are violated.

Figure 37. Bootstrapped difference ($n = 10,000$) in TVOD and RVOD average school sizes, 1980-1983. TVOD "matches" were accumulated over circles with radii of 30 nautical miles, 14 days before and 14 days after the date of the RVOD sightings.

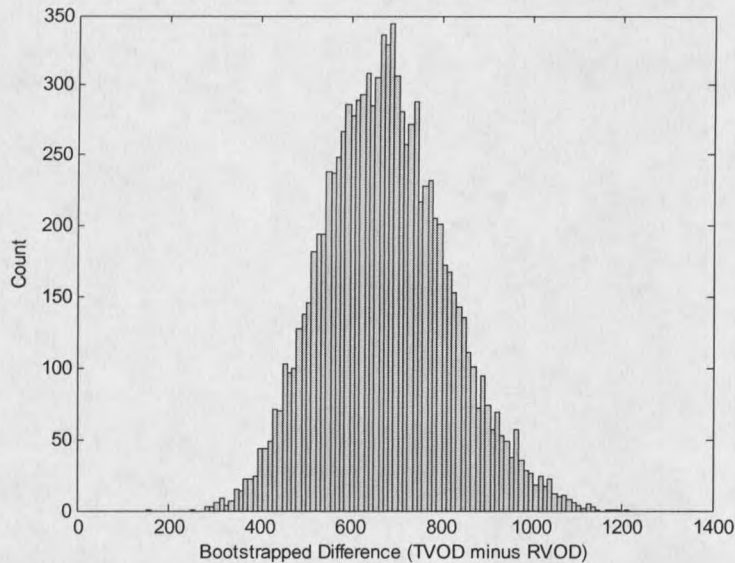
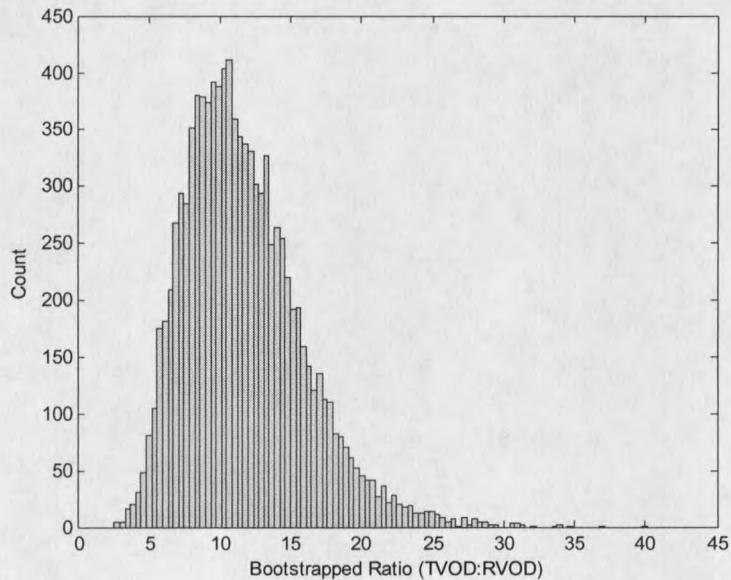


Figure 38. Bootstrapped ratio ($n = 10,000$) of TVOD to RVOD average school sizes, 1980-1983. TVOD "matches" were accumulated over circles with radii of 30 nautical miles, 14 days before and 14 days after the date of the RVOD sightings.



For all combinations of time and space considered, the TVOD average school size was larger than the RVOD average school size. A temporal trend was found in the difference between RVOD and TVOD school sizes (Figures 39-42). The difference between the periods 1980-1983 and 1998-2000 appears significant in all cases because the confidence intervals do not overlap at the 0.90 level. Increasing the radius of the spatial region from 30 nm to 150 nm has more of an effect on the sample size than when the length of the temporal window is increased from 14 to 30 days (Table 4), explaining the narrower confidence intervals in Figures 41-42. Confidence intervals are smaller over the periods 1986-'90 and 1998-'00 than the period 1980-'83, because of the larger sample sizes in later years.

Figure 39. Bootstrapped difference of RVOD average school size subtracted from TVOD average school size. The spatial region used to accumulate "matches" was a circle with radius 30 nautical miles. The temporal period used to accumulate "matches" was 14 days before and 14 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.

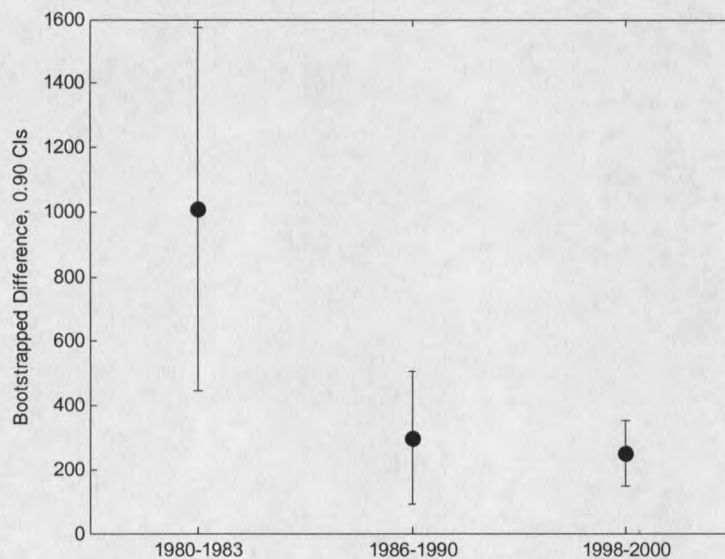


Figure 40. Bootstrapped difference of RVOD average school size subtracted from TVOD average school size. The spatial region used to accumulate “matches” was a circle with radius 30 nautical miles. The temporal period used to accumulate “matches” was 30 days before and 30 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.

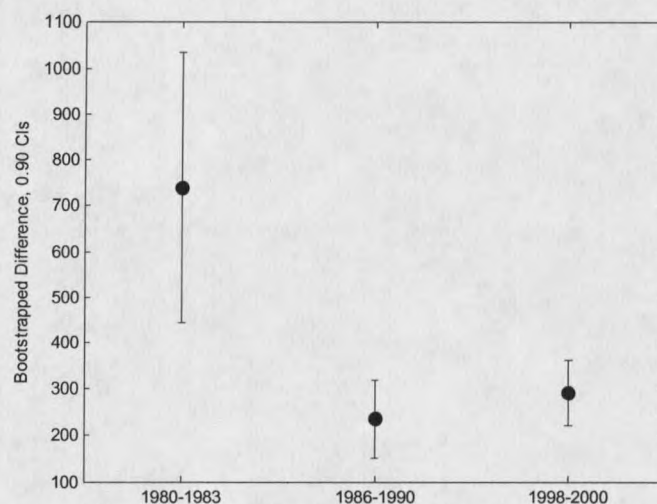


Figure 41. Bootstrapped difference of RVOD average school size subtracted from TVOD average school size. The spatial region used to accumulate “matches” was a circle with radius 150 nautical miles. The temporal period used to accumulate “matches” was 14 days before and 14 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.

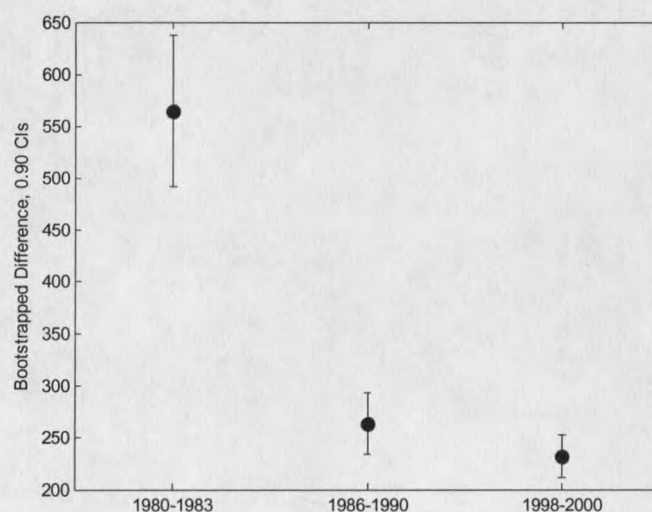
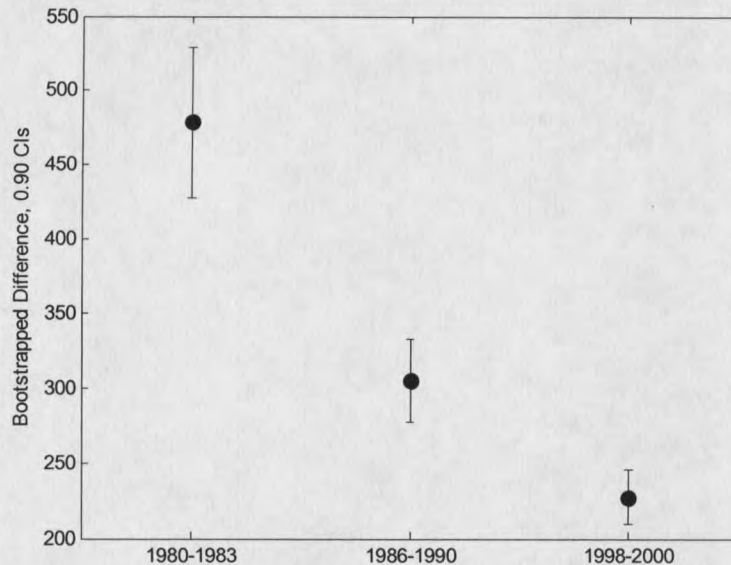


Figure 42. Bootstrapped difference of RVOD average school size subtracted from TVOD average school size. The spatial region used to accumulate “matches” was a circle with radius 150 nautical miles. The temporal period used to accumulate “matches” was 30 days before and 30 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.



A decreasing trend is also apparent in the ratio of TVOD average school sizes to RVOD average school sizes (Figures 43-46). The ratio should be interpreted as a measure of relative change in the mean school size because it is unitless, unlike the mean difference. In the interval 1980-1983, TVOD average school sizes appear to be about 5 times larger than RVOD school sizes. The magnitude of the difference appears to have decreased to about 3.5 over the period 1998-2000 (Figures 43-46). For most regions of time and space considered, the 0.90 confidence intervals over the period 1980-'83 do not overlap the 0.90 confidence intervals computed from the 1998-'00 data.

Figure 43. Bootstrapped ratio of TVOD average school size to RVOD average school size. The spatial region used to accumulate “matches” was a circle with radius 30 nautical miles. The temporal period used to accumulate “matches” was 14 days before and 14 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.

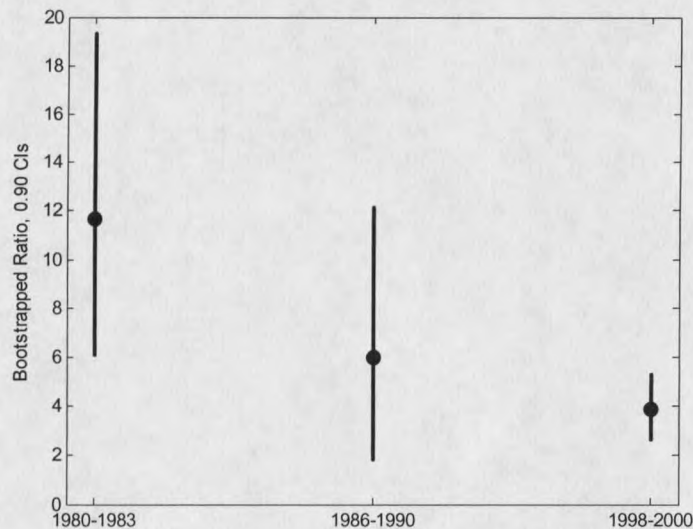


Figure 44. Bootstrapped ratio of TVOD average school size to RVOD average school size. The spatial region used to accumulate “matches” was a circle with radius 30 nautical miles. The temporal period used to accumulate “matches” was 30 days before and 30 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.

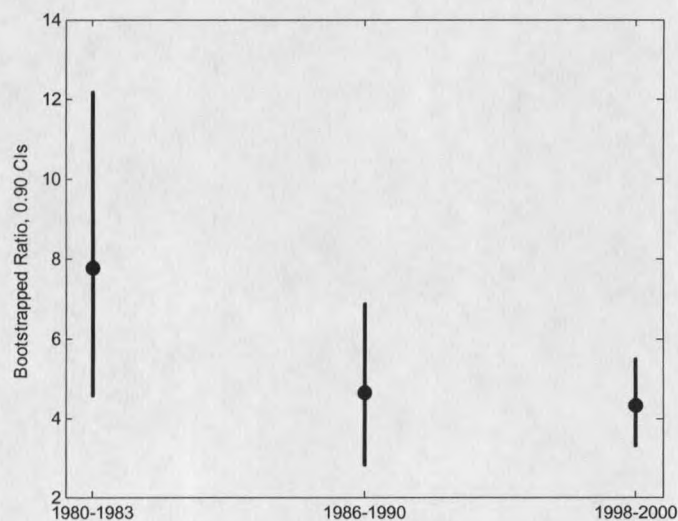


Figure 45. Bootstrapped ratio of TVOD average school size to RVOD average school size. The spatial region used to accumulate “matches” was a circle with radius 150 nautical miles. The temporal period used to accumulate “matches” was 14 days before and 14 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.

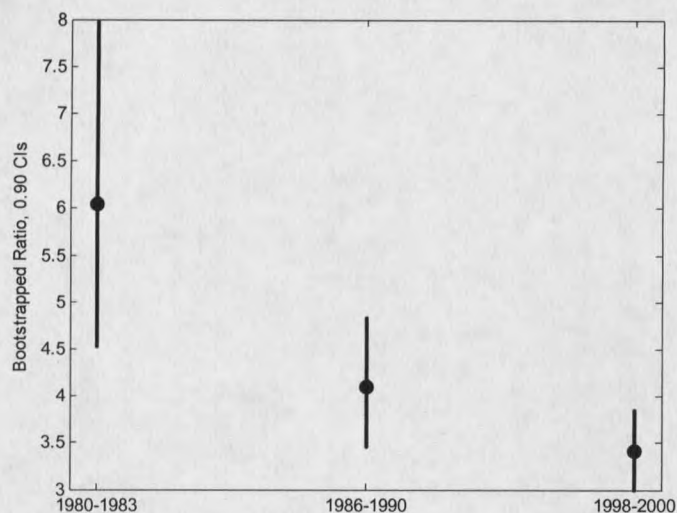
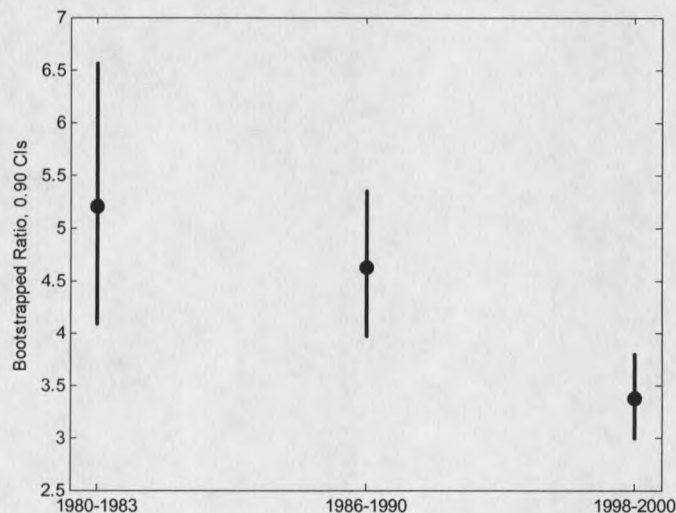


Figure 46. Bootstrapped ratio of TVOD average school size to RVOD average school size (Interval 1 = 1980-'83, Interval 2 = 1986-'90, Interval 3 = 1998-'00). The spatial region used to accumulate “matches” was a circle with radius 150 nautical miles. The temporal period used to accumulate “matches” was 30 days before and 30 days after each RVOD sighting. Bootstrapped confidence intervals were generated at a 0.90 level.



Results from paired t-tests conducted on the RVOD and TVOD school sizes in each interval were compared to the estimated means and confidence intervals generated with the bootstrap procedure (Figures 47-50). For all intervals, the difference was found to be significant ($p < 0.001$). The trend in a decreasing difference between TVOD and RVOD schools is still evident since 1980. The major difference between the two methods is that the confidence intervals generated by the t-tests are more sensitive to larger sample sizes than the bootstrap method (Figures 42,50). One assumption of the t-test that that may be violated in this analysis is that the variance is not the same between TVOD and RVOD observations. If a management decision were to be made from the results of this test, the observations in each sample would have to be standardized by their respective sample standard deviations before the t-test was conducted.

Figure 47. Estimated mean difference (TVOD – RVOD) and 95% confidence intervals for *S. attenuata* school sizes, based on paired t-tests within each interval. The spatial region used to accumulate “matches” was a circle with radius 30 nautical miles. The temporal period used to accumulate “matches” was 14 days before and 14 days after each RVOD sighting.

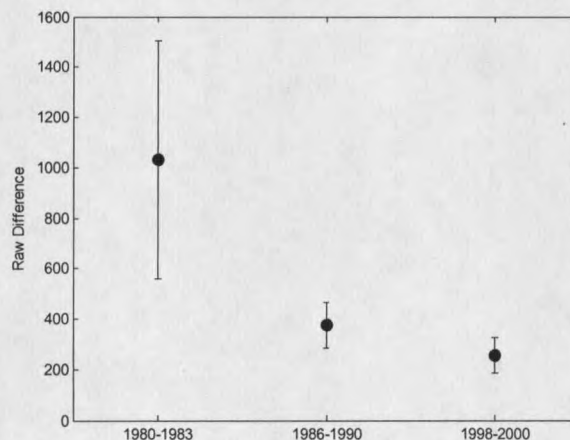


Figure 48. Estimated mean difference (TVOD – RVOD) and 95% confidence intervals for *S. attenuata* school sizes, based on paired t-tests within each interval. The spatial region used to accumulate “matches” was a circle with radius 30 nautical miles. The temporal period used to accumulate “matches” was 30 days before and 30 days after each RVOD sighting.

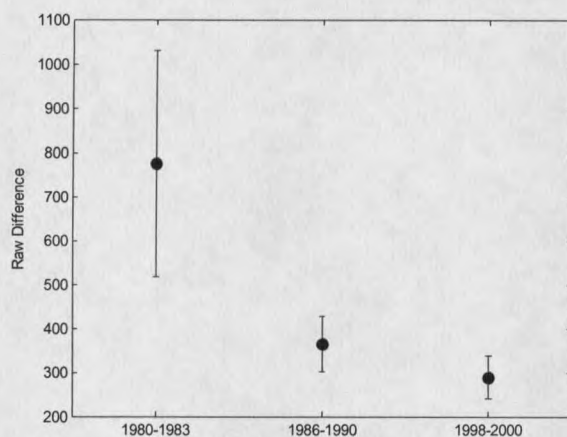


Figure 49. Estimated mean difference (TVOD – RVOD) and 95% confidence intervals for *S. attenuata* school sizes, based on paired t-tests within each interval. The spatial region used to accumulate “matches” was a circle with radius 150 nautical miles. The temporal period used to accumulate “matches” was 14 days before and 14 days after each RVOD sighting.

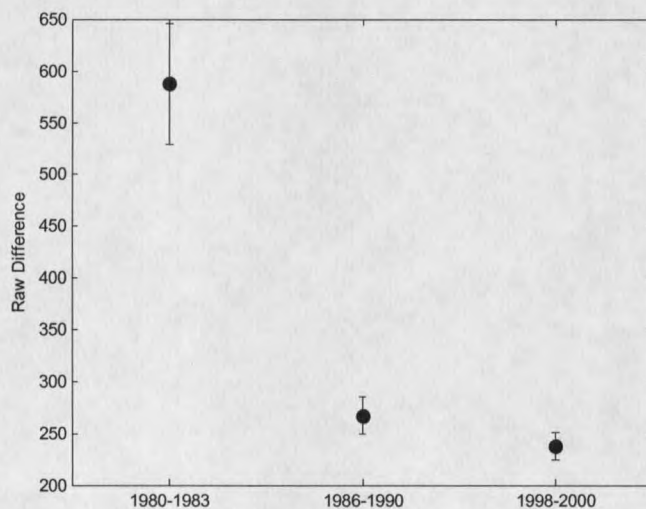
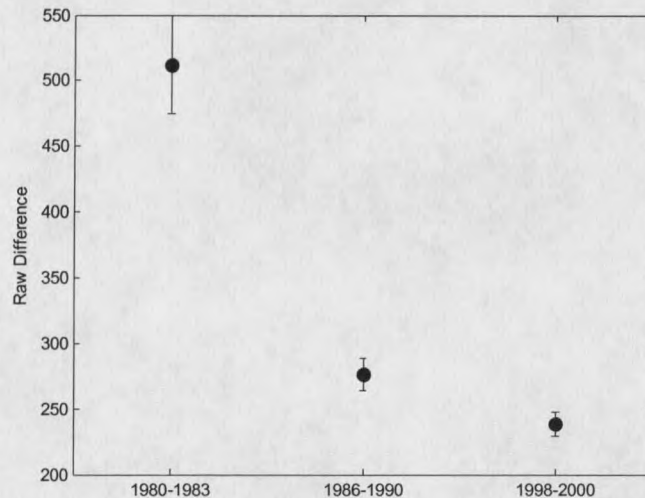


Figure 50. Estimated mean difference (TVOD – RVOD) and 95% confidence intervals for *S. attenuata* school sizes, based on paired t-tests within each interval. The spatial region used to accumulate “matches” was a circle with radius 150 nautical miles. The temporal period used to accumulate “matches” was 30 days before and 30 days after each RVOD sighting.



Discussion

Over the period 1980-2000, the largest reported *S. attenuata* school size in the northeastern stock region (as defined by Perrin et al., 1985, and implemented by Anganuzzi et al., 1989) in Beaufort conditions less than 4 was 1327 individuals in the RVOD, compared to 9999 individuals in the TVOD (TVOD estimates are constrained by 4 digits). School sizes in the RVOD are less prone to bias because they are calculated by averaging three independent observer estimates, with each observer having a unique correction factor calibrated with comparisons of estimates to aerial photographs. Tuna vessel observers with no previous research vessel experience have been found to perform similarly to research vessel observers when estimating school sizes from research vessels

(Cologne et al., 1984), however tuna vessel observers may perform differently on tuna vessels. Ideally, photographic equipment mounted on the vessel, helicopter, or satellite, may be used to calibrate observations from tuna vessel observers.

Although the RVOD and TVOD sightings are not being made on the same school, the underlying distribution of school sizes being sampled should be the same. If no biases are involved in the recording of data, the expected values of any two independent observations are equal to the mean, and the expected value of their difference is zero. By using observations occurring in the same spatial and temporal locations, we were able to eliminate possible factors affecting the distribution of true dolphin school sizes, as well as factors affecting the distribution of the differences between RVOD and TVOD sightings.

One historical hypothesis for explaining the difference between RVOD and TVOD estimates was that TVOD sightings are collected from different spatial locations within the ETP. There is still a large difference between RVOD and TVOD estimates when possible temporal and spatial biases are removed in the present analysis, indicating that we can safely reject this hypothesis. The most likely explanations for the difference is that either a reporting bias exists, in which tuna vessel observers have a tendency to overestimate *S. attenuata* school sizes, or that tuna vessels selectively report larger schools.

If the overestimation of *S. attenuata* school sizes has been proportionally constant over time, the relative abundance as calculated by the IATTC will not be affected. If a time-varying trend exists in the ratio of TVOD to RVOD observations over the period 1980-2000, abundance estimates from TVOD will be compromised. The trend in both the difference of mean school sizes and the ratio of mean school sizes is consistent across

all regions of time and space considered in this analysis. Small numbers of RVOD observations in some years, and lack of observations in others, preclude complete analysis of the possible inter-annual differences between RVOD and TVOD estimates. Because of changes in fishing technology within the tuna fleet since 1980, there may be inherent aspects of the TVOD that have changed the reporting bias or selectivity of the tuna fleet.

The decrease of TVOD shipboard sightings and increase in TVOD sightings involving the helicopter has already been analyzed (Figure 51, Lennert-Cody et al., 2001). Over 1980-2000, the probability that a reported sighting leads to a set has increased for both sightings involving the helicopter (sightings where the helicopter is entered as the sighting method) and sightings not involving the helicopter (sightings where the helicopter is not entered as the sighting method), but to a greater extent for sightings involving the helicopter (Figure 52, Lennert-Cody et al., 2001). Sets on schools involving the helicopter are reported to be larger than sets not involving the helicopter (Figure 53). One possible reason for these differences in sightings involving the helicopter is that helicopters may report fewer small dolphin schools to the vessel, and this reporting may be subject to a trend. Because larger *S. attenuata* schools tend to be associated with more tuna, recorded TVOD school sizes that are set on tend to be larger, on average, than reported schools sighted but not set on (Figure 54). As the probability of a reported sighting leads to a set increases, the estimate of average school size will be weighted more heavily by larger dolphin schools, and will become less representative of the actual population. In addition to technological changes, there may have been significant changes in the observer training program between 1980-2000. These changes

in tuna vessel search methods are possible reasons why the reporting bias or selective reporting by tuna vessels has changed since 1980, and may explain the temporal trend in the difference between RVOD and TVOD dolphin school sizes.

Figure 51. Proportion of the TVOD *S. attenuata* sightings that are used to estimate school size and have the helicopter entered as the sighting method (plus or minus 1 standard error).

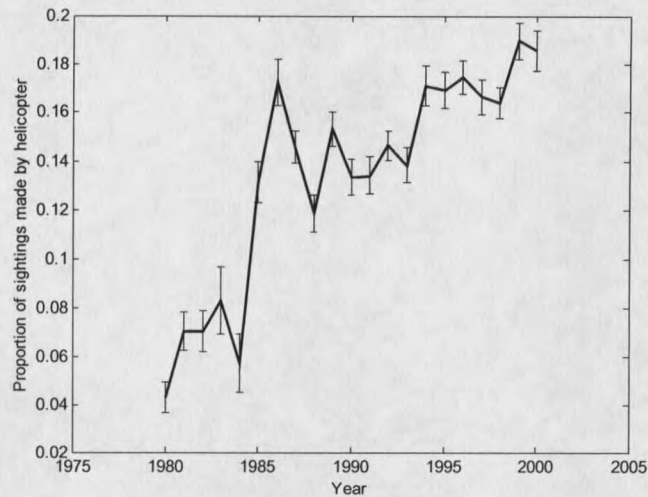


Figure 52. Probability of TVOD *S. attenuata* sightings leading to a set, for sightings used to estimate average school size (plus or minus 1 standard error). The solid line represents sightings where the helicopter is entered as the sighting method, the dashed line represents all other sightings.

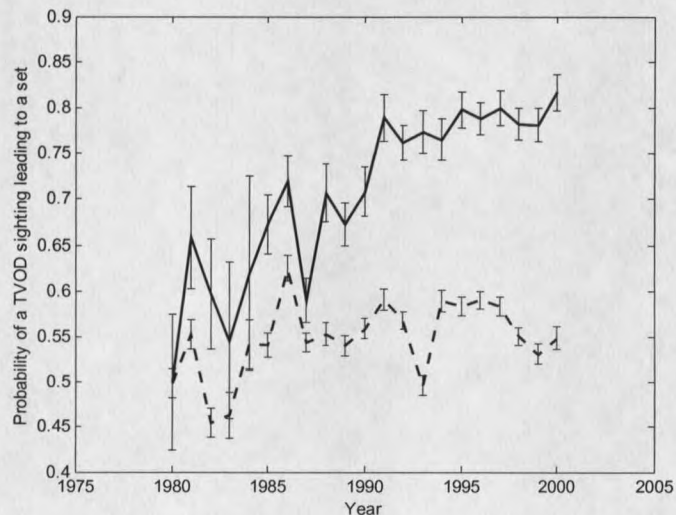


Figure 53. Average size of *S. attenuata* schools set on for sightings used to estimate average school size (plus or minus 1 standard error). The solid line represents sightings where the helicopter is entered as the sighting method, the dashed line represents all other sightings.

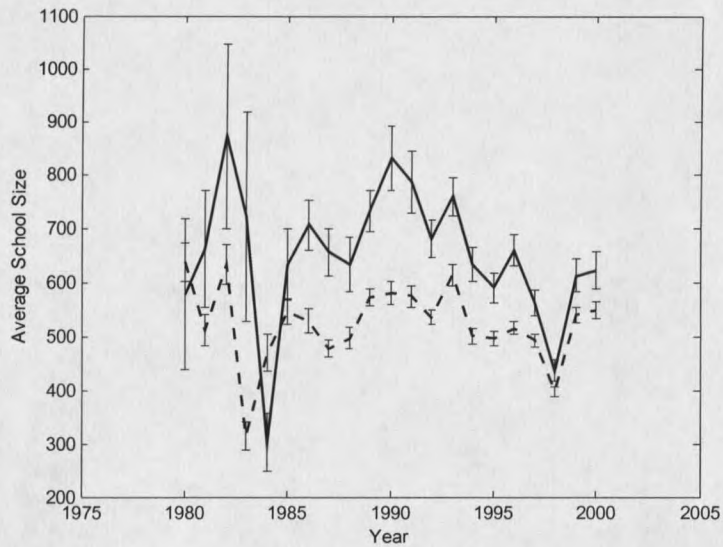
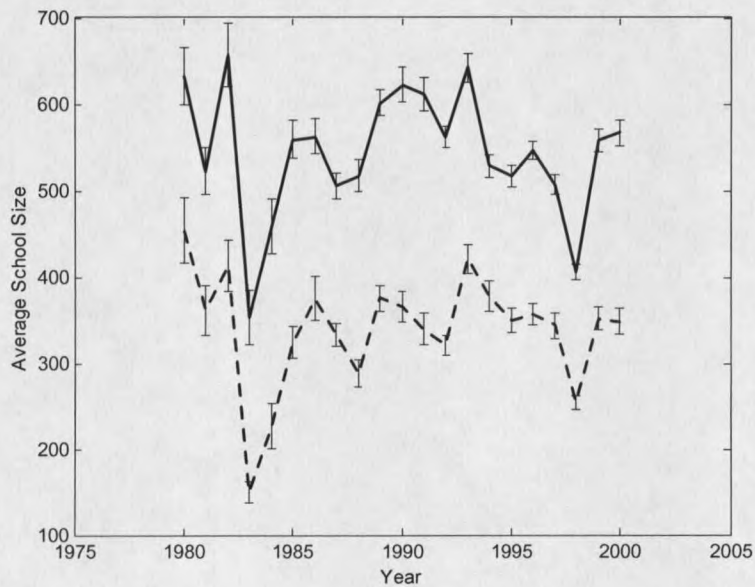


Figure 54. Average *S. attenuata* school size estimates in the TVOD (plus or minus 1 standard error). The solid line represents the average school size of schools set on, the dashed line represents the average school size of schools not set on.



The overestimation of TVOD dolphin schools represents a critical bias, because it exhibits a clear temporal trend. Inference of trends in abundance based on the TVOD index is dependent on our ability to correct for this bias. It is impossible to calculate year-specific correction factors, as RVOD surveys are only conducted in some years, and data in any given year is relatively sparse. As a rough correction, TVOD abundance estimates in years with RVOD surveys were rescaled based on the bootstrapped ratio of TVOD:RVOD school sizes estimated in this analysis (Figure 55). To account for the trend in the contribution of "set" estimates to average school size estimates over time, year specific bias factors were calculated, assuming that the probability of a sighting leading to a set had remained constant at the 1980 level. These bias correction factors were incorporated into the rescaled estimates, along with the estimated rate of overestimation from better searching technology (Chapter 3) to produce final bias-corrected estimates (Figure 56). These final corrected estimates are only slightly more correlated to the NMFS estimates calculated by Gerrodette et al., 2002 (0.706 versus 0.723). Some years in the TVOD index (1983, 1987) appear to deviate substantially from the RVOD estimates, and the cause for this discrepancy has not been examined. Abundance based on TVOD in other years correlates strongly with the NMFS abundance estimates, suggesting that the TVOD may contain valuable information that could be used for years without research vessel surveys.

Figure 55. Rescaled TVOD *S. attenuata* abundance estimates, incorporating the trend in the overestimation of school sizes reported by tuna vessel observers (dots are original relative abundance estimates, asterisks are rescaled estimates).

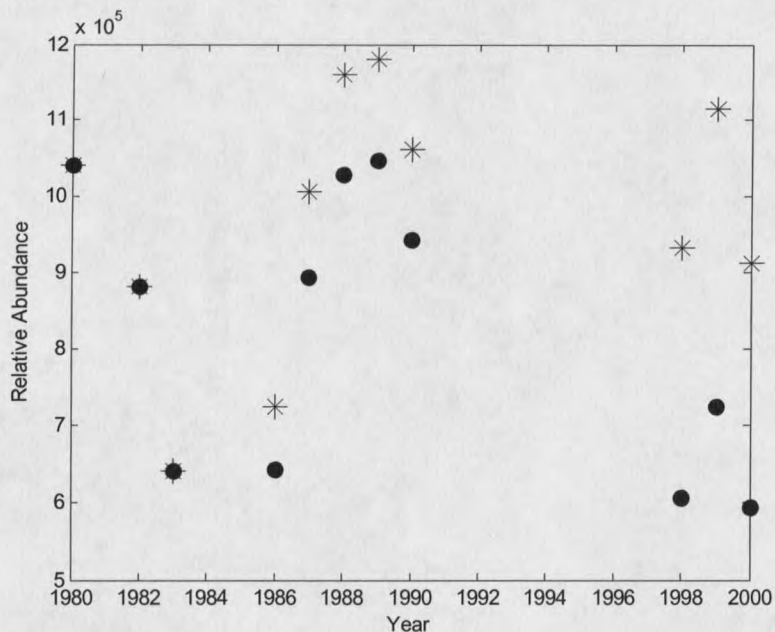
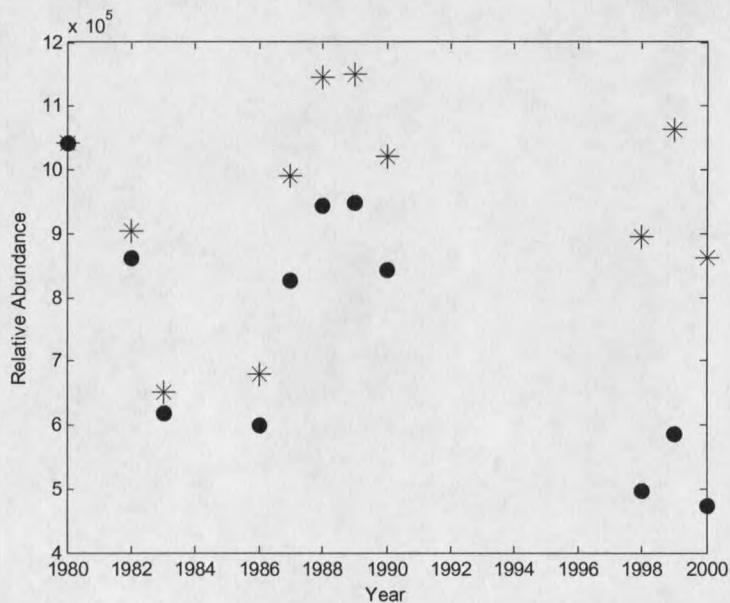


Figure 56. Rescaled TVOD *S. attenuata* abundance estimates, correcting for biases associated with the non-random distribution of effort, change in the probability of a sighting leading to a set over time, and change in the ratio of TVOD:RVOD school size estimates.



SUMMARY

As a preliminary analysis, I examined general trends in estimates of average school size, encounter rate, $f(0)$, and total abundance of *S. attenuata* for data collected aboard tuna vessels and research vessels. Tuna vessel data did appear to contain some information, as both RVOD and TVOD average school size estimates appeared to respond to years with strong ENSO events.

The first bias I attempted to quantify and correct for was the non-random distribution of search effort in the ETP. The IATTC algorithm does appear to correct for the majority of the bias associated with the non-random distribution of search effort and non-random distribution of dolphin schools. This bias did not appear to have an intra-annual component, but did appear to have a spatial component that indicated tuna vessels were aggregating more over the time series in regions of space with larger average school size. I assumed the bias to be approximately linear, and after performing Bayesian linear regressions and least squares regressions, I was able to estimate the slope parameter of the trend. The spatial bias was relatively small, but I rescaled the entire time series of estimates to examine the possible underestimation or overestimation that may be caused by such a trend.

The second bias I attempted to correct for was known changes in search technology since 1980. Tuna vessels have become more efficient at finding dolphins, particularly dolphin schools that are larger than average. It is difficult to quantify changes in technology, without having reliable information on helicopter and radar use in

the tuna fleet (the tuna vessel data only has a record of whether radar or a helicopter was present, and whether the radar or helicopter was entered as the sighting method). As a proxy, I examined the increasing trend of a probability leading to a set (as this incorporates both helicopter use and selectivity for larger schools) to estimate the degree that average school size has been overestimated in recent years (or underestimated in early years). This trend also appears to have a linear component, which I used to rescale the estimates of relative abundance based on TVOD.

The final bias I examined was the difference between dolphin schools reported by tuna vessels, and dolphin schools reported by research vessels. The magnitude of the difference appears quite large, but appears to have decreased significantly since 1980. I attempted to correct for the bias, using estimates from research vessel data pooled across three intervals of years. For each interval, I examined the difference and ratio of the sample mean to generate confidence intervals, which I compared to confidence intervals generated with a standard paired t-test.

The biases associated with changes in searching and changes in fishing technology since 1980 do not prohibit inference based on tuna vessel observer data. These biases are both intrinsic to the TVOD data set, meaning the bias in one year may be estimated relative to another year of the time series. The bias involved with overestimating *S. attenuata* school sizes poses more of a problem. I attempted to roughly correct for this bias using pooled estimates from research vessel surveys in multiple years (due to small RVOD samples in some years and no samples in others). The rescaled TVOD estimates I presented should not be used for inference of trends, because year-specific correction factors need to be calculated. Until the overestimation by tuna vessel

observers is corrected for each year of the time series, a time-varying bias will remain in the TVOD.

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APPENDICES

Variables in TVOD sightings files.

- 1) Cruise number
- 2) Year
- 3) Month
- 4) Day
- 5) Sighting number
- 6) Time
- 7) Sighting cue
- 8) Sighting method
- 9) Bearing
- 10) Radial distance
- 11) Beaufort
- 12) Water temperature
- 13) Latitude
- 14) Longitude
- 15) Position accuracy code
- 16) Vessel on/off effort
- 17) Observer on/off effort
- 18) Sighting led to a set (yes/no)
- 19) Search type
- 20) Observer's initial estimate of school size (including species composition)
- 21) Crew's initial estimate of school size (including species composition)
- 22) Observer's "set estimate" of school size (including species composition)
- 23) Data source (NMFS observer/IATTC observer)

Variables in TVOD effort files.

- 1) Longitude
- 2) Latitude
- 3) Cruise number
- 4) Year
- 5) Month
- 6) Day
- 7) Observer on/off effort
- 8) Vessel on/off effort
- 9) Beaufort
- 10) Nautical miles searched
- 11) Data source (NMFS observer/IATTC observer)

TVOD Sighting Cues.

- 1) Birds
- 2) Splashes
- 3) Mammals
- 4) Ships
- 5) Unknown
- 6) Whale blow

TVOD Sighting Methods.

- 1) Crow's nest
- 2) 20X binoculars from crow's nest
- 3) 20X binoculars (one person)
- 4) 20X binoculars (more than one person)
- 5) Helicopter
- 6) Other (includes observer sightings)
- 7) Radar

TVOD Search Methods.

- 1) No search mode
- 2) General search
- 3) Searching for dolphins
- 4) Searching for schooling fish

Variables in TVOD gear files.

- 1) Cruise number
- 2) Vessel number
- 3) Departing year
- 4) Arriving year
- 5) Helicopter onboard (yes/no)
- 6) Radar onboard (yes/no)
- 7) Data source (NMFS observer/IATTC observer)

Deletion criteria to avoid introducing biases.

- 1) Any sighting belonging to a cruise already marked for deletion is deleted.
- 2) When the analysis of only a quarter of a year is done, cruises with months that do not match that particular interval of months are deleted (e.g. intervals of months 1-3, 4-6, 7-9, 10-12).
- 3) If the sighting was first made by the observer, it is assumed to have already been missed by the crew (biasing radial distance) and is deleted.
- 4) Any sighting made while the vessel was off-effort (or the status was unknown) is deleted.
- 5) Any sighting with a sighting angle greater than 100 degrees and less than 260 degrees is deleted.
- 6) If estimates made through 20X or 25X binoculars are to be deleted, those sightings are removed (by default they are retained).
- 8) If sightings made from the crow's nest are to be deleted, those sightings are removed (by default they are retained).
- 9) If sightings made by the helicopter or by radar are to be deleted, those sightings are removed (by default they are retained).
- 10) If a sighting has no position (latitude or longitude = -99), the program opens a file of interpolated positions, searching for an interpolated position with the same cruise number, month, day, and time. Interpolated positions are not calculated for the following reasons: a cruise has ended, more than 5 days of events without positions has occurred after the current event, or there are more than 300nm between positions. If an interpolated position is not found, the sighting is deleted.
- 11) Any sighting recorded outside of the ETP boundary is deleted.
- 12) Any sighting occurring in a region that is not within a stock boundary is deleted.
- 13) If the distance or sighting angle for a sighting is not known, then the sighting is deleted.
- 14) If the Beaufort conditions exceed Beaufort 3 conditions (or the Beaufort is unknown), the sighting is deleted.
- 15) Any sighting made when the observer was off-effort (or the observers' status was unknown) is deleted.
- 16) If the bearing or distance are missing for a particular sighting, then all data from that day is deleted.

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