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DEVELOPMENT OF A FISHERY INDEPENDENT INDEX OF SBT ABUNDANCE

FRDC FINAL REPORT

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DIVISION OF **FISHERIES**

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NON-TECHNICAL SUMMARY

- The annual aerial survey for southern bluefin tuna was conducted in the summer season of 1995 over the Great Australian Bight. The data collected in the survey allowed various surface abundance indices of SBT to be calculated. These indices were considered for the first time the CCSBT Scientific Meeting.

- The main abundance estimates in 1995 (number of schools per unit area and biomass per unit area) were slightly higher than the 1994 estimates, but these increases were not large enough to be statistically significant and should therefore be interpreted with caution.

- Statistical analysis of environmental conditions during the survey was conducted to determine the most important variables to incorporate in the new models incorporating environmental factors currently under development.

- The aerial survey results began to overlap with some cohorts in the VPA stock assessment results in 1995. Evaluation of this initial overlapping data suggests that the aerial survey may provide useful input to the VPA analysis but a longer time series of indices is required before a final evaluation is possible.

BACKGROUND

All recent assessments of SBT indicate that the parental stock is at historically low levels. The current parental stock biomass has been judged to be below "commonly used scientific measures of biologically safe parental biomass" and concerns exist about the risk of poor recruitment and the possibility of recruitment collapse. There is also a large amount of uncertainty about whether the current catch quotas are sufficient to allow for rebuilding of the SBT stock.

The current analytical assessment methods for SBT have a 4 to 5 year time lag in the estimates of the number of recruits due to time lags in receiving catch data and the lack of any reliable index of juvenile abundance. In addition, there is a high degree of uncertainty associated with most recent estimates of recruitment as they are largely determined by the most recent juvenile catch rates. Therefore, current trends in recruitment remain one of the major unknowns in evaluating the status of this stock and its potential to rebuild under current catch levels. Moreover, no fishery-independent information on stock or juvenile abundances exists. Lack of such information is a major source of uncertainty in the SBT stock assessments and a limitation in evaluating the likelihood of stock re-building under current catches.

All recent scientific and management meetings both under the previous informal tri-lateral arrangement and now under the Convention of the Conservation of Southern Bluefin Tuna have considered the development of a fishery-independent index of SBT recruitment to have a very high research priority. In response to this need, a developmental aerial survey program was initiated in 1990/91, and experimental surveys using line transect methods have been conducted annually during the fishing season in the Great Australian Bight since then.

In June 1993 a large scale five year collaborative research program involving CSIRO and the Japanese National Research Institute of Far Seas Fisheries (NRIFSF) was established for the purpose of monitoring the abundance of juvenile SBT and the development of a fishery-independent index of juvenile abundance. The aerial survey project was established as one of the main projects within this program. Funding for the aerial survey component of this collaborative research program has come from a variety of Japanese and Australian sources; the Australian sources include CSIRO, SBTMAC, FRDC and FRRF.

Each year a workshop is held to review and prioritise the collaborative research for the coming year. At the 1995 workshop, the aerial survey was re-affirmed as one of the highest priority projects.

NEED

Analyses of the four previous surveys conducted between 1990/91 and 1994 indicate that the data can be used to provide estimates of the number of schools, total biomass and biomass by cohort for fish at the surface with reasonable coefficients of variation. However, the ability of the aerial survey to detect temporal trends in the actual population will depend upon the variability associated with the index and the length of the time series. The variability associated with the index stems from a combination of sampling error and process error. [1]

While it is possible to estimate the amount of sampling error from the results of a single survey, the amount of process error can only be evaluated when a sufficiently long time series of abundance estimates are available for comparison with other measures of abundance and for internal consistency comparisons. Given the promising results from the surveys to date, there is a need to conduct a fifth survey in order to continue the time series of estimates necessary for the development and evaluation of this SBT recruitment index.

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[1] Sampling error is a function of survey design and methodology. Its magnitude depends on the amount of survey effort. Process error comprises fluctuations in the signal due to other variability such as the proportion of schools at the surface and the proportion of schools within the bight.

OBJECTIVES

1. To conduct an aerial survey for southern bluefin tuna over the Great Australian Bight in the summer season of 1995 and estimate various surface abundance indices of SBT.

2. To conduct research which will contribute to the development of methods for reducing the variability associated with the aerial survey indices. (Note that while FRDC funding provided partial support for work in 1994/95, the overall project is multi-year and the development of these indices was anticipated to take more than a single year. As such this second objective was a multi-year one which extended beyond the scope of the FRDC funding and research in this area is still continuing.)

The first objective was fully achieved. Significant progress was made on the second objective with work having been conducted on (1) analytical/statistical models that incorporate environmental data on conditions during the survey (2) initial evaluation of the survey results in relativity to VPA stock assessment results and (3) evaluations of the potential for LIDAR to assist in the surveys.

METHODS

ANALYSIS OF 1995 AERIAL SURVEY DATA

The aerial survey is based on sample survey line transect methodology. The data were analysed using non-parametric kernel estimators; see Chen (1994a, b) for details of the methodology. To date, estimates of the density of SBT schools, total biomass and biomass by cohort for fish at the surface have been developed.

INFLUENCE OF ENVIRONMENTAL FACTORS

Statistical analyses using both non-parametric and parametric regression techniques were performed in order to determine if surface windspeed, cloudcover, air temperature, or sea surface temperature affected the distances (from the transect) at which schools were sighted or the sizes of the detected schools.

COMPARISON OF ESTIMATES FROM THE AERIAL SURVEY AND VPA RESULTS

On page 14 of the report in Appendix 1, we give details of the method used to calculate the abundance estimates for each age class in each year of the aerial survey, and also the method used to calculate the relative number of SBT in each age cohort. (The temporal trend in these figures can be directly compared with abundance estimates from VPA.)

EVALUATION OF LIDAR

LIDAR (Light Detecting and Ranging) is a technology developed for the US Department of Defence which has only recently been declassified. LIDAR has the ability to detect individual fish or schools up to a depth of around 35m at an altitude of 1500 feet with a swath width of 85m as in the aerial survey. As such it has the potential to improve estimates of school size and fish size in aerial surveys, thereby reducing the variability of biomass estimates; see Hunter and Churnside (1995).

A technical review of information on suitable LIDAR instruments was conducted and a field trial of the KAMAN Aerospace Fisheye LIDAR system was planned, but for logistic reasons, a field trial could not be conducted in 1995. The Fisheye instrument has been further developed during 1995: the swath width and penetration have been improved, and a lighter more compact and a version of the equipment has been developed. Moreover, the system has been adapted for Aerocommander planes (as used in the aerial survey) and so the survey plane would not require modifications to trial the equipment. Good progress on logistical arrangements for a trial in the 1996 survey season has been made.

DETAILED RESULTS

ANALYSIS OF 1995 AERIAL SURVEY DATA

The results of the analysis of the 1995 aerial survey data are given in the report in Appendix 1.

INFLUENCE OF ENVIRONMENTAL FACTORS

Graphs showing the nonparametric regression estimates of the relationships between perpendicular sighting distance and various environmental factors are given on pages 50–57 of the report tabled in Appendix 1. The squares of the estimates of the linear correlation coefficients are shown on each plot, and the *p*-value for the test of the hypothesis that $r = 0$.

There is a statistically significant tendency for both sighting distance and school size to increase in warmer air temperatures outside the plane at 1500 feet. It is not clear how the air temperature outside the plane is related to school size. There may be a link with haze, or temperature just above the sea surface. However, in the latter case, we might expect distance and school size to be related to surface sea temperature, but this was not consistently found to be the case.

COMPARISON OF ESTIMATES FROM THE AERIAL SURVEY AND VPA RESULTS

On pages 15–16 of the report in Appendix 1, we show graphs of the relative number of SBT in the 1989–1993 age cohorts in the entire Bight, and in the 1988–1993 age cohorts for the eastern Bight. The eastern Bight figures are more complete (the 1992 survey covered only the eastern Bight) but have higher sampling error. The figure on page 16 suggests that there were more SBT in the 1989 year class than the 1988 year class. The numbers in each year class decreased between 1989 and 1991, increased slightly in 1992 then decreased again in 1993.

These initial results were in general agreement with the VPA results for the 1988 to 1990 cohorts (the 1990 cohort is the most recent one for which a VPA estimate is available). However, several years of observation of the variation in the two series is necessary before a final evaluation of the usefulness of the aerial survey indices for the VPA analysis is possible.

BENEFITS

The research benefits the Australian SBT fishing industry. Improved and more timely assessment of the SBT resource will provide a better basis for setting catch limits.

INTELLECTUAL PROPERTY

None

FURTHER DEVELOPMENT

- The aerial survey should continue for at least another 3–5 years in order to have a long enough time series to evaluate the usefulness of the indices derived from the aerial survey and complete the statistical research required to reduce the process error in the estimates.

- A field test of LIDAR technology should be conducted as soon as feasible, and if warranted, methods should be developed for incorporating this technology into the aerial survey design.

STAFF

The staff employed on the project were:-

Ann Cowling	CSOF5	Statistician
Song Chen	CSOF5	Statistician
James Forbes		Computer Programmer
Tom Polacheck	CSOF7	Senior Research Scientist

This FRDC grant was used towards Ann Cowling and Song Chen's salaries in 1994/95.

FINAL COST

See separate attachment.

DISTRIBUTION

SBTMAC Members. (Please note that Appendix I has already received extensive distribution including at the CCSBT Scientific Committee, SBT Recruitment Monitoring Workshop and AFMA – SBTMAC reports).

REFERENCES

Chen, S. X. (1994a). A kernel estimate for density of a biological population using line transect sampling. *Applied Statistics*, to appear.

Chen, S. X. (1994b). Studying the school size effect in line transect sampling using the kernel method. Technical Report CSIRO Biometrics Unit.

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Appendix 1

Data Analysis of the Aerial Surveys (1991–1995) for Juvenile Southern Bluefin Tuna in the Great Australian Bight

Ann Cowling Song Chen Tom Polacheck

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1 Introduction

All recent assessments of southern bluefin tuna (SBT) indicate that the parental stock is at historically low levels. The current spawning stock is estimated to be below 13–30% of the 1980 level and 11-19% of the 1960 level. Recent assessments also indicate that recruitment was declining in the 1980's. The current parental stock biomass has been judged to be below "commonly used scientific measures of biologically safe parental biomass" and concerns exist about the risk of poor recruitment and the possibility of recruitment collapse.

The current analytical assessment methods for SBT have a 4 to 5 year time lag in the estimates of the number of recruits due to time lags in receiving catch data and the lack of any index of juvenile abundance. Current trends in recruitment remain one of the major unknowns in evaluating the status of this stock and its potential to rebuild under current catch levels. Moreover, little fishery independent information on stock or juvenile abundances exists. Lack of such information is a major limitation to improving the precision of the more recent abundance estimates from the VPA assessments. At present, catch rates from longline vessels provide the only information on the relative abundance of juvenile fish. However, interpretation of longline catch rates as indices of abundances, particularly for juvenile fish, is difficult (and becoming increasingly so) due to changes in targeting, areas of operation, and retention practices.

Recent scientific and management meetings on SBT have considered the development of a fishery independent index of SBT recruitment to have a very high research priority. In response to this need, a developmental aerial survey project was initiated in 1990/91, and surveys using line transect methods have been conducted annually during the fishing season in the Great Australian Bight since then. The main objectives of the survey are:

1. to estimate the surface abundance of SBT in the Bight region during the summer season of each survey year,
2. to establish a relative abundance index of SBT recruitment over a medium to long term time span.

While stock assessment can proceed on the basis of a relative measure of recruitment, unbiased estimates of the absolute abundance (both surface and sub-surface) would provide an even better basis for reducing current uncertainties in SBT stock assessment, thereby improving advice to fishery management.

The ability of the aerial survey indices to detect temporal trends in the actual population will depend upon the variability associated with the index and the length of the time series. It is unlikely that temporal trends can be detected until we have accumulated comparable survey data for another 3–5 years.

In Section 2 of this report, we review the three different survey designs used in 1990/91, 1992 and 1993–1995. The statistical methods used in the data collection and analysis are briefly outlined in Section 3, and the results of the data analysis are presented in Section 4. In Section 5, we describe the environmental conditions experienced during each survey season. Finally, in Section 6, we discuss the results, and their implications. There are a number of appendices to this report containing more detailed results of the data analysis.

2 Survey design

The 1990/91 and 1992 surveys were designed and conducted by David Morgan (Morgan 1991, 1992). A survey design workshop attended by scientists from Australia and Japan was held in November 1992 in Hobart to carefully examine the results of the two previous surveys and discuss various associated survey design issues. The design of the 1993–1995 surveys was based on the protocols agreed at that workshop. The main differences between the 1993–1995 surveys and the two previous surveys are in the area surveyed, the amount of survey effort, the stratification used, and the shape of the trackline.

Meaningful comparisons of the survey results between years can only be made if the data is consistent from year to year. Therefore, before presenting the results, we shall review the three survey designs and examine their differences.

2.1 1990/91 survey

The 1990/91 survey (Morgan 1991) was a feasibility study. The survey area comprised four fixed 1° bands of longitude (128–129°W, 130–131°W, 132–133°W, and 134–135°W) across the Bight. The formal survey was run from November 1990 to April 1991, with some SBT surfacing trials conducted after April.

Four zones were defined within each band: coastal, mid-shelf, shelf-edge and off-shelf zones. These zones did not constitute a statistical stratification as each zone was given the same search effort/unit area. The survey data showed that few sightings were made in the off-shelf zone, and so in the following surveys the off-shelf zone was deleted.

The transect lines of the 1990/91 survey comprised fixed north/south and random east/west lines: Figure 2.1 on page 4 shows the transect lines of the fifth replicate.

The 1990/91 survey flew when the wind speed at the sea surface was below 12 knots. However, the survey data showed that few sightings were made when the wind speed was over 10 knots. Thus in the following years, the survey would start only in sea surface winds of 8 knots or less and would remain operating if the wind speed was less than 10 knots.

2.2 1992 survey

Because of funding constraints, the 1992 survey (Morgan 1992) was restricted to two months and a limited area. It operated only in January and February, and covered just the two eastern 1° bands (132–133°W, 134–135°W). Its aims were to focus on specific methodological and design aspects of the survey. As mentioned above, it excluded the off-shelf stratum and flew only in winds of 10 knots or less. The survey used the same transect line design as the 1990/91 survey.

2.3 1993–1995 surveys

The 1993-1995 surveys covered all of the Bight from 128°W to 135°W, from the coast to the 700–800 meter depth contour of the continental shelf. The survey area was divided into 5 parallel east/west blocks which ran from the coast to the shelf-edge, on the basis that each block could be surveyed in one flying day.

No stratification of survey effort was made in the 1990/91 and 1992 surveys. However, the experience of commercial SBT spotters indicates that more sightings are made in the inshore and shelf-edge areas. This led the survey design workshop to suggest placing more search effort in these two areas in order to reduce the sampling error. Consequently, the 1993–1995 surveys were stratified into inshore, middle and shelf-edge areas. The definitions of these strata were basically the same as the definitions of the coastal, mid-shelf and shelf-edge zones in the 1990/91 and 1992 surveys. Commercial spotters also identified three small "hot spots" in the most eastern block where there is a very high probability of sighting tuna schools. These high density "hot spots" were also separately stratified in the 1993–1995 surveys.

The trackline design of the 1990/91 and 1992 surveys did not ensure that all areas had equal probability of being searched. It was also found that there was a tendency for east/west transects to have higher sighting rates than north/south transects. These considerations led to a new transect line design as follows: within each block, three north/south track lines were randomly positioned, and connected in the inshore and shelf-edge strata with zig-zag lines (see Figure 2.2 on page 4). These zig-zag lines in the inshore and shelf-edge areas placed more survey effort in these two strata than in the middle stratum.

To increase the chance of observing SBT schools at the surface, the 1993–1995 surveys operated only between 11am and dusk (true local time), and if all the following weather conditions were met:

1. The cloud cover must be relatively light.
2. The visibility must be good.
3. The wind speed at the sea surface must be 8 knots or less. However, once the survey has been initiated, then it may continue as long as the wind speed does not exceed 10 knots.

Note that, as mentioned earlier in this report, the 1990/91 survey used a less constrained wind condition whereas the 1992 survey used the 8 knot wind limit given above. The 1994 and 1995 surveys used two planes in January and February, and one in March in order to increase the survey effort and reduce sampling error.

For more detail on the design of the 1993–1995 surveys, see the Report on the Aerial Survey Design Workshop (1992), and Chen and Polacheck (1993).

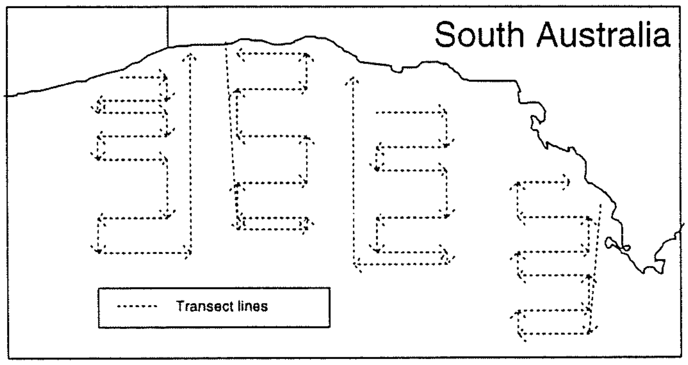


Figure 2.1: Design of 1991 survey showing the area covered, and the transect lines of the 5th replicate

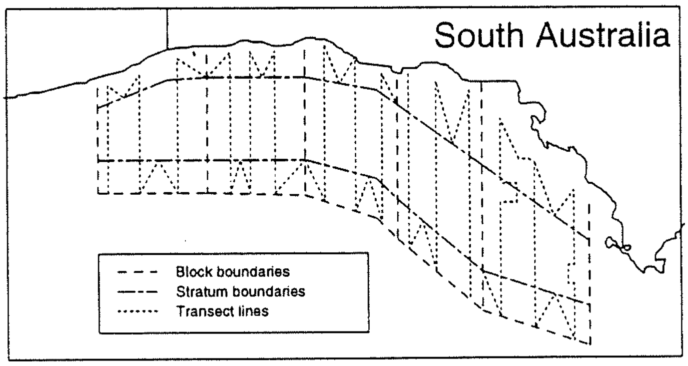


Figure 2.2: Design of 1993–1995 surveys showing the area covered, the block and stratum boundaries, and the transect lines of the 5th replicate of the 1995 aerial survey

2.4 Comparability of data sets

The 1990/91 survey had 9 replicates of data collected between November 1990 and April 1991, with the first 3 replicates in 1990, Replicates 4 to 8 from January to March 1991 (apart from one block in Replicate 4 surveyed in December 1990), and Replicate 9 in April 1991. The 1992 to 1995 surveys were all conducted between 1 January and 31 March. There were 5 replicates of data in 1992, 4 replicates in 1993, and 8 replicates in 1994 and 1995.

Based on these differences, the following data selection plan was used to allow valid comparisons between years.

1. To make the 1990/91 survey comparable with the 1993–1995 surveys, only the survey effort and sightings made between January and March 1991, from coastal, mid-shelf and shelf-edge zones, and in wind speeds less than 10 knots were included. This makes the survey period, area and wind condition comparable to the 1993–1995 surveys. From now on, we shall call this subset of the 1990/91 dataset the 1991 survey.

2. The 1992 survey only covered two 1° bands (132–133°W and 134–135°W). To make the 1991 survey comparable with the 1992 survey, we use only that part of the data corresponding to these two bands. From the 1993–1995 surveys, we use only Blocks 4 and 5 when making comparisons with the 1992 survey. (See Figures 2.1 and 2.2).

Tables 2.1 and 2.2 on page 6 give the survey effort and number of sightings for each survey. In Table 2.1, the 1990/91 results are based on all the 1990/91 survey data, whereas those of 1991 are based on the data from Replicates 4–8 only, omitting data collected in the off-shelf zone and in wind speeds over 10 knots. Thus the last four columns of Table 2.1 are comparable. In Table 2.2, all five columns are comparable. Table 2.1 and 2.2 show that 1992 and 1993 had the highest sighting rates. In 1994 and 1995 the sighting rates dropped to 1991 levels. In the eastern Bight, the 1995 sighting rate was slightly below the rates for the previous four years of the survey.

It should be noted that we list the number of independent sightings in the tables. There may be multiple patches in a single sighting, but the basic unit for the statistical analysis is a sighting rather than a patch. In the rest of this report, we shall also use the term school to mean sighting. There was some confusion in a similar table in Chen and Polacheck (1993), in which the term school was used to mean patch in the 1990/91 and 1992 surveys, but sighting in the 1993 survey.

	1990/91	1991	1993	1994	1995
Total flying time	390	223	213	405	438
Total time in effort	141	35	112	215	206
Total miles searched in effort	17,560	8,016	10,363	20,463	20,698
No. of SBT sightings	162	114	273	294	295
No. of SBT sightings per 100 miles	0.92	1.42	2.63	1.44	1.43

Table 2.1: Search effort and sighting rates for the entire Bight (1990/91 and 1993–1995). The terms sighting and sighting rate refer to the primary observation of a group of one or more patches.

	1991	1992	1993	1994	1995
Total flying time	NA	87	NA	NA	NA
Total time in effort	70	35	52	93	92
Total miles searched in effort	4,399	4,292	4,665	8,968	9,137
No. of SBT sightings	85	110	135	153	147
No. of SBT sightings per 100 miles	1.93	2.56	2.89	1.71	1.61

Table 2.2: Search effort and sighting rates for the eastern Bight (1991–1995). Note that the data has been restricted to Bands 1 and 2 in the 1991 and 1992 surveys, and Blocks 4 and 5 in the 1993–1995 surveys.

3 Statistical methodology

The main objective of the statistical analysis of the aerial survey data is to estimate two measures of the surface abundance of SBT:

1. D_0, the number of SBT schools per unit area,
2. D_1, the biomass per unit area.

Of the two measures, D_1 is the more relevant for monitoring SBT recruitment because it contains information on both the number of sightings and the school size. Let N be the total number of SBT schools in the survey area of size A, and write μ_y for the average school size. Then,

$$D_0 = N/A \qquad \text{and} \qquad D_1 = \mu_y N/A.$$

The aerial survey uses line transect theory, which has been used for many decades to estimate the abundance of wildlife (see for example Seber 1982, Buckland et al 1993). To collect our data by line transect sampling, a plane traverses the survey area along randomly generated non-overlapping transect lines. The survey plane is equipped with a satellite based Global Positioning System (GPS) to allow accurate measurement of location (latitude and longitude). Three locations are recorded for each sighting: the position of the plane when a school is first detected, the position of the plane when it breaks from the transect to close on the school, and the location of the school. These data allow the perpendicular distance from the school to the transect line (needed for the application of line transect methods) to be calculated accurately. While circling a detected tuna school, two spotters give independent estimates of the size of the school (in tons) and average fish size (in kg). These size estimates are based on many years of commercial spotting experience, and calibration of the estimates with the subsequent catches by fishing boats. Chen and Polacheck (1993) give more detailed information on the school size and fish size estimates, and the calculation of sighting distances.

In clustered populations, large clusters may be more likely to be detected than small ones. In our SBT survey, the detection probability has been found to depend on the cluster size as well as the distance from the transect. Consequently, the mean cluster size, $\bar{y}$, is positively biased as an estimator of μ_y. Various approaches to estimating D_0 and D_1 for clustered populations have been proposed, see for example Buckland et al (1993 p13).

In our analysis of the aerial survey data, we take the approach described in Chen (1994b). Suppose that n SBT schools are independently detected, giving bivariate observations (x_1, y_1), (x_2, y_2), $\ldots$, (x_n, y_n), where x_i and y_i are the perpendicular distance from the school to the transect line, and the estimated school size of the ith detected school. Let $f(x, y)$ and $g(x, y)$ be the probability density function from which the sample is drawn, and the conditional probability of detecting a school given its perpendicular distance x from the transect line and school size y; g is commonly known as the detection function.

Under most conditions, g is a monotonically decreasing function of x and an increasing function of y. This means that schools are more likely to be detected if they are larger and/or closer to the transect line. We assume that all surface schools on the transect line are detected with probability one regardless of their size, i.e. that $g(0, y) = 1$ for all $y > 0$. However, even if this is not the case, provided $g(0, y)$ is relatively constant from year to year, we will still obtain a valid relative index of abundance.

Standard line transect theory (see for example Buckland et al 1993), shows that

$$D_0 = E(n)\, f_x(0)/2L \quad \text{and} \quad D_1 = E(n)\, \beta(0)/2L, \tag{3.1}$$

where n is the total number of sightings, L is the total length of the transect lines, f_x is the marginal probability density function of the sighting distance x, and $\beta(0) = \int_0^\infty y f(0, y) dy$. We can view $\beta(0)$ as an expected school size weighted by the conditional probability density at the transect given school size, so that $\beta(0) = E\{s f(0|s)\}$.

From the expressions in (3.1), estimates for D_0 and D_1 can be formed as:

$$\widehat{D}_0 = n\, \hat{f}_x(0)/2L \quad \text{and} \quad \widehat{D}_1 = n\, \hat{\beta}(0)/2L \tag{3.2}$$

where $\hat{f}_x(0)$ and $\hat{\beta}(0)$ are estimates of $f(0)$ and $\beta(0)$ respectively. Clearly, the estimation of $f(0)$ and $\beta(0)$ is critical in estimating D_0 and D_1.

Parametric estimates for $f(0)$ and $\beta(0)$ can be obtained by assuming a parametric form for the detection function $g(x, y)$. Parametric estimation essentially assumes that the sighting conditions remain constant throughout the survey period and region, at least within each survey day. However, in reality, the survey plane flies about 800 kilometres per survey day between the shore and the continental shelf edge, and usually travels through varying weather conditions in terms of wind speed, cloud cover, glare and so on. It is obvious that the sighting function $g(x, y)$ changes from time to time. Therefore non-parametric estimates, which are robust against changing $g(x, y)$, are more appropriate in our survey.

We use the non-parametric kernel method to estimate the probability density function $f(x, y)$, and hence $f_x(0)$ and $\beta(0)$. Interested readers can find details of the derivation of the estimators in Chen (1994a, 1994b).

A bias-corrected estimator of μ_y, $\widehat{SS}$, is given by

$$\widehat{SS} = \widehat{D}_1/\widehat{D}_0$$

where $\widehat{D}_1$ and $\widehat{D}_0$ are given in (3.2). In Table A.13 in Appendix A.2, we show the adjusted and unadjusted estimates of μ_y for 1993–1995.

Burnham et al (1980, p44ff) list four properties that an estimator should possess for robust estimation of $f_x(0)$. In order of importance they are model robustness, pooling robustness, a shape criterion and estimator efficiency. Kernel estimators are model robust since they are able to fit closely a wide variety of true $f(x, y)$ shapes. The next most important property is pooling robustness. Suppose that the data is comprised of a number, r, of subsets or classes, each of which may have different densities and detection functions; for example, strata, blocks, replicates, weather conditions, spotters, or school size. An estimation method is said to be pooling robust if the overall estimate of abundance is identical whether the data are analysed pooled, or a separate estimate calculated for each class and the results then properly combined. We test the pooling robustness of the kernel based estimators below.

The shape criterion of Burnham et al is that the detection function should have a "shoulder" near $x = 0$, ie satisfy the condition $\frac{\partial}{\partial x} g(x,y)\Big|_{x=0} = 0, \forall y$. We use the "reflection" method of correcting our kernel estimator for boundary effects (see for example Silverman 1985 p30), which results in $g(x,y)$ having the property that $\frac{\partial}{\partial x} g(x,y)\Big|_{x=0} = 0, 0 \leq y < \infty$, and the shape criterion is satisfied.

An estimator should also be efficient in the sense that it should have as small a sampling variance as possible. Chen (1994b) gives some empirical comparisons of various estimators which show that the kernel estimator is relatively efficient.

In order to investigate the pooling robustness of the kernel estimator in this application, the estimates $\widehat{D}_0$ and $\widehat{D}_1$ in equation (3.2) were calculated in two different ways. Let there be n_j sightings in the jth class, and let L_j be the length of the transect in the jth class, $j = 1, \ldots, r$. Using the first method, we estimate $\beta(0)$ and $f_x(0)$ separately for each class, obtaining $\hat{\beta}_j(0)$ and $\hat{f}_{xj}(0)$ for the jth class. The resulting abundance estimates, $\widehat{D}_{0j}$ and $\widehat{D}_{1j}$, are given by

$$\widehat{D}_{0j} = n_j \hat{f}_{xj}(0)/2L_j \quad \text{and} \quad \widehat{D}_{1j} = n_j \hat{\beta}_j(0)/2L_j.$$

In this report, we denote these estimates "replicate estimates" as we subset the data from each stratum (or the whole data set in 1991) into replicates.

With the second method, the data are pooled over the classes, and $\beta(0)$ and $f_x(0)$ are estimated using this pooled dataset. We estimate D_0 and D_1 for each class using

$$\widehat{D}_{0j} = n_j \hat{f}_x(0)/2L_j \quad \text{and} \quad \widehat{D}_{1j} = n_j \hat{\beta}(0)/2L_j$$

for the jth class. We call these estimates "pooled estimates".

In both cases, the total abundance estimates are obtained as a weighted average of the $\widehat{D}_{0j}$ and $\widehat{D}_{1j}$'s. If the classes are strata, then the weights are the (unequal) stratum weights, whereas if the classes are blocks or replicates, the weights are equal.

The pooled and replicate abundance estimates for the entire Bight for 1991 and 1993–1995 are given in Tables A.1 to A.7 on pages 24 to 30, and for the eastern Bight for 1991–1995 in Tables A.8 to A.12 on pages 31 to 33. It should be noted that due to low numbers of observations (or no observations), it may be impossible to calculate a replicate estimate for a given stratum and replicate. When the pooled and replicate estimates for each replicate are compared in any year, it can be seen that the two estimation methods give similar values for both $\widehat{D}_1$ and $\widehat{D}_0$: the estimates are within two standard errors of each other. Therefore our kernel methodology does satisfy Burnham et al's pooling robustness criterion.

Henceforward in our discussions of results in this report, we use only the pooled estimates, as they have the smaller standard errors (this follows as the pooled estimates are based on many more observations than the replicate estimates).

4 Surface abundance estimates (1991–1995)

In this section, we present summaries of the estimates of SBT abundance. More detailed tables showing both pooled and replicate estimates at the stratum by replicate level can be found in Appendix A.1 on page 24. In Section 5, we compare the environmental conditions over the five years of the survey.

When examining the abundance estimates for a particular year, we should also consider the relative environmental conditions in that year because the abundance index from these aerial surveys is only informative after we allow for the environment conditions. When comparing the 1991–1995 survey results, we should bear in mind that different areas were covered in the 1991, 1992, and 1993–1995 surveys (as previously described in Section 2) and so the results from the two earlier and three later surveys are not strictly comparable. However, these warnings should not stop us from analysing the data and presenting the short term results as long as we are aware of the limitations of these results.

4.1 Surface abundance estimates for the entire Bight (1991 and 1993–1995)

In Table 4.1 and Figure 4.1 on page 12, we summarise the results for the entire Bight. It can be seen that the biomass estimate, $\widehat{D}_1$, fluctuates considerably from year to year without exhibiting any apparent trend. The density of sightings, $\widehat{D}_0$, does not change as dramatically as the biomass abundance (from 1993 to 1994 both $\widehat{D}_1$ and $\widehat{D}_0$ had their maximum change — decreases of 52.7% and 40.3% respectively). The additional variability in $\widehat{D}_1$ is due to fluctuations in the mean school size estimates since $D_1 = \mu_y D_0$.

In Tables A.2 to A.4 on pages 25 to 27, we present the pooled abundance estimates for 1993–1995 by stratum and by replicate-by-stratum. The pooled school size estimates for each stratum are given in Table A.13. It can be seen that

1. In 1993 and 1994, the inshore and shelf-edge strata had higher biomass abundance than the middle stratum, as anticipated in the survey design. In 1995, however, the middle stratum had the highest biomass abundance: more than double that on the shelf-edge.

2. In 1993 and 1994, the inshore and middle strata had lower school densities than the shelf-edge stratum. In 1995, the school densities were similar in these three strata.

3. From inshore, middle to shelf-edge stratum, there is a decrease in the school size estimates: it appears that SBT tend to congregate in larger schools in shallow water than in deep water. In 1995, the school sizes in the inshore stratum were much lower (less than half) than those in 1993 and 1994.

4.2 Surface abundance estimates for the eastern Bight (1991–1995)

In Table 4.2 and Figure 4.2 on page 13, we summarise the results for the eastern Bight. It can be seen that the biomass estimate, $\widehat{D}_1$, increased from 1991 to 1992, stayed at the same level in 1993 and dropped below the 1991 level in 1994. In 1995 it increased, but has not yet returned to the 1991 level. The density of sightings, $\widehat{D}_0$, was considerably lower in 1993–1995 than in 1991 and 1992.

In Tables A.8 to A.12 on pages 31 to 33, we present the abundance estimates for 1991–1995 by replicate. We note here that there is considerable variability in the abundance estimates between replicates, and discuss possible explanations in Section 6.

	1991	1993	1994	1995
No. of SBT sightings	114	273	294	295
Transect length (miles)	8,016	10,363	20,463	20,698
Sighting rate per 100 miles	1.42	2.63	1.44	1.43
$\widehat{D}_1$	62.4 (15.5)	128.2 (22.6)	60.6 (9.3)	103.2 (16.1)
$\widehat{D}_0$	1.74 (0.42)	1.81 (0.28)	1.08 (0.16)	1.62 (0.22)
Mean school size ($\widehat{D}_1/\widehat{D}_0$)	35.9 (6.2)	70.9 (16.6)	56.3 (10.4)	63.9 (7.6)
Sample mean ($\bar{y}$)	48.5	119.9	94.6	110.7

Table 4.1: Summary of abundance estimates for the entire Bight (1991 and 1993–1995)

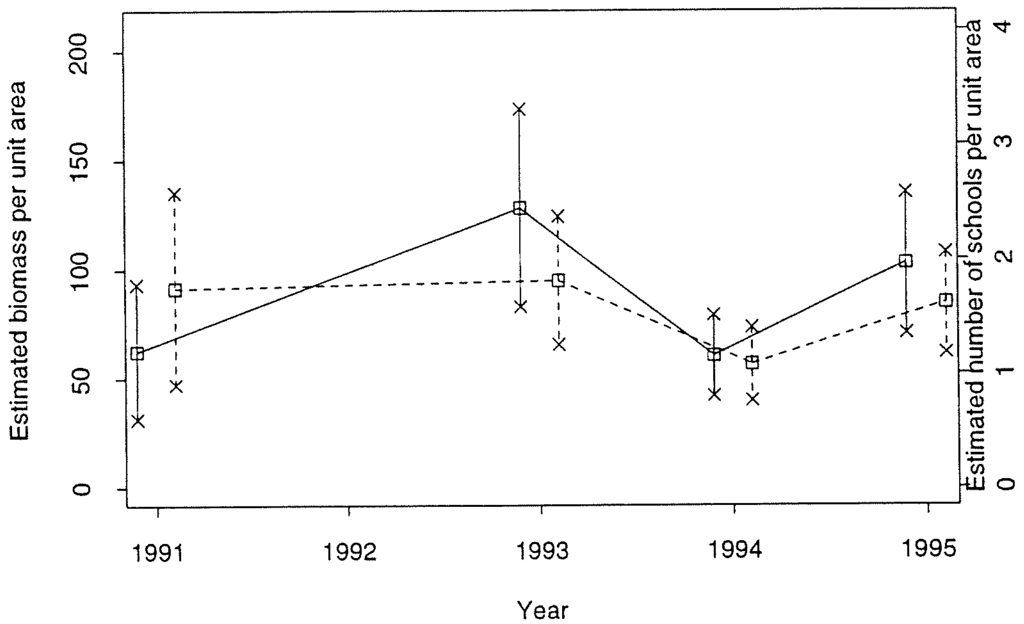


Figure 4.1: Abundance estimates for the entire Bight (1991, and 1993–1995). Estimate shown by □. Vertical bars show 2 standard errors above and below the estimate. Left scale shows estimated biomass per unit area, $\widehat{D}_1$. Right scale shows estimated number of schools per unit area, $\widehat{D}_0$. Plot on left is $\widehat{D}_1$, and on the right is $\widehat{D}_0$.

	1991	1992	1993	1994	1995
No. of SBT sightings	85	110	135	153	147
Transect length (miles)	4,399	4,292	4,665	8,968	9,137
Sighting rate per 100 miles	1.93	2.56	2.89	1.71	1.61
$\widehat{D}_1$	99.7 (28.1)	131.2 (35.8)	130.3 (34.0)	68.3 (13.2)	83.9 (20.7)
$\widehat{D}_0$	2.40 (0.66)	2.78 (0.54)	1.75 (0.35)	1.36 (0.26)	1.66 (0.32)
Mean school size ($\widehat{D}_1/\widehat{D}_0$)	41.5 (10.2)	47.2 (13.8)	74.5 (27.3)	50.2 (10.1)	50.6 (12.5)
Sample mean ($\bar{y}$)	57.2	91.3	119.9	97.6	92.0

Table 4.2: Summary of abundance estimates for the eastern Bight (1991–1995)

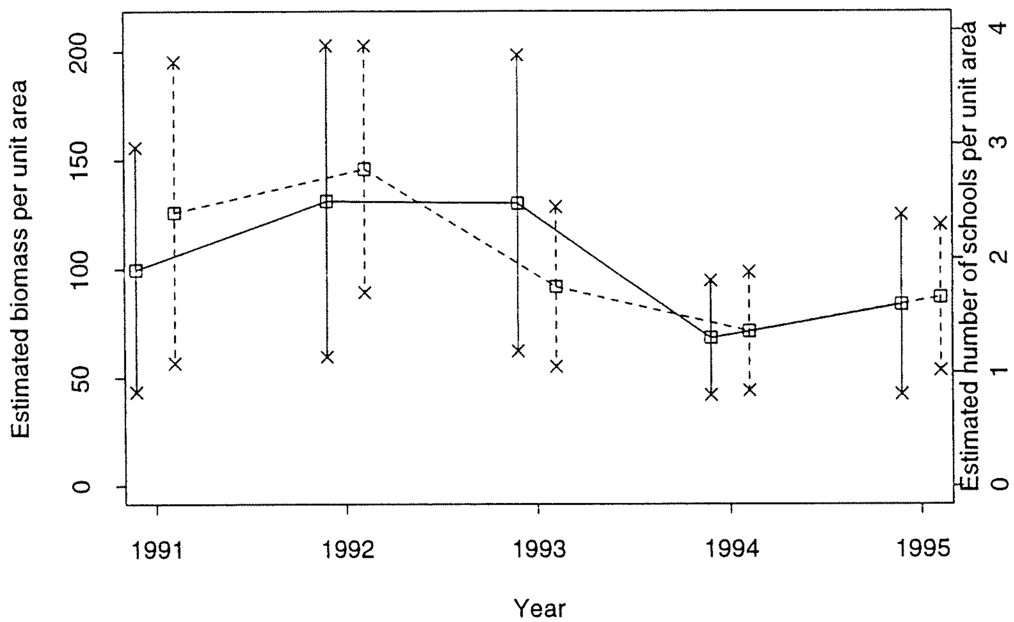


Figure 4.2: Abundance estimates for the eastern Bight (1991–1995). Estimate shown by □. Vertical bars show 2 standard errors above and below the estimate. Left scale shows estimated biomass per unit area, $\widehat{D}_1$. Right scale shows estimated number of schools per unit area, $\widehat{D}_0$. Plot on left is $\widehat{D}_1$, and on the right is $\widehat{D}_0$.

Age	0	1	2	3	4	5
Interval	[0, 0.7)	[0.7, 4.5)	[4.5, 12.2)	[12.2, 20.7)	[20.7, 30.5)	[30.5, 38.2)

Table 4.3: SBT fish weight intervals for each age class

4.3 Surface abundance estimates by fish age class

In the aerial survey, both the pilot and the spotter estimate the average fish size (in kg) of each detected patch of SBT. These estimates enable us to calculate the abundance of SBT in each age class using the SBT weight and age correspondence. In Table 4.3, we show the weight intervals associated with each age class, as used in the calculations. Based on the pilot and spotter's estimates of average fish size, we assign an age class to each sighting. We then calculate pooled abundance estimates $\widehat{D}_0$ and $\widehat{D}_1$ for that age class.

The results for the entire Bight are shown in Table 4.4, and for the eastern Bight in Table 4.5. It is clear that nearly all of the tuna spotted by the aerial survey are between 1 and 4 years old. The 3-year-old class is the most abundant, followed by the 2-year-old, then the 4-year-old classes. The one-year-old class was seen relatively frequently in 1991 compared with later years.

Estimated biomasses for the fish born in 1988–1993 can be extracted from these tables and compared at Age 1, . . ., Age 5 (although there is not yet a long enough time series of data for there to be a complete series for any age cohort). Using the fish weight intervals, these biomasses can be converted to numbers of fish relative to some reference point. Figures 4.3 and 4.4 show the estimated numbers of SBT relative to the number of 3-year-olds in the given cohort. The figure for the eastern Bight is based on a more complete series for each cohort as it includes results from 1992. The plot for the entire Bight is based on more data in those years it was conducted, and the estimates therefore have lower standard errors. However, because of the missing 1992 results, the figure for the entire bight is very difficult to interpret.

Figure 4.4 suggests that:

1. There are more SBT in the 1989 year class than the 1988 year class.
2. The numbers in each year class decreased between 1989 and 1991, increased slightly in 1992 then decreased again in 1993.

	Age	0	1	2	3	4	5
1991	n	0	11	40	59	4	0
	$\widehat{D}_1$	0.0	6.0 (1.5)	21.9 (5.4)	32.3 (8.0)	2.2 (0.5)	0.0
	$\widehat{D}_0$	0.00	0.17 (0.04)	0.61 (0.15)	0.90 (0.22)	0.06 (0.01)	0.00
1993	n	0	1	29	172	71	0
	$\widehat{D}_1$	0.0	0.8 (0.2)	19.5 (4.7)	85.6 (15.9)	22.4 (4.3)	0.0
	$\widehat{D}_0$	0.00	0.01 (0.01)	0.24 (0.05)	1.13 (0.17)	0.43 (0.08)	0.00
1994	n	0	9	64	169	49	3
	$\widehat{D}_1$	0.0	1.4 (0.2)	16.1 (3.5)	35.2 (5.4)	7.4 (1.4)	0.4
	$\widehat{D}_0$	0.00	0.04 (0.01)	0.16 (0.04)	0.65 (0.16)	0.21 (0.08)	0.01
1995	n	0	3	82	181	28	0
	$\widehat{D}_1$	0.0	1.0 (0.2)	30.4 (5.0)	62.8 (9.6)	9.0 (1.5)	0.0
	$\widehat{D}_0$	0.00	0.01 (0.00)	0.44 (0.06)	1.00 (0.14)	0.17 (0.03)	0.00

Table 4.4: Abundance estimates by fish age class for the entire Bight. The fish size estimates were agreed between the pilot and spotter, D. Hayman and K. White, in 1991, given by the pilot, D. Hayman, in 1993, and by the pilots, D. Hayman and K. Warren in 1994 and 1995.

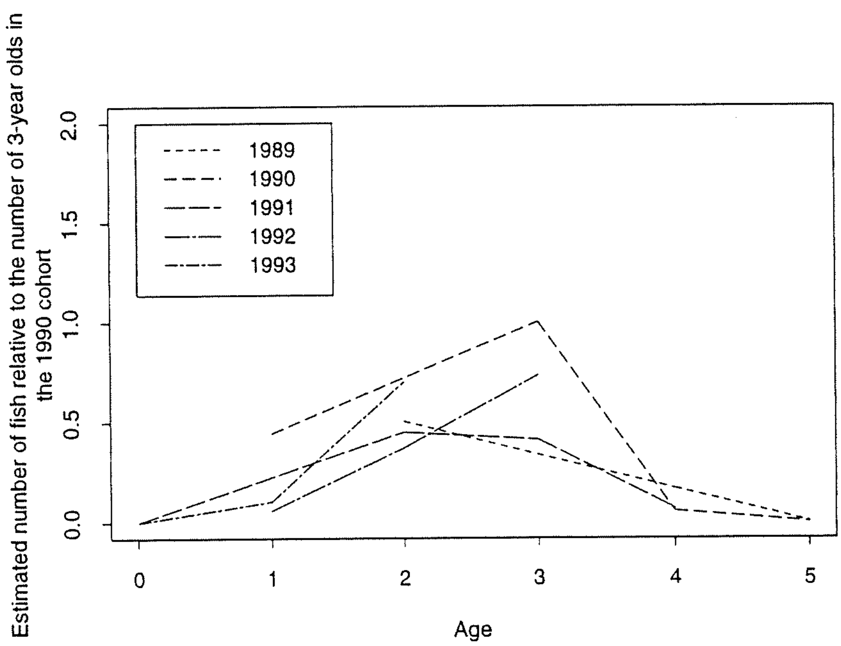


Figure 4.3: Estimated relative numbers of SBT for age cohorts born in indicated year for the entire Bight

	Age	0	1	2	3	4	5
1991	n	0	8	28	46	3	0
	$\widehat{D}_1$	0.0	9.4 (2.7)	32.9 (9.3)	54.0 (15.2)	3.5 (1.00)	0.0
	$\widehat{D}_0$	0.00	0.22 (0.06)	0.76 (0.21)	1.25 (0.34)	0.08 (0.02)	0.00
1992	n	0	0	12	88	9	0
	$\widehat{D}_1$	0.0	0.0	14.6 (3.7)	106.9 (27.1)	10.9 (2.8)	0.0
	$\widehat{D}_0$	0.00	0.00	0.33 (0.07)	2.40 (0.52)	0.25 (0.05)	0.00
1993	n	0	1	19	93	22	0
	$\widehat{D}_1$	0.0	1.4 (0.6)	24.4 (8.2)	90.5 (24.2)	14.1 (3.7)	0.0
	$\widehat{D}_0$	0.00	0.01 (0.01)	0.25 (0.06)	1.20 (0.23)	0.37 (0.10)	0.00
1994	n	0	2	37	91	23	0
	$\widehat{D}_1$	0.0	0.7 (0.2)	21.0 (5.6)	38.5 (7.2)	8.2 (2.0)	0.0
	$\widehat{D}_0$	0.00	0.03 (0.01)	0.18 (0.04)	0.88 (0.17)	0.32 (0.08)	0.00
1995	n	0	3	29	102	12	0
	$\widehat{D}_1$	0.0	2.0 (0.5)	17.0 (3.9)	57.6 (14.4)	7.3 (2.3)	0.0
	$\widehat{D}_0$	0.00	0.03 (0.01)	0.29 (0.05)	1.16 (0.23)	0.18 (0.04)	0.00

Table 4.5: Abundance estimates by fish age class for the eastern Bight. The fish size estimates were agreed between the pilot and spotter, D. Hayman and K. White, in 1991, given by the pilot, D. Hayman, in 1992 and 1993, and by the pilots, D. Hayman and K. Warren in 1994 and 1995.

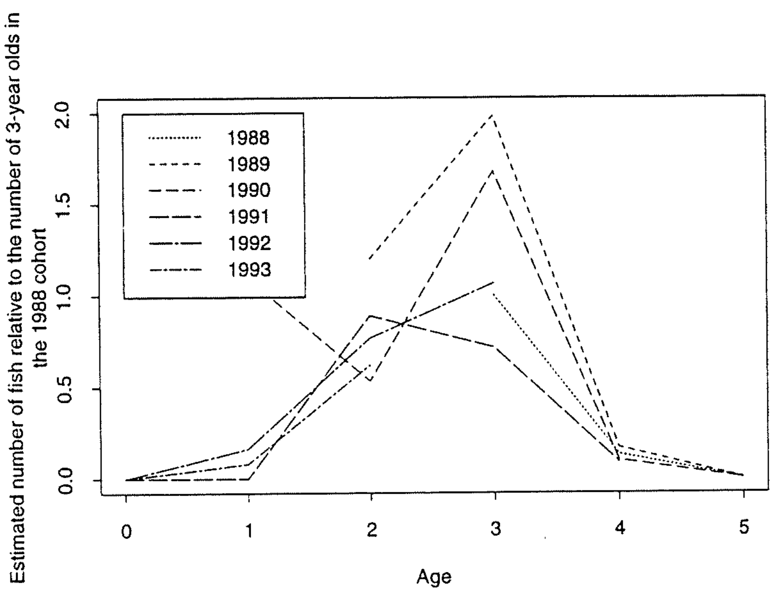


Figure 4.4: Estimated relative numbers of SBT for age cohorts born in indicated year for the eastern Bight

5 Comparison of environmental conditions during the survey (1991–1995)

Summaries of the abundance estimates for the entire Bight and the eastern Bight have been given in Tables 4.1 and 4.2. However, as previously mentioned, these estimates are based on data collected under varying environmental conditions. It is therefore very important to evaluate the effect of changes in environmental conditions on the estimates. This is particularly critical when comparing the estimates over the five years of the survey.

In Figures 5.1 and 5.2 on page 19, we show boxplots summarizing the percentage of the total search effort (measured in terms of percentage of total distance flown) spent in various wind speed conditions, cloud covers, air temperatures outside the plane and sea water temperatures at the surface. Wind-speed and cloud-cover are thought to influence the overall sighting conditions, and all four variables, but particularly sea surface temperature, are generally believed to affect surfacing behaviour.

The plots of sea surface temperature may not be strictly comparable from year to year, as different thermometers were used in 1991–1992, 1993, and 1994–1995, and ground truthing procedures varied from year to year.

Examination of the plots in Figures 5.1 for the entire Bight shows that:

1. In 1991, the survey spent more time in higher wind speeds than in the later years of the survey, as would be expected from the more relaxed wind restriction on survey operation. There do not appear to be marked differences in the wind conditions between the 1993 to 1995 surveys.

2. Between 1993 and 1995 the cloud cover increased and lower air and sea surface temperatures were observed each year.

Figure 5.2 for the eastern Bight also shows worsening weather conditions between 1993 and 1995: increasing windspeeds, increasing cloud cover and decreasing sea surface temperatures.

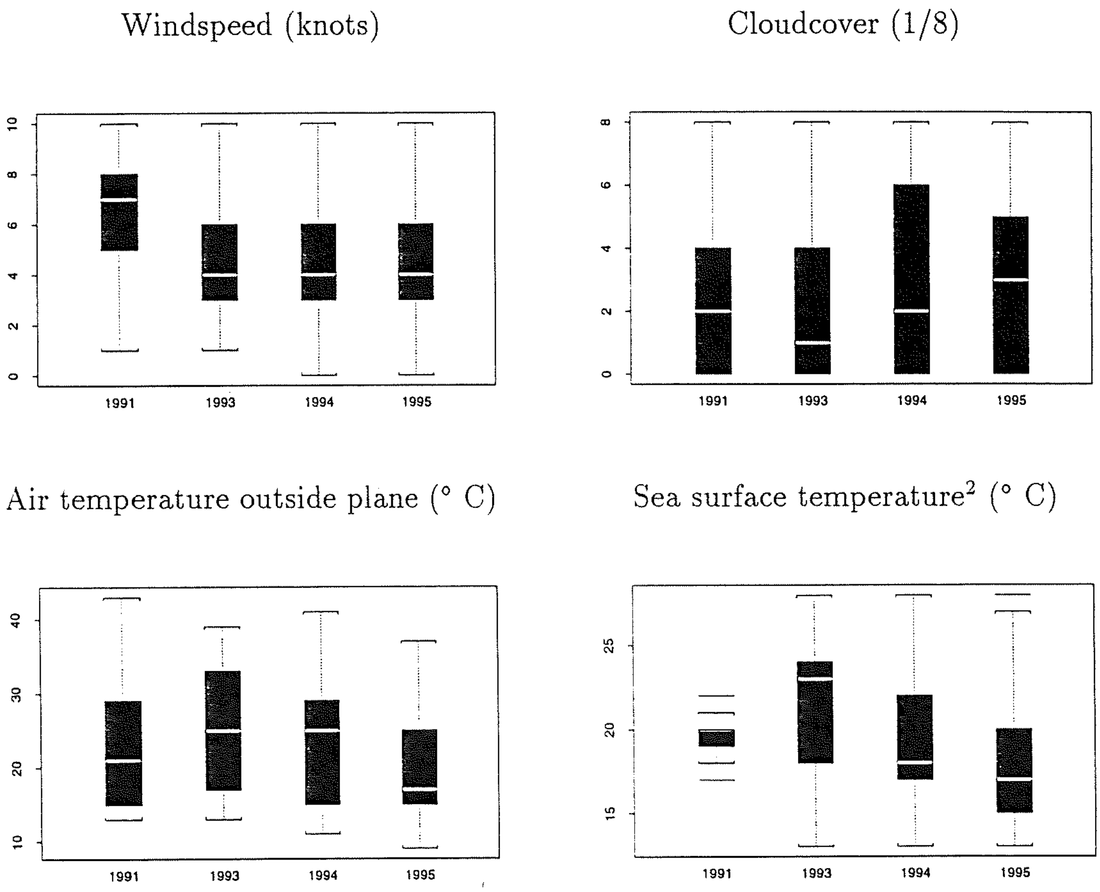
In Appendix A.3, we present figures giving more detailed plots of the percentage of the total search effort spent under these environmental conditions in the various years of the survey. Figures A.1 to A.4 compare the percentages of these factors in 1991 and 1993–1995 for the entire Bight, and in Figures A.5 to A.7, we give similar plots for the eastern Bight in 1991–1995.

In the 1993–1995 plots for the entire Bight (Figures A.1 to A.4), we also show the percentage of the sightings made under the various environmental conditions. Comparison of the percentage of survey effort and percentage of sightings allows identification of the environmental conditions which tend to be associated with high/low numbers of sightings per unit of survey effort:

1. The number of sightings per unit of survey effort is very low in windspeeds over 6 knots.

2. The number of sightings per unit of survey effort is higher when there is no low cloud and lower when there are 5 or more octals of low cloud.
3. The number of sightings per unit of effort is higher in warmer water temperatures than in lower temperatures. However, note that in 1995, when the water temperatures were lower than in other years, the number of sightings per unit of survey effort was lower in warm than in cold temperatures, indicating that there are factors other than temperature which make a habitat suitable for tuna.
4. The number of sightings per unit of effort is higher in warm air temperatures than in low temperatures.

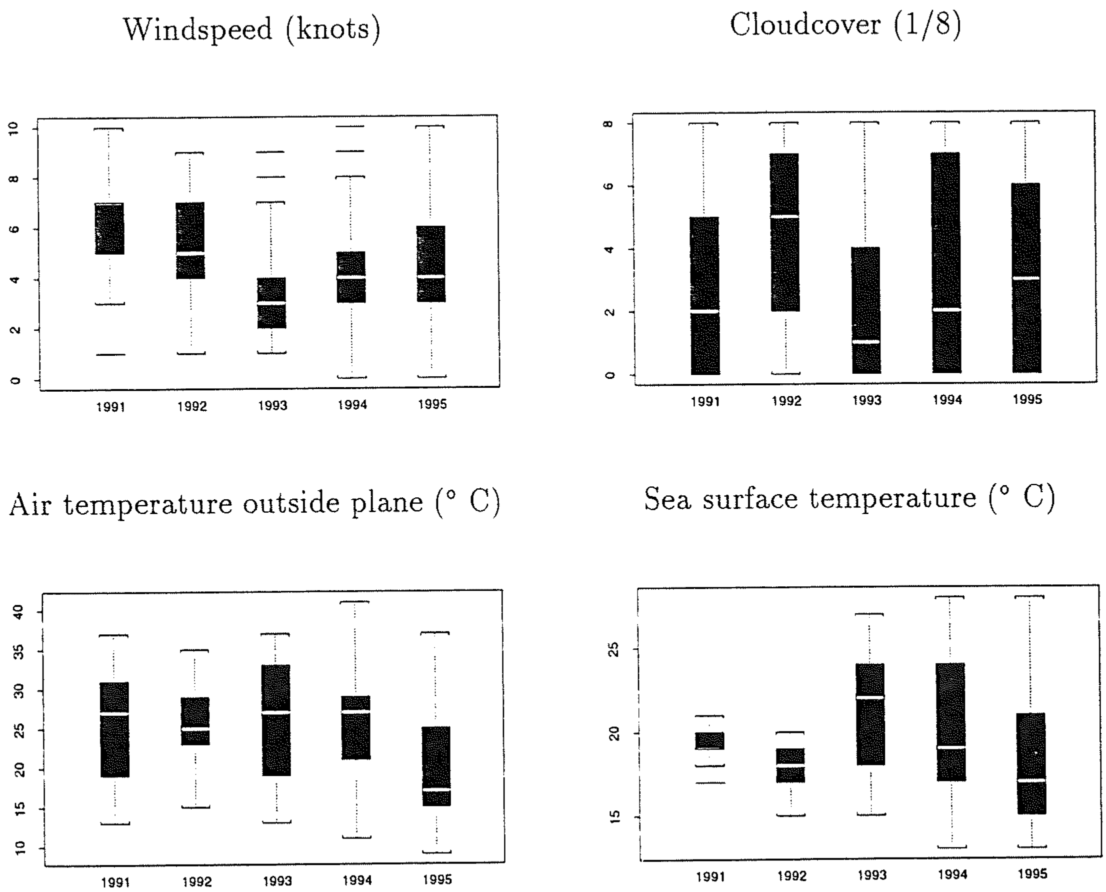
Figure 5.1: Boxplots[1] summarising environmental conditions during the survey for the entire Bight (1991, and 1993–1995)



[1]A boxplot shows a simplified summary of a distribution. The box contains the middle half of the data (one quarter of the data is above the box and one quarter below); the white horizontal line in the box shows the median (half the data is above the median and half below); the whiskers extending from the box extend to the most extreme non-outlier; outlying points are plotted individually.

[2]The plots of sea surface temperature may not be strictly comparable from year to year, as different thermometers were used in 1991–1992, 1993, and 1994–1995, and ground truthing procedures varied from year to year.

Figure 5.2: Boxplots summarising environmental conditions during the survey for the eastern Bight (1991–1995)



6 Discussion

Generally speaking, year to year variability in SBT surface abundance estimates is due to one or more of the following three factors:

1. Differences in the environmental conditions experienced during the surveys.

2. Differences in the survey areas and trackline designs.

3. Differences in real abundance.

We want to filter out factors 1 and 2 and obtain any difference in real abundance.

We believe that the effect of factor 2 is minimal after the reconfigurations of the data sets described in Section 2.4. Thus the environmental conditions are the most important factors influencing the abundance estimates.

Figures A.1 to A.4 indicate that environmental factors affect the number of sightings per unit of survey effort, for example, fewer sightings were made when it was windy, cloudy and cold. The environmental conditions are likely to influence both the detection function and the surfacing behaviour. However, the pooling robustness quality of the kernel abundance estimates means that the effects on the detection function are self-correcting.

In Figures A.15 to A.22 we examine possible relationships between the environmental conditions and both the perpendicular distance and the pilot's estimate of school size in 1991 and 1993–1995. Figures A.17 and A.21 show that there is a consistent and statistically significant tendency for both size and distance to increase with increasing air temperatures. This is perhaps due to schooling behavour — if larger schools form in warmer air temperatures, the sighting distances will tend to increase because of the tendency for larger schools to be detectable at greater distances than small schools. We also note it is not clear how the air temperature outside the plane (at 1500 feet) is related to school size. There may be a link with haze, or temperature just above the sea surface. However, in the latter case, we might expect distance and school size to be related to surface sea temperature, but this was not consistently found to be the case.

The influence of the environmental conditions on surfacing behaviour has not yet been addressed in the aerial survey analysis. In 1993, the surface abundance estimates were the highest in the survey. The weather conditions were also the best. It is possible that the absolute abundance of tuna has been constant from year to year, but a higher proportion of schools appeared at the surface in 1993 because of the better weather conditions. We plan to study tuna surfacing behaviour in different environmental conditions using the archival tag data together with the aerial survey data later this year.

We remarked earlier that that the variability in the estimates of $\widehat{D}_1$ is higher than that in the estimates of $\widehat{D}_0$. Since $D_1 = \mu_y D_0$, the proportionally higher variability in $\widehat{D}_1$ appears to be largely driven by changes in the mean school size estimates. To reduce sampling error in the school size (and fish size) estimates, more objective measures of these sizes, such as those obtained by LIDAR, are likely to prove useful.

It is important that each replicate should be surveyed as synoptically as possible to guard against double counting of schools as they move eastward through the Bight. One reason for using two planes in 1994 and 1995 is to allow a replicate to be completed in a single weather window.

It has been previously noted that there is considerable variation in the surface abundance estimates between replicates in any survey year. Possible reasons for this include non-synopticity of the data, and variations in the weather conditions experienced during different replicates.

To investigate the extent to which variability in weather conditions is a possible explanation of the variation between replicates, figures summarising the 1991 and 1993 weather conditions for each replicate are given in Appendix A.4. Appendix A.4.1 shows that in 1991, the few sightings made in Replicates 5 and 8 occurred in windy conditions with frequent low cloud and low temperatures. Correspondingly, the reason behind the many sightings made in Replicates 4, 6 and 7 may be the relatively less cloudy, calmer and warmer conditions experienced. Appendix A.4.2 shows that in 1993, Replicate 4 experienced colder, more cloudy conditions, which may explain in part the lower abundance in this replicate.

Acknowledgements

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A.1 Tables of surface abundance estimates

A.1.1 Entire Bight

In this section, we present detailed tables showing the pooled and replicate estimates of surface abundance for the entire Bight in 1991 and 1993–1995.

			Pooled estimates		Replicate estimates	
Replicate	n_i	L_i	$\widehat{D}_1$	$\widehat{D}_0$	$\widehat{D}_1$	$\widehat{D}_0$
4	44	1,549	124.7 (30.9)	3.48 (0.84)	158.7 (66.3)	2.66 (1.07)
5	1	1,518	2.9 (0.7)	0.08 (0.02)	NA	NA
6	28	1,918	64.1 (15.9)	1.79 (0.43)	13.1 (6.7)	1.00 (0.51)
7	40	1,696	103.5 (25.6)	2.89 (0.70)	106.2 (33.6)	3.85 (1.16)
8	1	1,335	3.3 (0.8)	0.09 (0.02)	NA	NA
Total	114	8,016	62.4 (15.5)	1.74 (0.42)	NA	NA

Table A.1: Pooled and replicate estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1991. The estimated standard error of each estimate is given in parentheses. The school size estimates were agreed between the pilot and spotter, D. Hayman and K. White. Lengths are in nautical miles.

Stratum		Replicate 1	2	3	4	Total
I	n_i	15	21	4	0	40
	L_i	734	670	660	546	2,609
	$\widehat{D}_1$	169.4 (68.9)	259.7 (105.6)	50.2 (20.4)	0.0 (0.0)	127.0 (51.7)
	$\widehat{D}_0$	1.24 (0.44)	1.90 (0.68)	0.37 (0.13)	0.0 (0.0)	0.93 (0.33)
M	n_i	38	12	21	4	75
	L_i	1,109	990	1,099	1,029	4,227
	$\widehat{D}_1$	202.1 (61.3)	71.5 (21.7)	112.7 (34.2)	22.9 (7.0)	104.7 (31.7)
	$\widehat{D}_0$	2.56 (0.68)	0.90 (0.24)	1.43 (0.38)	0.29 (0.08)	1.32 (0.35)
S	n_i	63	26	32	25	146
	L_i	893	835	860	747	3,335
	$\widehat{D}_1$	291.3 (64.1)	128.5 (28.3)	153.6 (33.8)	138.1 (30.4)	180.7 (39.7)
	$\widehat{D}_0$	5.86 (1.26)	2.59 (0.56)	3.09 (0.67)	2.78 (0.60)	3.64 (0.78)
H	n_i	3	5	2	2	12
	L_i	48	48	48	47	191
	$\widehat{D}_1$	537.7 (235.2)	896.2 (392.0)	358.5 (156.8)	366.1 (160.1)	540.5 (236.4)
	$\widehat{D}_0$	8.81 (3.87)	14.69 (6.45)	5.88 (2.58)	6.00 (2.64)	8.86 (3.89)
T	n_i	119	63	59	31	273
	L_i	2,784	2,543	2,667	2,369	10,363
	$\widehat{D}_1$	217.4 (40.1)	125.0 (25.3)	110.6 (21.2)	46.2 (8.1)	128.2 (22.6)
	$\widehat{D}_0$	3.08 (0.49)	1.54 (0.23)	1.62 (0.27)	0.83 (0.15)	1.81 (0.28)

Table A.2: Pooled estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1993. The estimated standard error of each estimate is given in parentheses. The school size estimates were given by the pilot, D. Hayman. Lengths are in nautical miles.

Stratum		Replicate								Total
		1	2	3	4	5	6	7	8	
I	n_i	13	5	21	18	13	12	8	7	97
	L_i	555	678	693	665	700	706	759	793	5,549
	$\widehat{D}_1$	188.9	59.5	244.5	218.4	149.8	137.1	85.0	71.2	141.0
	$\hat{\sigma}_1$	50.9	16.0	65.8	58.8	40.3	36.9	22.9	19.2	38.0
	$\widehat{D}_0$	1.09	0.34	1.41	1.26	0.86	0.79	0.49	0.41	0.81
	$\hat{\sigma}_0$	0.31	0.10	0.40	0.36	0.25	0.23	0.14	0.12	0.23
M	n_i	2	4	8	13	15	19	12	11	84
	L_i	941	1,089	1,060	1,041	931	987	1,083	1,082	8,216
	$\widehat{D}_1$	5.3	9.2	18.8	31.2	40.2	48.1	27.7	25.4	25.5
	$\hat{\sigma}_1$	1.5	2.5	5.2	8.5	11.0	13.2	7.6	6.9	7.0
	$\widehat{D}_0$	0.13	0.23	0.47	0.78	1.01	1.21	0.69	0.64	0.64
	$\hat{\sigma}_0$	0.04	0.06	0.13	0.21	0.27	0.32	0.18	0.17	0.17
S	n_i	3	12	24	1	9	3	38	14	104
	L_i	785	863	770	930	696	683	967	843	6,538
	$\widehat{D}_1$	15.5	56.5	126.7	4.4	52.6	17.9	159.8	67.5	64.7
	$\hat{\sigma}_1$	3.4	12.5	28.0	1.0	11.6	3.9	35.3	14.9	14.3
	$\widehat{D}_0$	0.48	1.76	3.95	0.14	1.64	0.56	4.99	2.11	2.02
	$\hat{\sigma}_0$	0.11	0.38	0.86	0.03	0.36	0.12	1.09	0.46	0.44
H	n_i	2	4	0	0	0	0	1	2	9
	L_i	24	24	24	0	24	16	24	24	160
	$\widehat{D}_1$	1331	2662	0	0	0	0	666	1331	899
	$\hat{\sigma}_1$	776	1551	0	0	0	0	388	776	523
	$\widehat{D}_0$	36.4	72.8	0	0	0	0	18.2	36.4	24.6
	$\hat{\sigma}_1$	24.1	48.2	0	0	0	0	12.0	24.1	16.3
T	n_i	20	25	53	32	37	34	59	34	294
	L_i	2,306	2,654	2,547	2,636	2,351	2,392	2,833	2,741	20,463
	$\widehat{D}_1$	48.7	39.1	88.8	62.2	64.8	58.7	71.9	48.7	60.6
	$\hat{\sigma}_1$	10.5	6.9	14.9	12.7	10.5	10.5	10.4	7.0	9.3
	$\widehat{D}_0$	0.53	0.85	1.47	0.73	1.12	0.97	1.71	1.05	1.08
	$\hat{\sigma}_0$	0.11	0.19	0.23	0.14	0.18	0.19	0.28	0.16	0.16

Table A.3: Pooled estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1994. The school size estimates were given by the pilots, D. Hayman and K. Warren. Lengths are in nautical miles.

Stratum		Replicate 1	2	3	4	5	6	7	8	Total
I	n_i	13	15	15	5	17	12	9	1	87
	L_i	871	729	662	763	769	701	822	818	6,135
	$\widehat{D}_1$	114.0	157.2	173.1	50.0	168.8	130.8	83.6	9.3	108.3
	$\hat{\sigma}_1$	29.1	40.1	44.2	12.8	43.1	33.4	21.3	2.4	27.7
	$\widehat{D}_0$	1.48	2.04	2.24	0.65	2.19	1.70	1.08	0.12	1.40
	$\hat{\sigma}_0$	0.34	0.47	0.52	0.15	0.51	0.39	0.25	0.03	0.32
M	n_i	13	17	18	18	22	17	20	4	129
	L_i	1,012	995	934	962	901	876	995	961	7,636
	$\widehat{D}_1$	89.9	119.6	134.8	130.9	171.0	135.9	140.8	29.2	118.3
	$\hat{\sigma}_1$	19.6	26.1	29.5	28.6	37.4	29.7	30.8	6.4	25.8
	$\widehat{D}_0$	1.21	1.62	1.82	1.77	2.31	1.84	1.90	0.39	1.60
	$\hat{\sigma}_0$	0.25	0.33	0.38	0.37	0.48	0.38	0.39	0.08	0.33
S	n_i	1	10	3	11	7	13	12	4	61
	L_i	843	923	709	904	764	809	878	810	6,641
	$\widehat{D}_1$	5.2	47.4	18.5	53.3	40.1	70.3	59.8	21.6	40.2
	$\hat{\sigma}_1$	1.6	14.9	5.8	16.7	12.6	22.0	18.7	6.8	12.6
	$\widehat{D}_0$	0.20	1.82	0.71	2.04	1.53	2.69	2.29	0.83	1.54
	$\hat{\sigma}_0$	0.06	0.52	0.20	0.58	0.44	0.77	0.65	0.24	0.44
H	n_i	3	3	3	3	3	3	0	0	18
	L_i	40	24	40	38	40	40	24	40	286
	$\widehat{D}_1$	1,918	3,196	1,918	2,018	1,918	1,918	0.0	0.0	1,909
	$\hat{\sigma}_1$	851	1,419	852	896	851	852	0.0	0.0	715
	$\widehat{D}_0$	26.77	44.63	26.78	28.18	26.77	26.78	0.00	0.00	22.47
	$\hat{\sigma}_0$	10.23	17.04	10.23	10.76	10.23	10.23	0.00	0.00	8.58
T	n_i	30	45	39	37	49	45	41	9	295
	L_i	2,766	2,671	2,345	2,668	2,474	2,426	2,719	2,628	20,698
	$\widehat{D}_1$	81.2	120.7	121.5	103.1	146.1	125.7	110.1	23.4	103.2
	$\hat{\sigma}_1$	12.9	17.8	19.1	17.1	23.2	19.0	18.4	4.0	16.1
	$\widehat{D}_0$	1.12	1.89	1.73	1.70	2.19	2.09	1.82	0.44	1.62
	$\hat{\sigma}_0$	0.16	0.25	0.24	0.25	0.31	0.29	0.27	0.07	0.22

Table A.4: Pooled estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1995. The school size estimates were given by the pilots, D. Hayman and K. Warren. Lengths are in nautical miles.

Stratum		Replicate 1	2	3	4	Total
I	n_i	15	21	4	0	40
	L_i	734	670	660	546	2,609
	$\widehat{D}_1$	270.1 (181.8)	201.4 (87.2)	6.7 (5.8)	0.0 (0.0)	
	$\widehat{D}_0$	1.33 (0.79)	1.48 (0.62)	0.50 (0.50)	0.0 (0.0)	
M	n_i	38	12	21	4	75
	L_i	1,109	990	1,099	1,029	4,227
	$\widehat{D}_1$	248.5 (109.9)	27.6 (19.1)	133.2 (58.7)	1.0 (0.9)	
	$\widehat{D}_0$	2.31 (0.84)	0.50 (0.35)	2.08 (0.90)	0.26 (0.30)	
S	n_i	63	26	32	25	146
	L_i	893	835	860	747	3,335
	$\widehat{D}_1$	136.1 (44.2)	127.6 (58.2)	267.5 (105.4)	143.2 (57.6)	
	$\widehat{D}_0$	3.58 (1.22)	2.80 (1.36)	3.45 (1.42)	4.73 (1.79)	
H	n_i	3	5	2	2	12
	L_i	48	48	48	47	191
	$\widehat{D}_1$	246.1 (268.9)	914.6 (644.4)	259.9 (238.9)	32.2 (39.0)	
	$\widehat{D}_0$	0.40 (0.31)	15.35 (12.58)	5.88 (5.29)	10.50 (112.98)	
T	n_i	119	63	59	31	273
	L_i	2,784	2,543	2,667	2,369	10,363
	$\widehat{D}_1$	226.7 (72.7)	88.4 (24.6)	139.6 (41.2)	33.9 (13.4)	122.2 (22.0)
	$\widehat{D}_0$	2.40 (0.57)	1.28 (0.39)	2.09 (0.61)	1.28 (0.45)	1.76 (0.26)

Table A.5: Replicate estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1993. The estimated standard error of each estimate is given in parentheses. The school size estimates were given by the pilot, D. Hayman. Lengths are in nautical miles.

Stratum		Replicate 1	2	3	4	5	6	7	8	Total
I	n_i	13	5	21	18	13	12	8	7	97
	L_i	555	678	693	665	700	706	759	793	5,549
	$\widehat{D}_1$	188.2	0.7	215.0	165.3	92.0	93.3	305.6	53.5	
	$\hat{\sigma}_1$	140.0	0.6	102.3	106.9	61.2	49.0	283.9	47.7	
	$\widehat{D}_0$	0.67	0.02	2.13	0.74	1.66	1.34	0.70	0.54	
	$\hat{\sigma}_0$	0.44	0.02	0.78	0.53	0.92	0.72	0.50	0.37	
M	n_i	2	4	8	13	15	19	12	11	84
	L_i	941	1,089	1,060	1,041	931	987	1,083	1,082	8,216
	$\widehat{D}_1$	NA	4.5	9.9	14.5	22.3	39.5	19.7	61.1	NA
	$\hat{\sigma}_1$		4.4	6.4	9.3	14.0	22.2	12.0	35.9	
	$\widehat{D}_0$	NA	0.11	0.30	0.89	0.25	1.38	1.36	0.75	NA
	$\hat{\sigma}_0$		0.10	0.22	0.57	0.15	0.76	0.74	0.36	
S	n_i	3	12	24	1	9	3	38	14	104
	L_i	785	863	770	930	696	683	967	843	6,538
	$\widehat{D}_1$	5.4	9.4	64.6	NA	38.9	12.1	255.9	50.4	NA
	$\hat{\sigma}_1$	6.4	5.9	43.2		41.6	9.9	74.5	24.2	
	$\widehat{D}_0$	0.48	1.10	0.69	NA	1.07	0.41	8.06	3.04	NA
	$\hat{\sigma}_0$	0.61	0.77	0.43		0.99	0.30	2.28	1.31	
H	n_i	2	4	0	0	0	0	1	2	9
	L_i	24	24	24	0	24	16	24	24	160
	$\widehat{D}_1$	NA	4,558	0	0	0	0	NA	NA	NA
	$\hat{\sigma}_1$		3,300	0	0	0	0			
	$\widehat{D}_0$	NA	231.9	0	0	0	0	NA	NA	NA
	$\hat{\sigma}_0$		169.7	0	0	0	0			
T	n_i	20	25	53	32	37	34	59	34	294
	L_i	2,305	2,654	2,547	2,636	2,351	2,392	2,833	2,741	20,463
	$\widehat{D}_1$	38.8	20.2	63.4	41.1	40.0	43.7	131.4	56.9	54.4
	$\hat{\sigma}_1$	27.9	11.5	23.0	21.9	17.4	16.1	59.6	23.1	10.1
	$\widehat{D}_0$	0.25	1.10	0.75	0.65	0.72	1.14	2.78	1.23	1.08
	$\hat{\sigma}_0$	0.17	0.60	0.22	0.34	0.31	0.46	0.68	0.37	0.15

Table A.6: Replicate estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1994. The school size estimates were given by the pilots, D. Hayman and K. Warren. Lengths are in nautical miles.

Stratum		Replicate 1	2	3	4	5	6	7	8	Total
I	n_i	13	15	15	5	17	12	9	1	87
	L_i	871	729	662	763	769	701	822	818	6,134
	$\widehat{D}_1$	37.3	58.8	33.5	102.0	285.8	159.0	135.1		
	$\hat{\sigma}_1$	23.8	36.2	20.4	103.1	165.6	116.7	104.2		
	$\widehat{D}_0$	1.23	1.77	0.57	1.84	2.79	1.20	1.02		
	$\hat{\sigma}_0$	0.71	0.94	0.45	1.87	1.41	0.67	0.66		
M	n_i	13	17	18	18	22	17	20	4	129
	L_i	1,012	995	934	962	901	876	995	960	7,636
	$\widehat{D}_1$	89.7	66.9	163.2	28.9	170.8	102.1	15.3	4.6	
	$\hat{\sigma}_1$	40.2	36.9	77.5	11.9	83.6	78.3	13.7	4.5	
	$\widehat{D}_0$	1.08	0.90	2.93	2.44	1.62	1.06	0.80	1.12	
	$\hat{\sigma}_0$	0.48	0.51	1.40	0.92	0.74	0.72	0.58	0.98	
S	n_i	1	10	3	11	7	13	12	4	61
	L_i	843	923	709	904	764	809	878	810	6,727
	$\widehat{D}_1$	NA	84.6	4.3	16.0	66.1	38.6	70.3	2.0	
	$\hat{\sigma}_1$	NA	79.4	3.0	9.4	60.5	15.6	52.8	2.4	
	$\widehat{D}_0$	NA	1.59	0.75	2.90	0.77	3.91	1.07	0.37	
	$\hat{\sigma}_0$	NA	1.52	0.61	1.70	0.63	1.61	0.59	0.51	
H	n_i	3	3	3	3	3	3	0	0	18
	L_i	40	24	40	38	40	40	24	40	286
	$\widehat{D}_1$	661	1,366	280	2,848	2,268	2,476	0.0	0.0	
	$\hat{\sigma}_1$	671	991	259	2,975	1,760	2,071	0.0	0.0	
	$\widehat{D}_0$	30.6	40.8	10.3	46.4	9.7	16.0	0.00	0.00	
	$\hat{\sigma}_0$	25.0	31.4	9.4	38.3	8.0	10.6	0.00	0.00	
T	n_i	30	45	39	37	49	45	41	9	295
	L_i	2,766	2,671	2,345	2,668	2,474	2,426	2,719	2,628	20,698
	$\widehat{D}_1$	60.4	73.8	100.9	49.9	176.5	106.7	51.9	3.1	77.9
	$\hat{\sigma}_1$	23.3	29.0	44.0	23.9	59.6	50.6	25.3	2.6	12.9
	$\widehat{D}_0$	0.96	1.37	1.98	2.57	1.68	1.80	0.90	0.72	1.50
	$\hat{\sigma}_0$	0.32	0.50	0.81	0.76	0.53	0.57	0.38	0.57	0.20

Table A.7: Replicate estimates of SBT surface abundance (per 1,000 square miles) for the entire Bight for 1995. The school size estimates were given by the pilots, D. Hayman and K. Warren. Lengths are in nautical miles.

A.1.2 Eastern Bight

In this section, we present both the pooled and replicate estimates of surface abundance for the eastern Bight in 1991 and 1993–1995.

			Pooled estimates		Replicate estimates	
Replicate	n_i	L_i	$\widehat{D}_1$	$\widehat{D}_0$	$\widehat{D}_1$	$\widehat{D}_0$
4	33	937	181.8 (51.3)	4.37 (1.20)	215.6 (111.2)	2.86 (1.41)
5	1	556	9.3 (2.6)	0.22 (0.06)	NA	NA
6	22	1,070	106.1 (29.9)	2.55 (0.70)	11.4 (9.0)	0.64 (0.48)
7	28	1,057	136.6 (38.6)	3.29 (0.90)	149.6 (53.0)	4.87 (1.63)
8	1	779	6.6 (1.9)	0.16 (0.04)	NA	NA
Total	85	4,399	99.7 (28.1)	2.40 (0.66)	NA	NA

Table A.8: Pooled and replicate estimates of SBT surface abundance (per 1,000 square miles) for the eastern Bight for 1991. The estimated standard error of each estimate is given in parentheses. The school size estimates were agreed between the pilots, D. Hayman and K. White. Lengths are in nautical miles.

			Pooled estimates		Replicate estimates	
Replicate	n_i	L_i	$\widehat{D}_1$	$\widehat{D}_0$	$\widehat{D}_1$	$\widehat{D}_0$
1	30	1,077	36.3 (15.9)	2.37 (0.94)	145.2 (36.8)	3.26 (0.70)
2	39	1,133	365.4 (159.2)	3.38 (1.27)	179.4 (45.5)	4.03 (0.87)
3	19	821	57.1 (32.2)	1.46 (0.77)	120.7 (30.6)	2.71 (0.58)
4	6	880	44.9 (31.0)	1.59 (0.99)	35.6 (9.0)	0.80 (0.17)
5	16	381	152.3 (55.9)	5.11 (1.82)	218.9 (55.5)	4.92 (1.06)
Total	110	4,292	131.2 (35.8)	2.78 (0.54)	128.1 (37.9)	2.98 (0.49)

Table A.9: Pooled and replicate estimates of SBT surface abundance (per 1,000 square miles) for the eastern Bight for 1992. The estimated standard error of each estimate is given in parentheses. The school size estimates were given by the pilot, D. Hayman. Lengths are in nautical miles.

			Pooled estimates		Replicate estimates	
Replicate	n_i	L_i	$\widehat{D}_1$	$\widehat{D}_0$	$\widehat{D}_1$	$\widehat{D}_0$
1	55	1,293	202.4 (54.5)	2.65 (0.54)	273.8 (114.0)	2.24 (0.70)
2	43	1,210	168.3 (47.6)	1.90 (0.37)	70.7 (22.6)	0.96 (0.43)
3	15	1,202	56.5 (16.2)	0.75 (0.16)	36.1 (30.2)	0.76 (0.43)
4	22	960	65.0 (16.6)	1.55 (0.40)	22.5 (10.2)	2.29 (0.94)
Total	135	4,665	130.3 (34.0)	1.75 (0.35)	100.8 (30.1)	1.56 (0.33)

Table A.10: Pooled and replicate estimates of SBT surface abundance (per 1,000 square miles) for the eastern Bight for 1993. The estimated standard error of each estimate is given in parentheses. The school size estimates were given by the pilot, D. Hayman. Lengths are in nautical miles.

			Pooled estimates		Replicate estimates	
Replicate	n_i	L_i	$\widehat{D}_1$	$\widehat{D}_0$	$\widehat{D}_1$	$\widehat{D}_0$
1	19	1,029	81.5 (19.2)	0.97 (0.18)	NA	NA
2	18	1,196	52.9 (10.1)	1.42 (0.32)	NA	NA
3	26	1,203	95.7 (21.4)	1.39 (0.26)	74.7 (33.8)	0.80 (0.26)
4	11	1,115	57.7 (14.9)	0.51 (0.13)	10.4 (8.9)	0.03 (0.02)
5	15	964	62.6 (15.4)	0.86 (0.27)	41.7 (34.0)	0.50 (0.35)
6	6	933	25.9 (6.4)	0.29 (0.08)	4.8 (2.9)	0.13 (0.11)
7	36	1,279	92.0 (17.7)	2.93 (0.65)	NA	NA
8	22	1,249	63.4 (11.4)	1.70 (0.35)	83.5 (41.5)	1.92 (0.72)
Total	153	8,968	68.3 (13.2)	1.36 (0.26)	NA	NA

Table A.11: Pooled and replicate estimates of SBT surface abundance (per 1,000 square miles) for the eastern Bight for 1994. The estimated standard error of each estimate is given in parentheses. The school size estimates were given by the pilots, D. Hayman and K. Warren. Lengths are in nautical miles.

			Pooled estimates		Replicate estimates	
Replicate	n_i	L_i	$\widehat{D}_1$	$\widehat{D}_0$	$\widehat{D}_1$	$\widehat{D}_0$
1	17	1,388	73.5 (19.7)	1.16 (0.26)	38.3 (18.2)	1.03 (0.35)
2	23	1,093	138.0 (35.7)	2.18 (0.48)	118.5 (47.4)	2.25 (0.83)
3	16	1,016	68.5 (14.3)	1.08 (0.20)	14.2 (18.6)	0.28 (0.18)
4	21	1,132	84.6 (24.1)	2.26 (0.55)	37.2 (19.1)	1.45 (0.84)
5	16	1,096	54.7 (13.2)	0.86 (0.19)	83.1 (51.8)	1.10 (0.63)
6	35	1,154	178.2 (52.4)	3.66 (0.80)	172.0 (86.3)	3.03 (1.22)
7	16	1,197	59.7 (13.7)	1.43 (0.29)	53.5 (38.1)	0.54 (0.30)
8	3	1,061	14.4 (4.2)	0.38 (0.09)	NA	NA
Total	147	9,137	83.9 (20.7)	1.66 (0.32)	64.6 (15.1)	1.21 (0.23)

Table A.12: Pooled and replicate estimates of SBT surface abundance (per 1,000 square miles) for the eastern Bight for 1995. The estimated standard error of each estimate is given in parentheses. The school size estimates were given by the pilots, D. Hayman and K. Warren. Lengths are in nautical miles.

A.2 School size estimates for 1993–1995

		Inshore	Middle	Shelf	Hot	Overall
1991	$\widehat{SS}$					35.9 (6.2)
	$\bar{y}$					48.5
1993	$\widehat{SS}$	141.6 (49.4)	77.2 (23.5)	50.9 (6.9)	NA	70.9 (16.6)
	$\bar{y}$	187.4	116.3	71.3	90.2	119.9
1994	$\widehat{SS}$	167.1 (46.4)	41.6 (8.2)	33.4 (4.8)	NA	56.3 (10.4)
	$\bar{y}$	147.7	78.3	59.8	78.4	94.6
1995	$\widehat{SS}$	78.5 (16.7)	82.0 (11.6)	25.5 (7.8)	70.4 (29.5)	63.9 (7.6)
	$\bar{y}$	123.5	131.1	50.1	107.3	110.7

Table A.13: Mean school size (μ_y) estimates for 1991 and 1993–1995 surveys using all 1991 data, and pooled data within each stratum in 1993–1995. The estimate adjusted for size bias is $\widehat{SS}$, and the unadjusted estimate is $\bar{y}$.

A.3 Figures showing environmental conditions during the survey by year

A.3.1 Entire Bight

Figures A.1 to A.4 show the percentage of the survey effort and the percentage of the sightings made in different environmental conditions in the entire Bight in 1991 and 1993–1995. Comparison of these percentages allows identification of the environmental conditions which tend to be associated with high/low numbers of sightings per unit of survey effort. The percentage of the survey effort is measured in terms of percentage of total distance flown.

Figure A.1: Percentage of survey effort and percentage of sightings by wind speed for the entire Bight (1991 and 1993–1995)

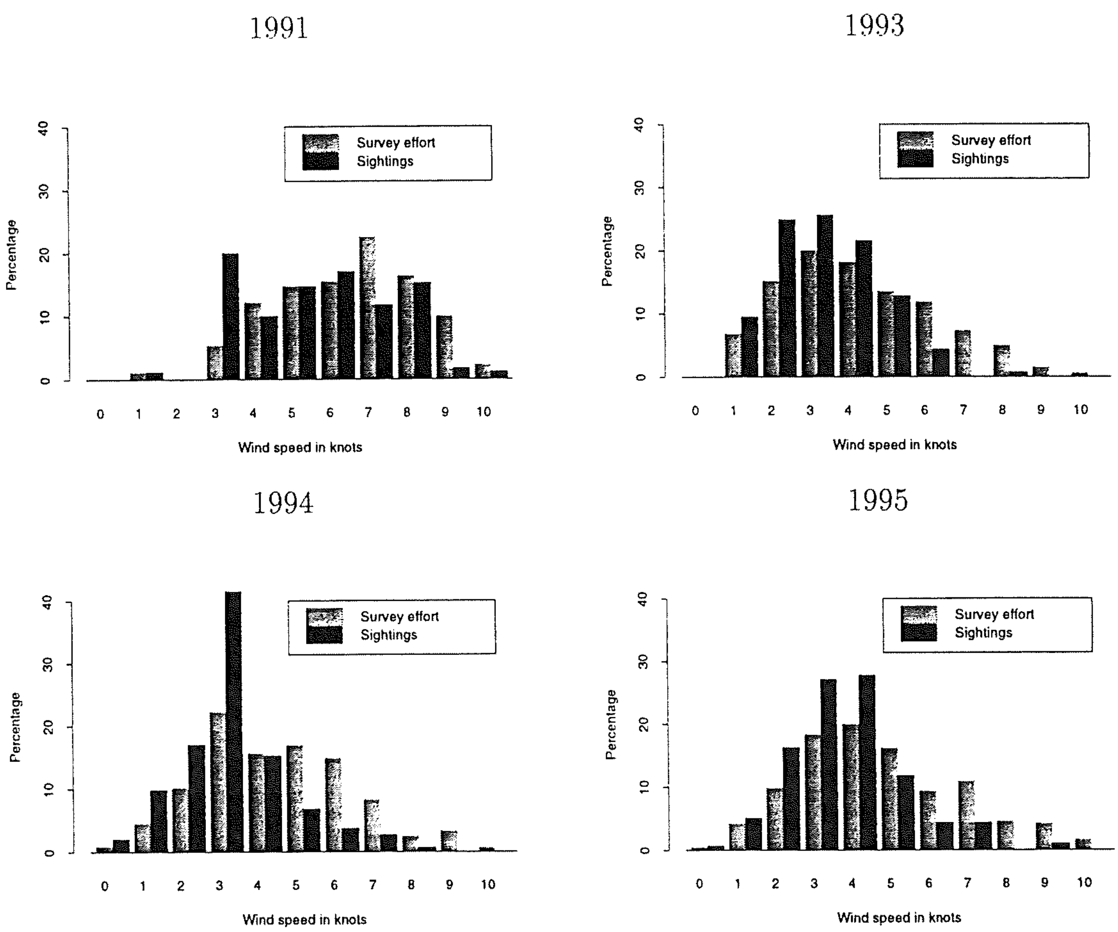


Figure A.2: Percentage of survey effort and percentage of sightings by cloud cover for the entire Bight (1991 and 1993–1995)

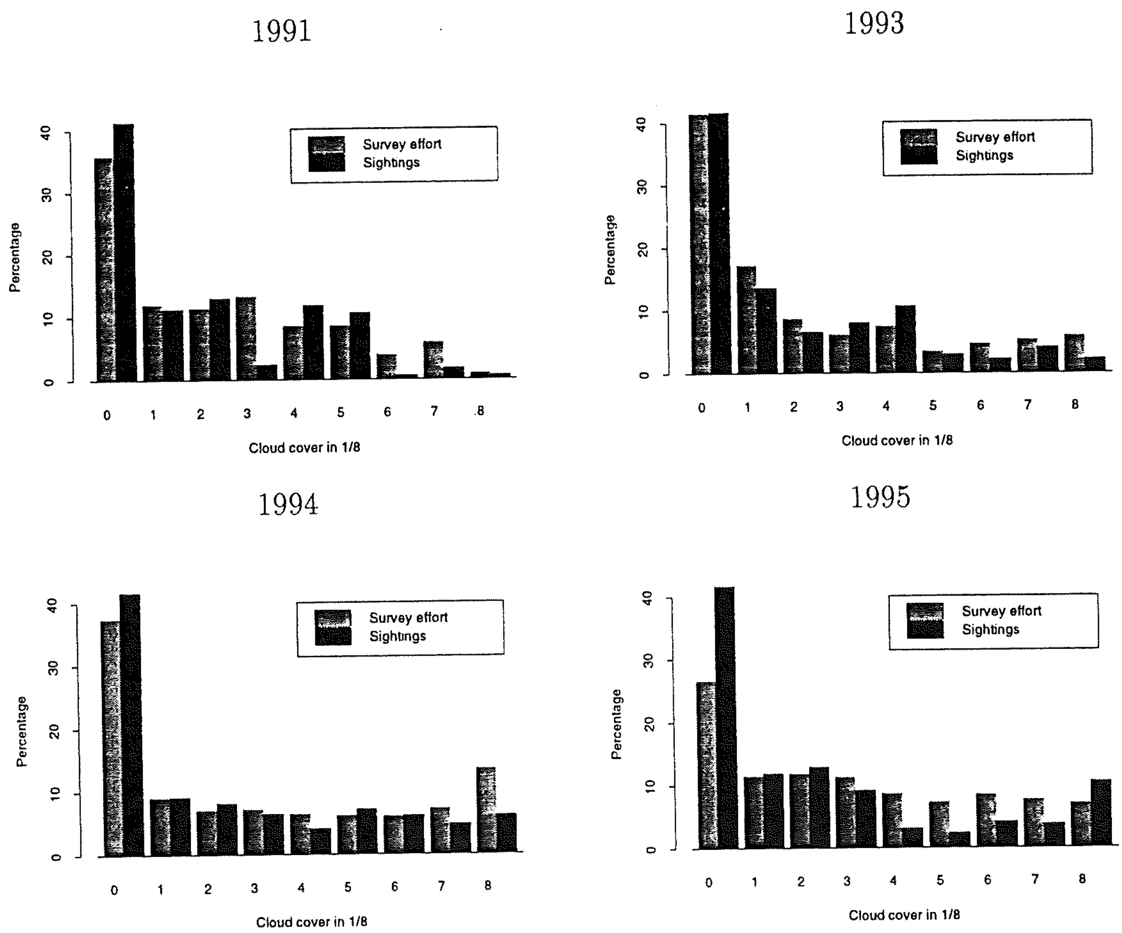


Figure A.3: Percentage of survey effort and percentage of sightings by air temperature for the entire Bight (1991 and 1993–1995)

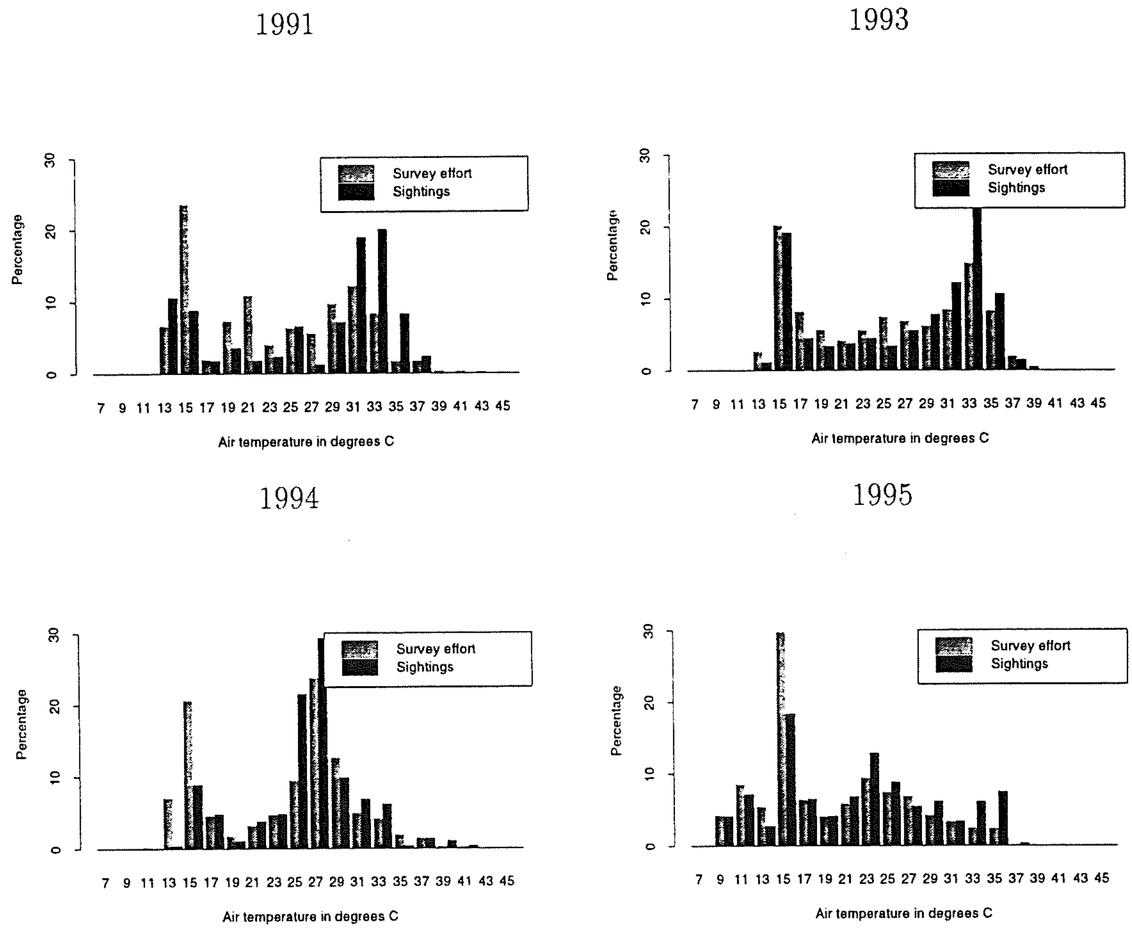
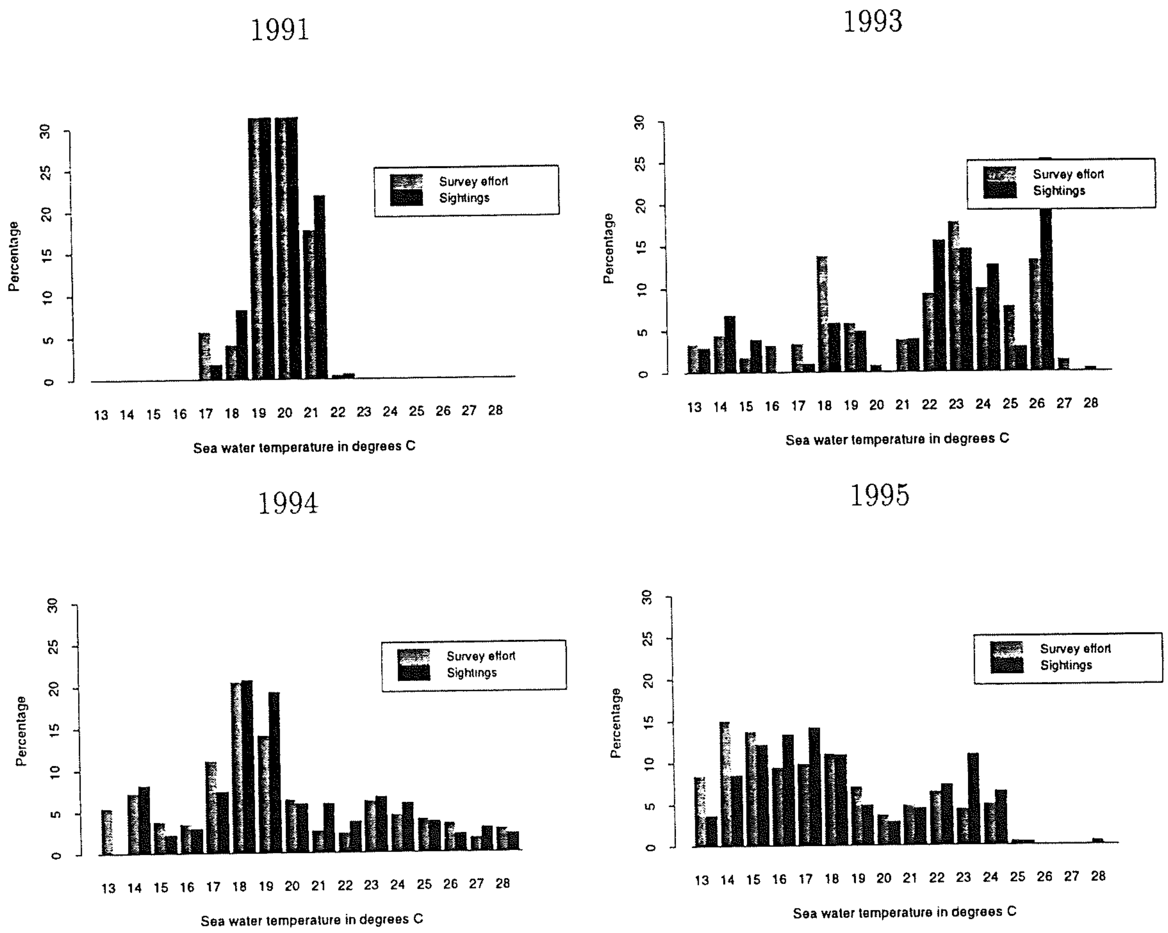


Figure A.4: Percentage of survey effort and percentage of sightings by sea water temperature for the entire Bight (1991 and 1993–1995)



A.3.2 Eastern Bight

Figure A.5: Percentage of survey effort spent in different wind speeds for the eastern Bight (1991–1995)

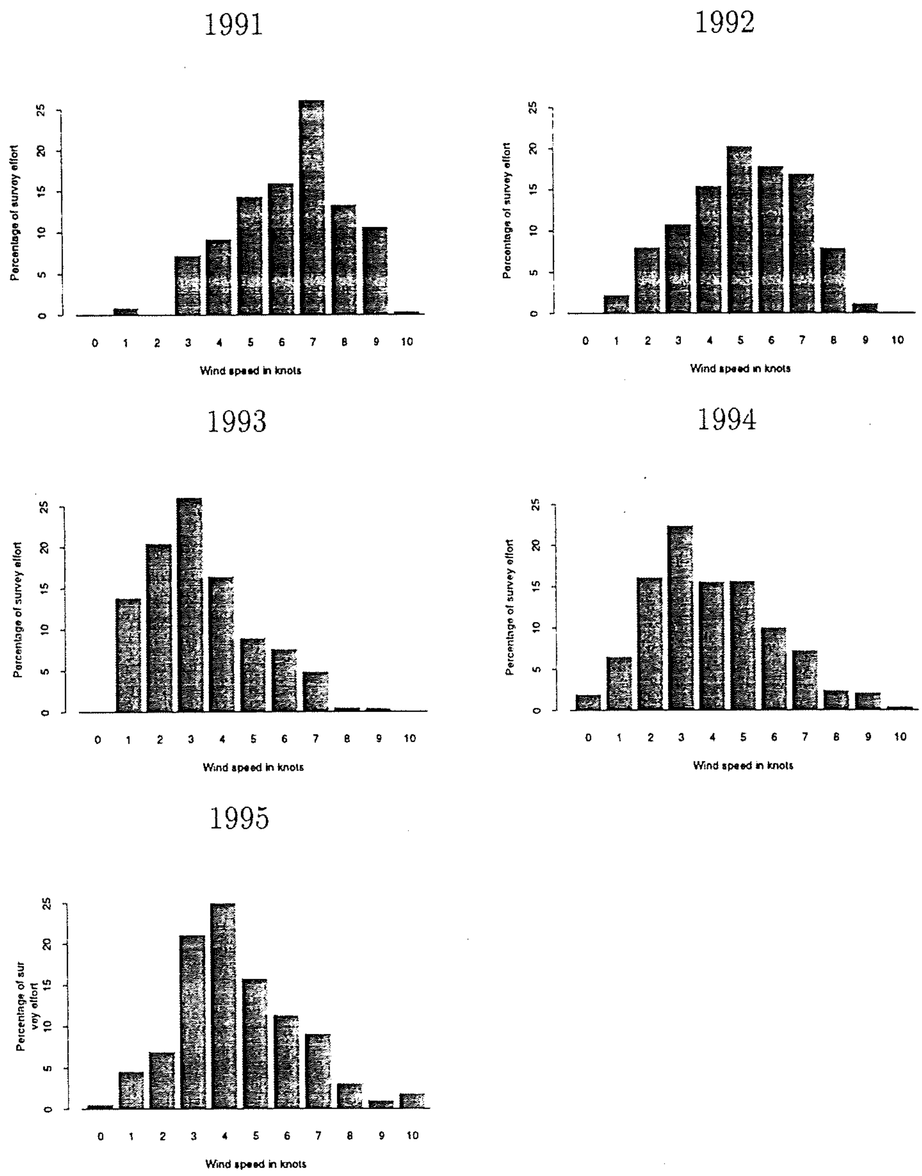


Figure A.6: Percentage of survey effort spent in different cloud cover conditions for the eastern Bight (1991–1995)

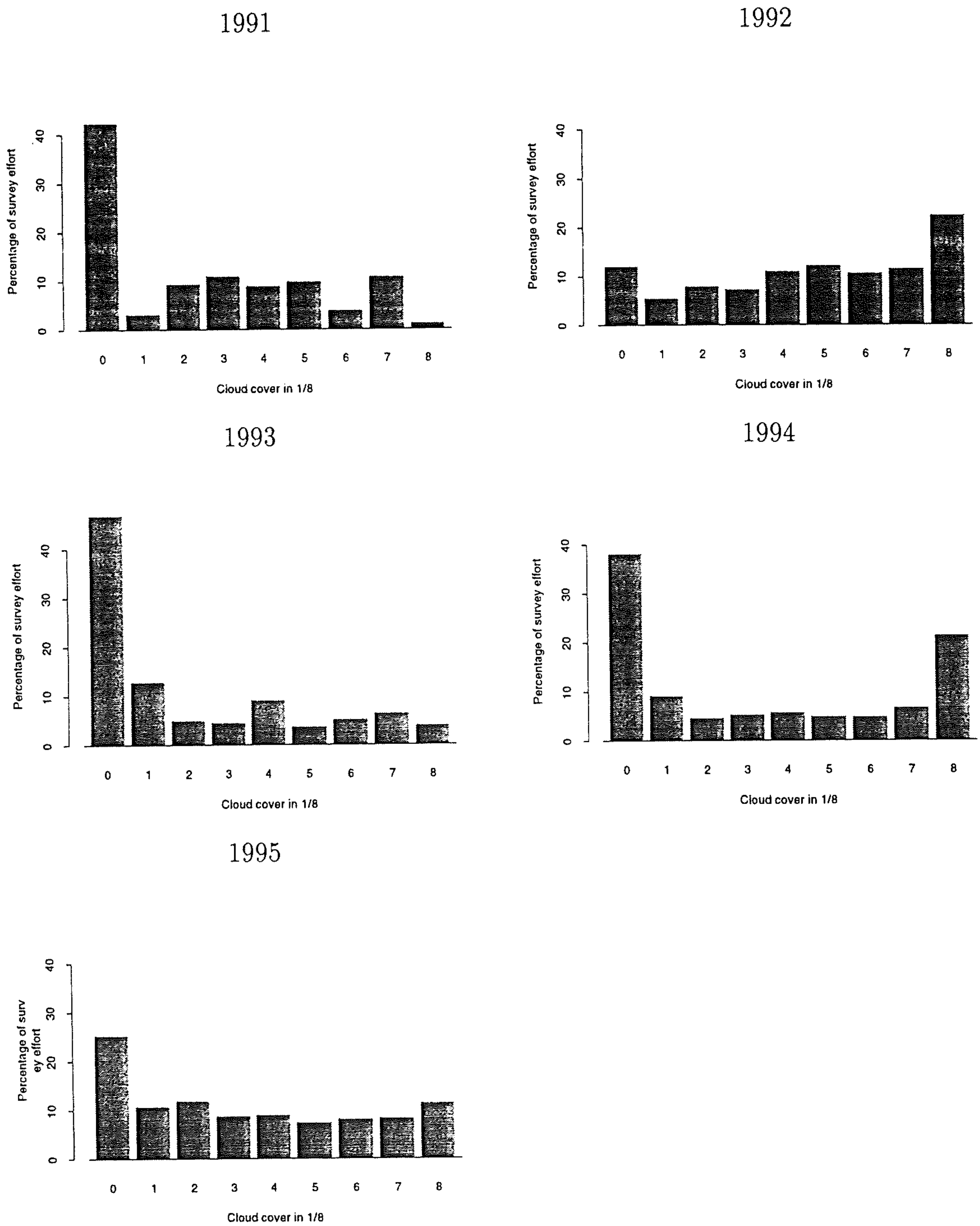


Figure A.7: Percentage of survey effort spent in different air temperatures for the eastern Bight (1991–1995)

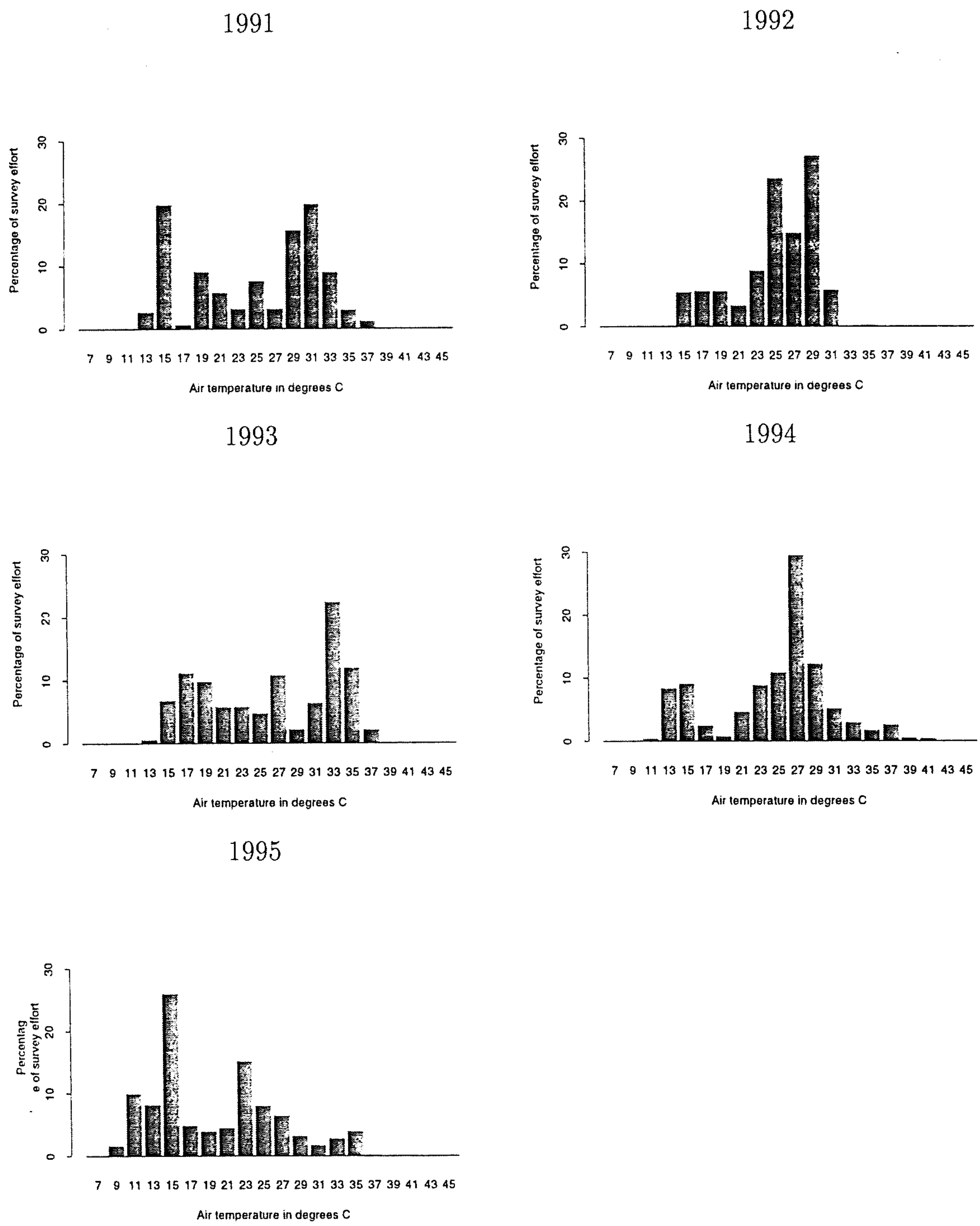
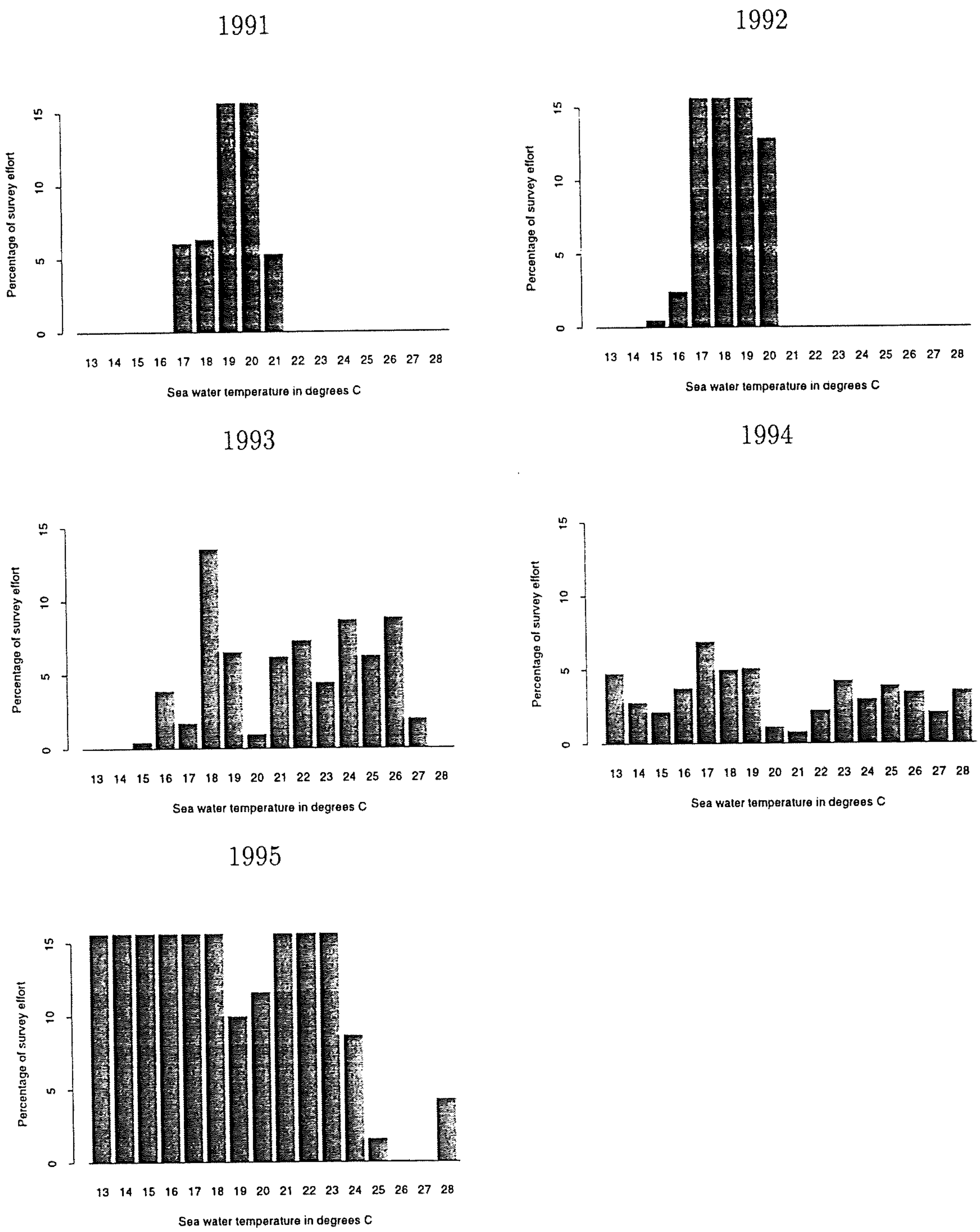


Figure A.8: Percentage of survey effort spent in different sea water temperatures for the eastern Bight (1991–1995)



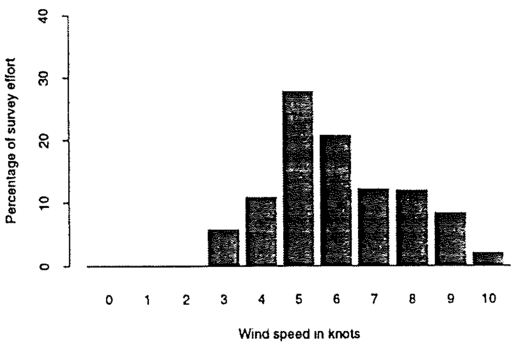
A.4 Figures showing environmental conditions during the survey in 1991 and 1993 by replicate

A.4.1 1991

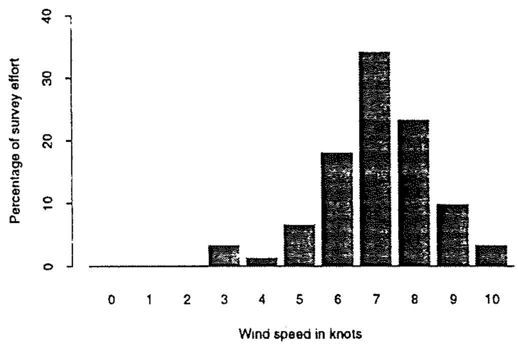
The figures show that the few sightings made in Replicates 5 and 8 occurred in windy conditions with frequent low cloud and low temperatures. Correspondingly, the reason behind the relatively many sightings made in Replicates 4, 6 and 7 may be the comparatively less cloudy, calmer and warmer conditions experienced.

Figure A.9: Percentage of survey effort spent in different wind speeds for the entire Bight (1991) by replicate

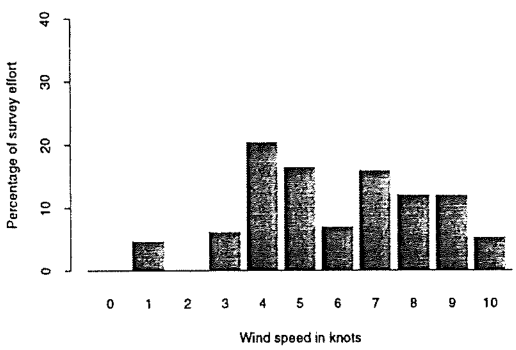
Replicate 4: 30 Dec – 9 Jan



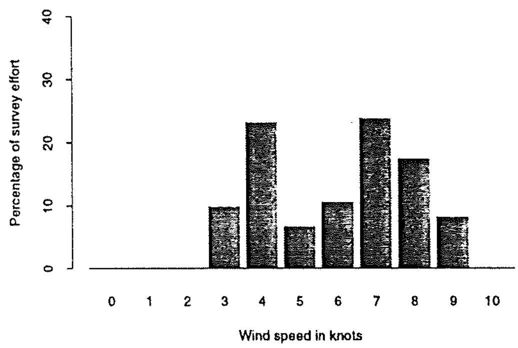
Replicate 5: 11 Jan – 20 Jan



Replicate 6: 28 Jan – 2 Feb



Replicate 7: 13 Feb – 6 Mar



Replicate 8: 18 Mar – 8 April

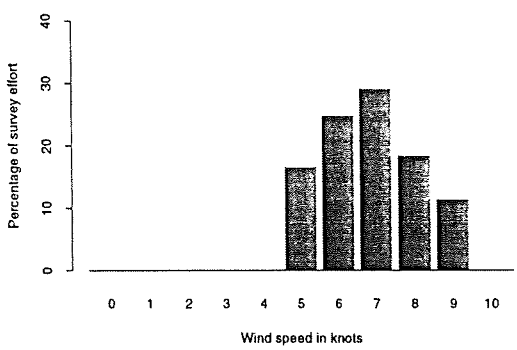


Figure A.10: Percentage of survey effort spent in different cloud cover conditions for the entire Bight (1991) by replicate

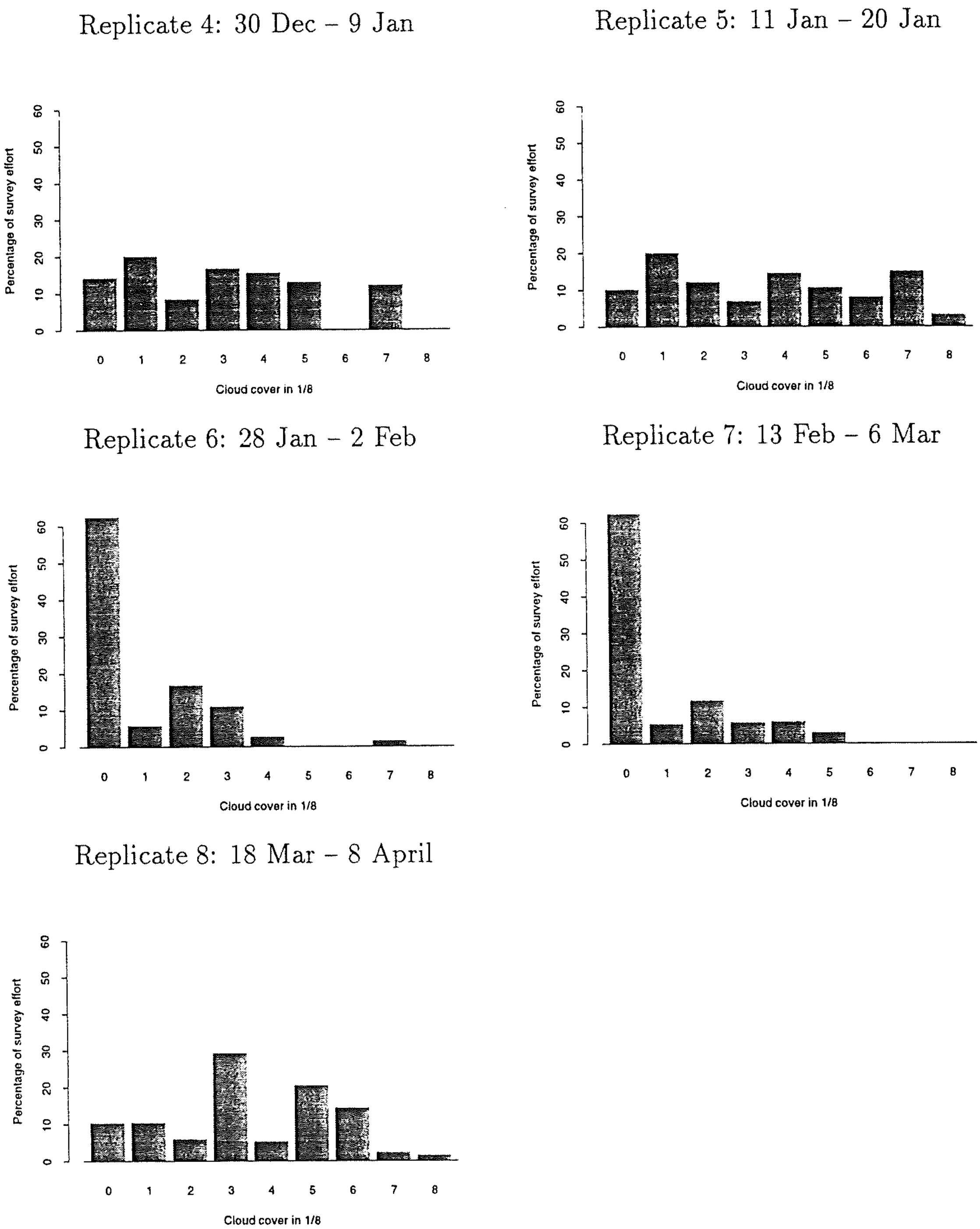
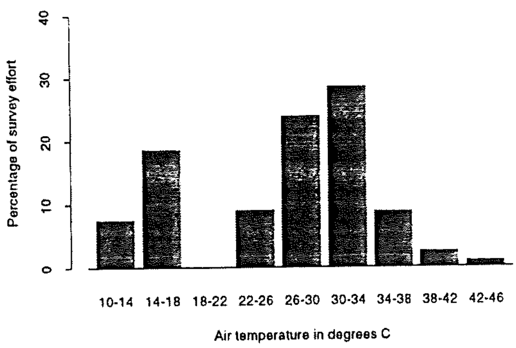
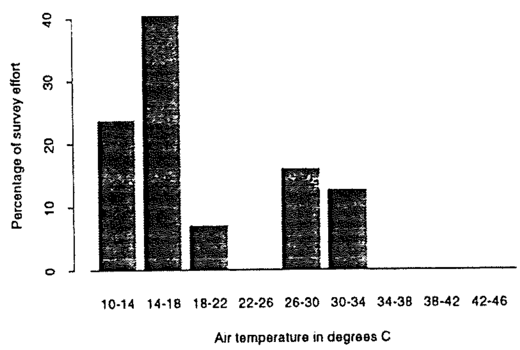


Figure A.11: Percentage of survey effort spent in different air temperatures for the entire Bight (1991) by replicate

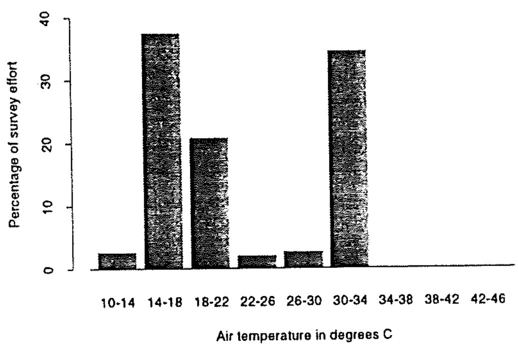
Replicate 4: 30 Dec – 9 Jan



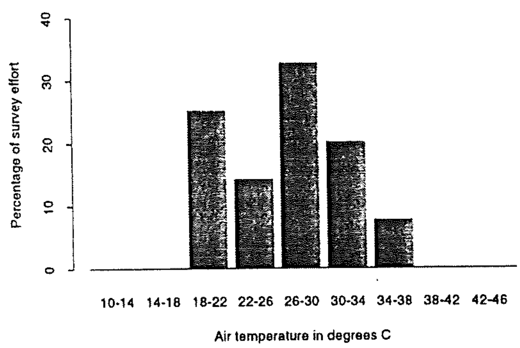
Replicate 5: 11 Jan – 20 Jan



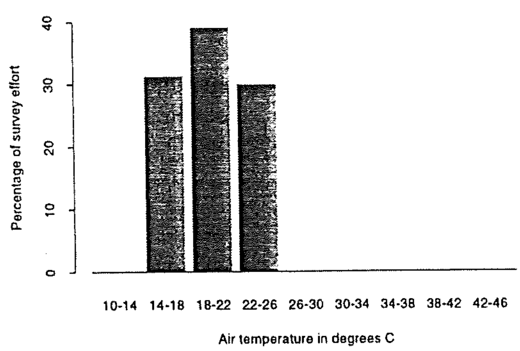
Replicate 6: 28 Jan – 2 Feb



Replicate 7: 13 Feb – 6 Mar



Replicate 8: 18 Mar – 8 April



A.4.2 1993

The figures show that the first 3 replicates had basically the same environmental conditions, and the last replicate experienced colder, more cloudy conditions. This may be part of the reason for lower abundance in this replicate.

Figure A.12: Percentage of survey effort spent in different wind speeds for the entire Bight (1993) by replicate

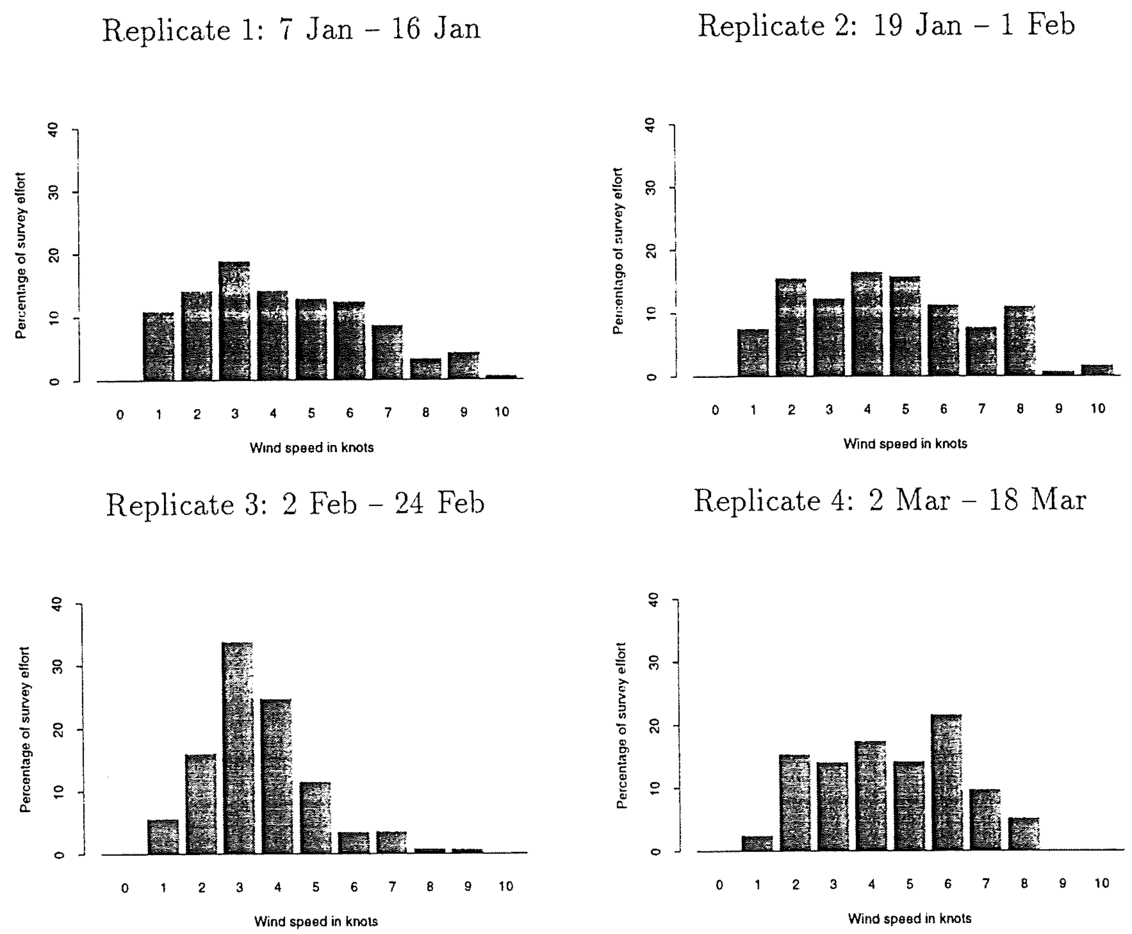


Figure A.13: Percentage of survey effort spent in different cloud cover conditions for the entire Bight (1993) by replicate

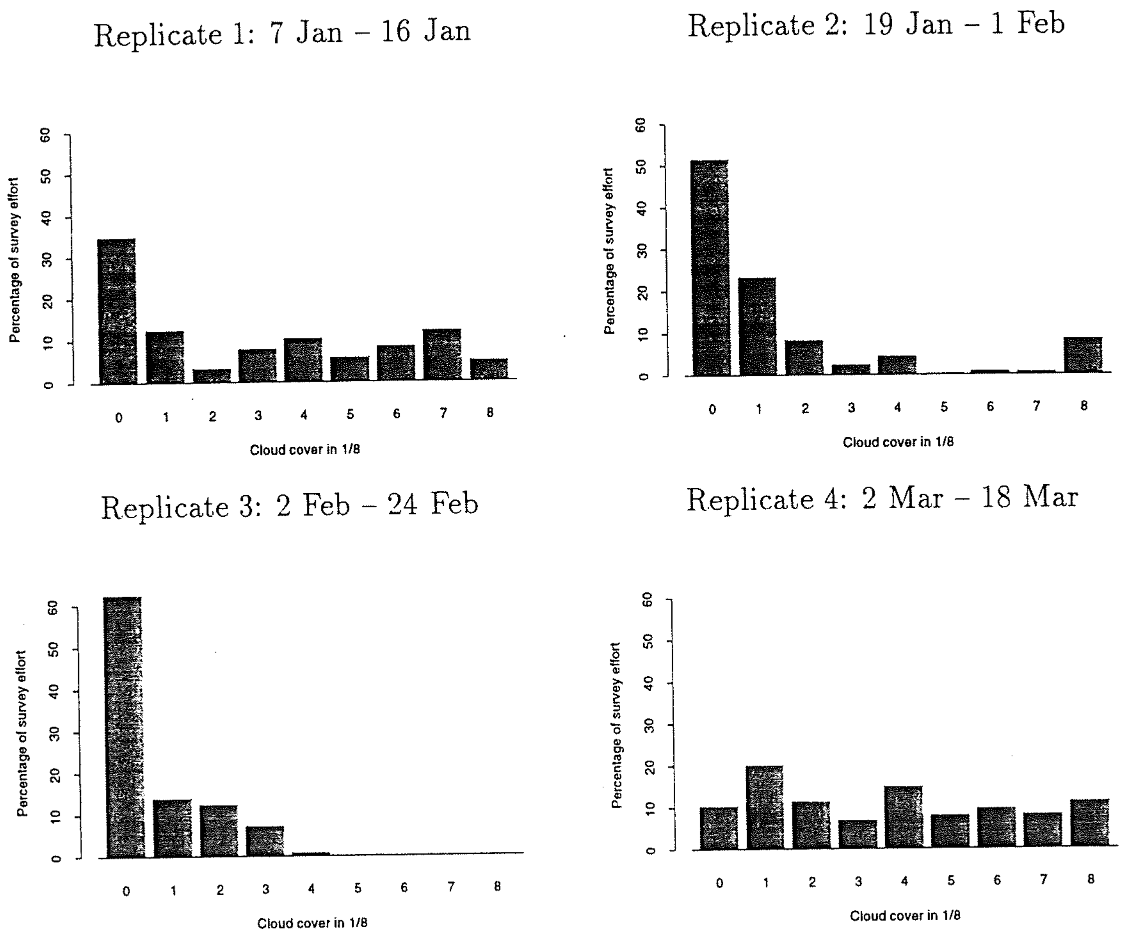
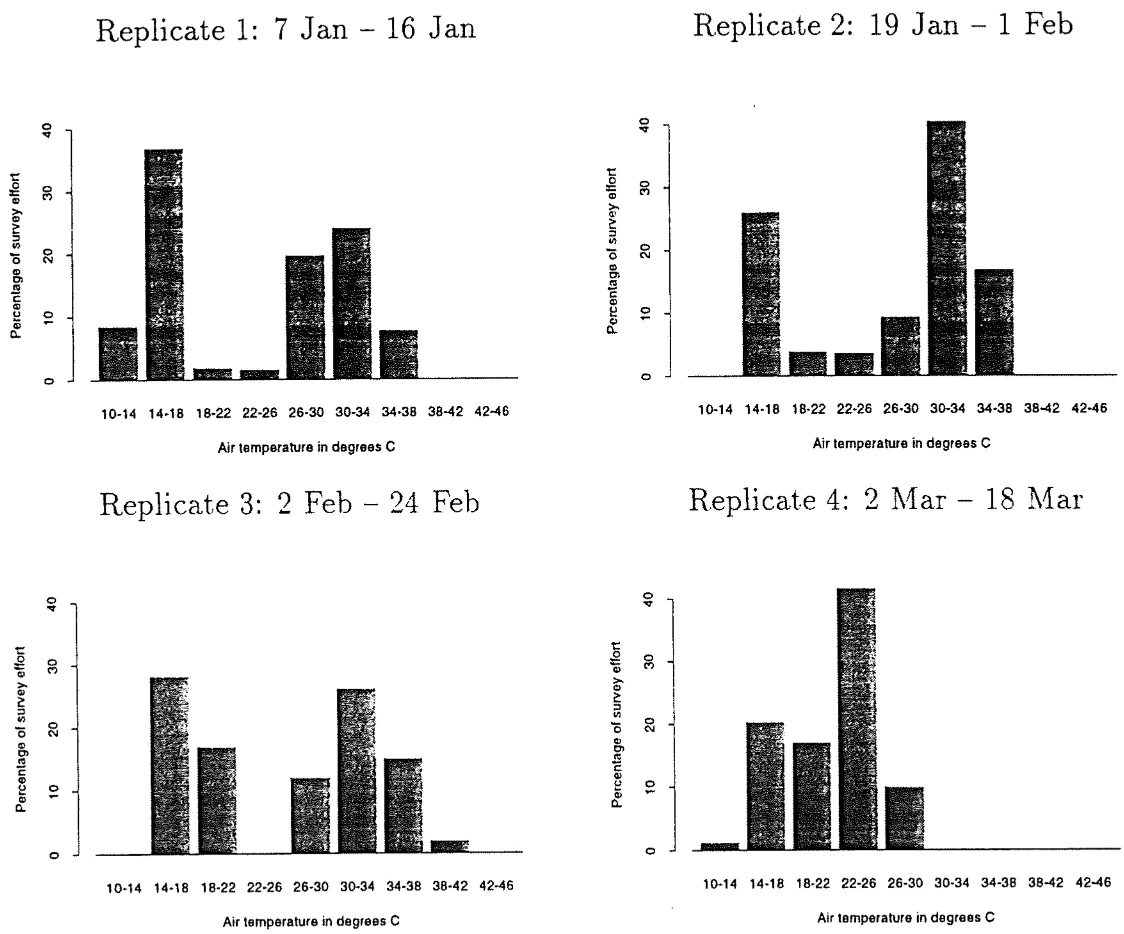


Figure A.14: Percentage of survey effort spent in different air temperatures for the entire Bight (1993) by replicate



A.5 Relationship between perpendicular sighting distance and environmental conditions

A non-parametric repression curve is shown on each plot (obtained using **supsmu** in Splus), together with the (maximum likelihood) estimate of the correlation, and the P-value of the test of the null hypothesis $\rho = 0$.

Figure A.15: Perpendicular distance versus windspeed

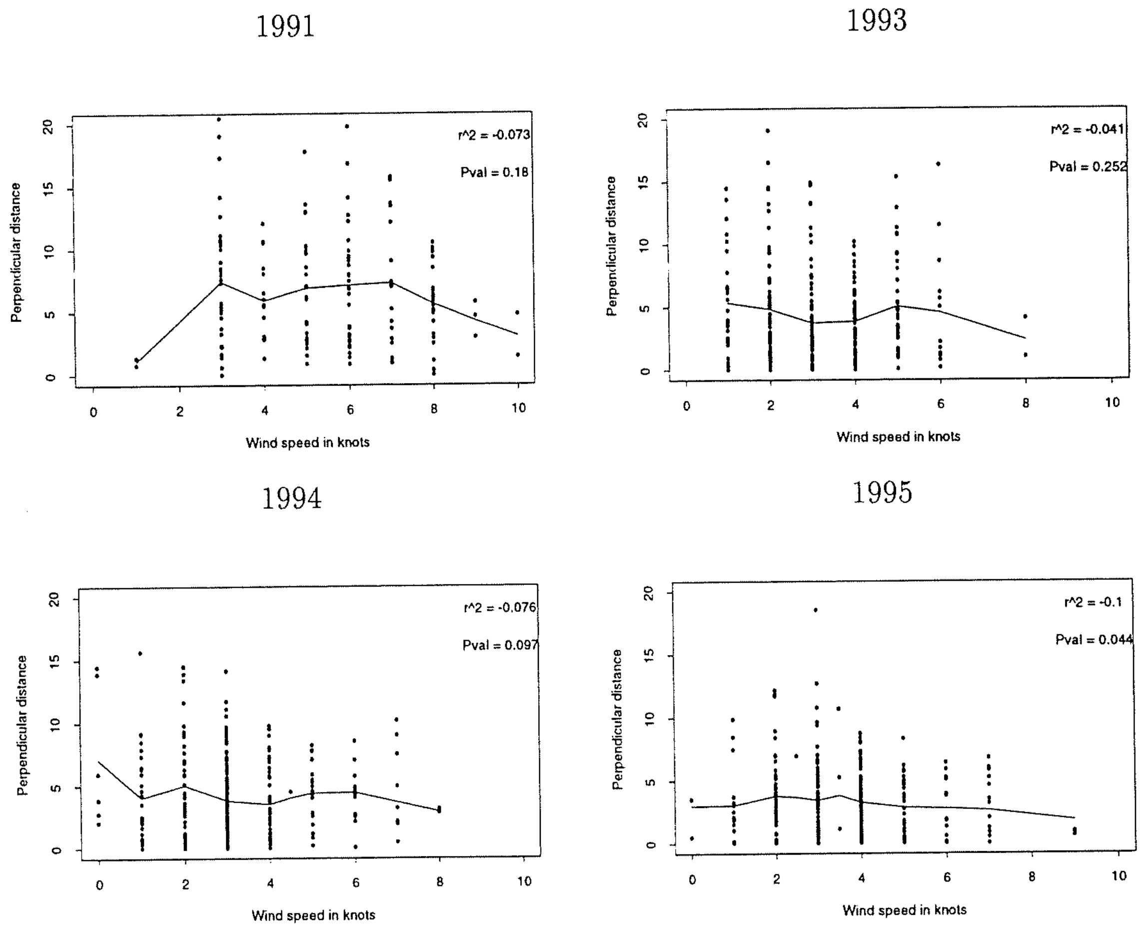


Figure A.16: Perpendicular distance versus cloudcover

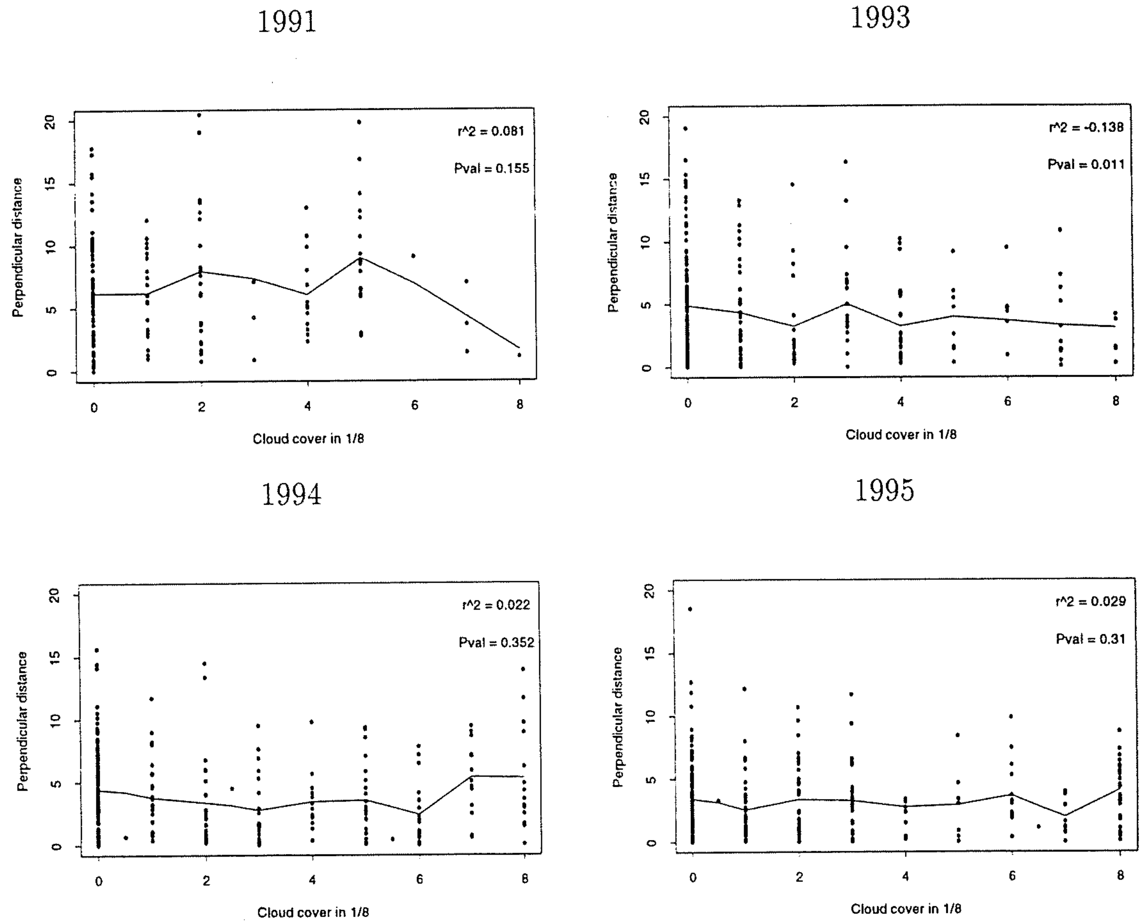


Figure A.17: Perpendicular distance versus air temperature

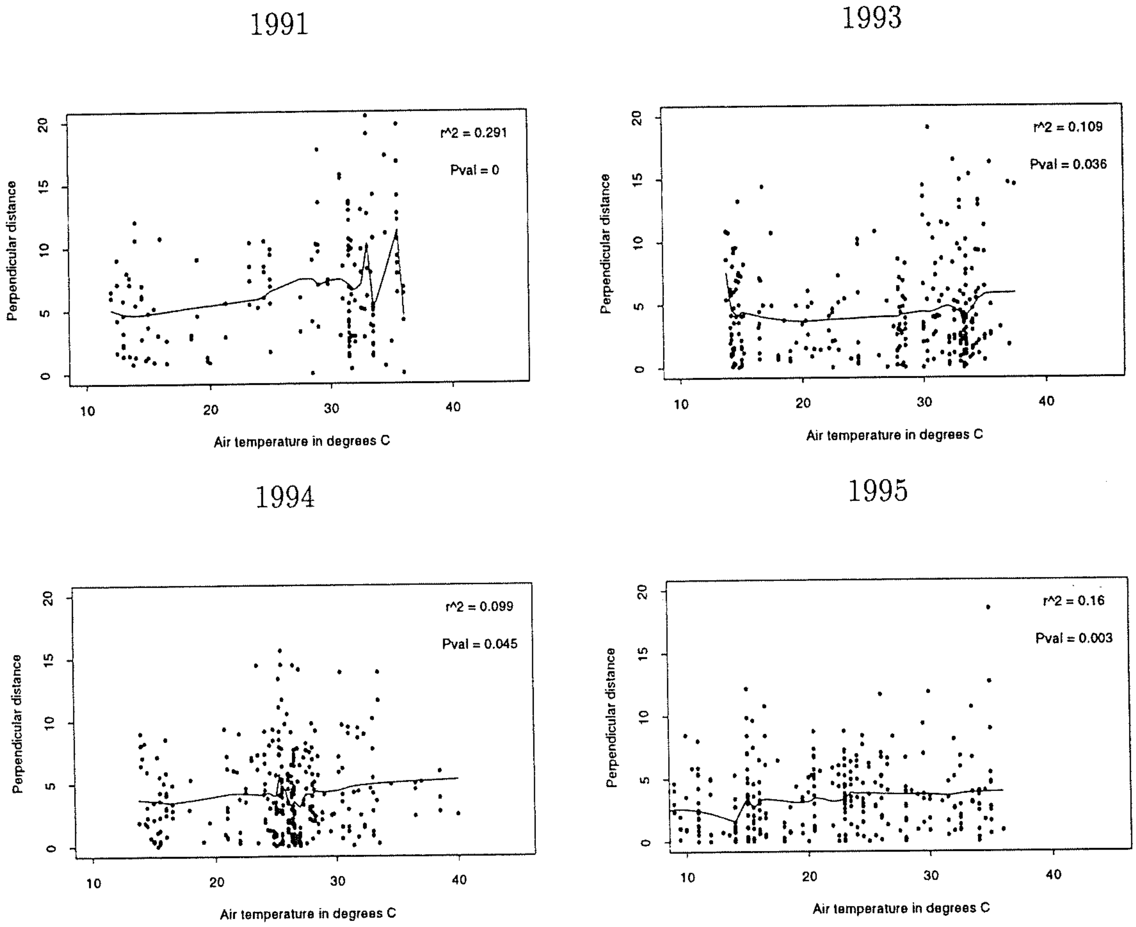
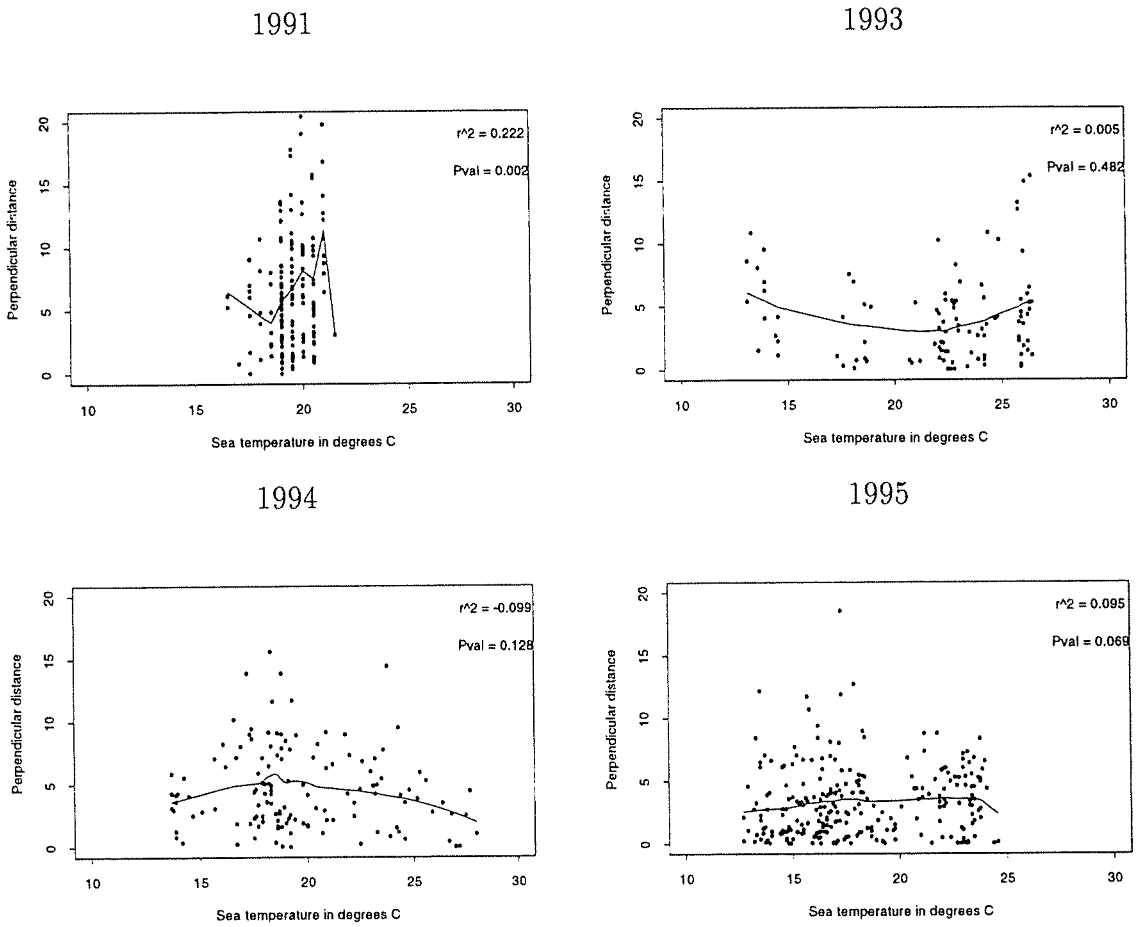


Figure A.18: Perpendicular distance versus sea surface temperature



A.6 Relationship between pilot's estimate of school size and environmental conditions

Figure A.19: Pilot's estimate of school size versus windspeed

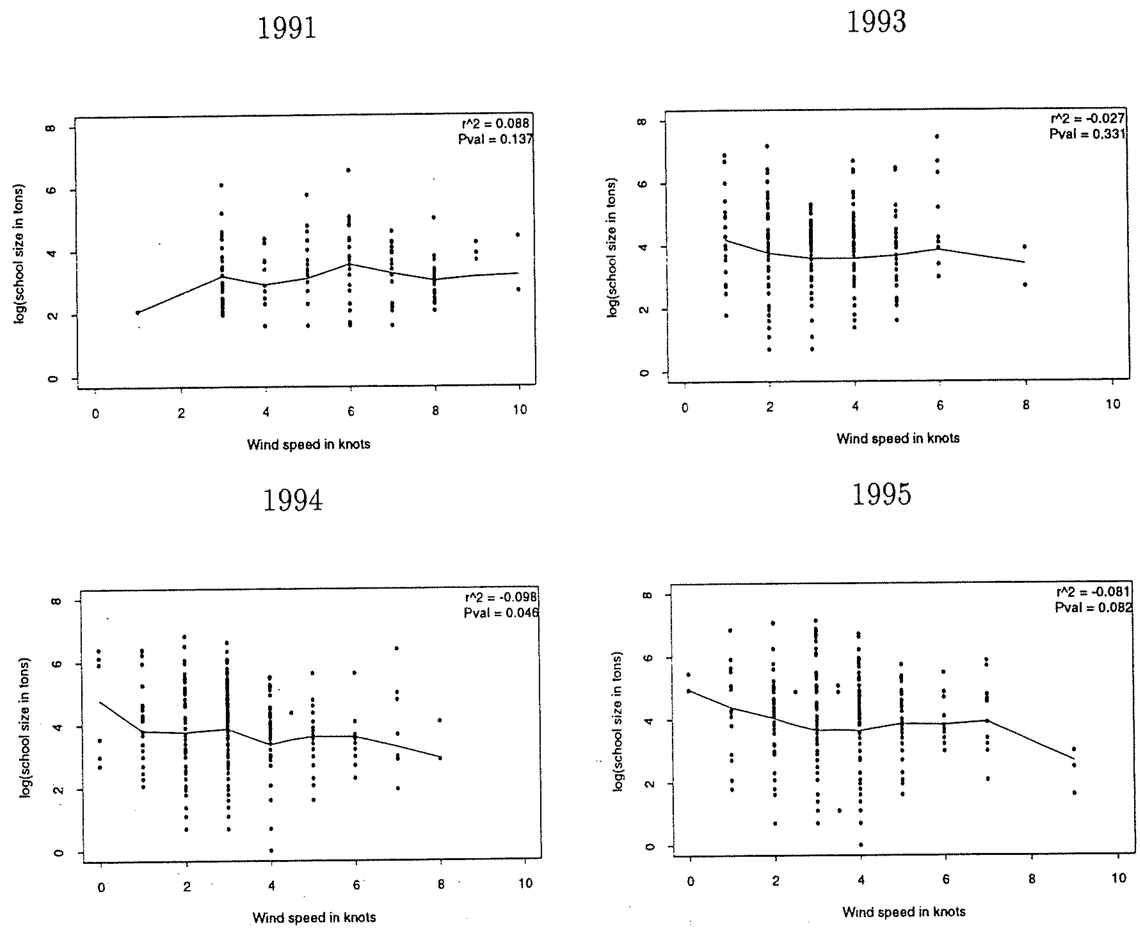


Figure A.20: Pilot's estimate of school size versus cloudcover

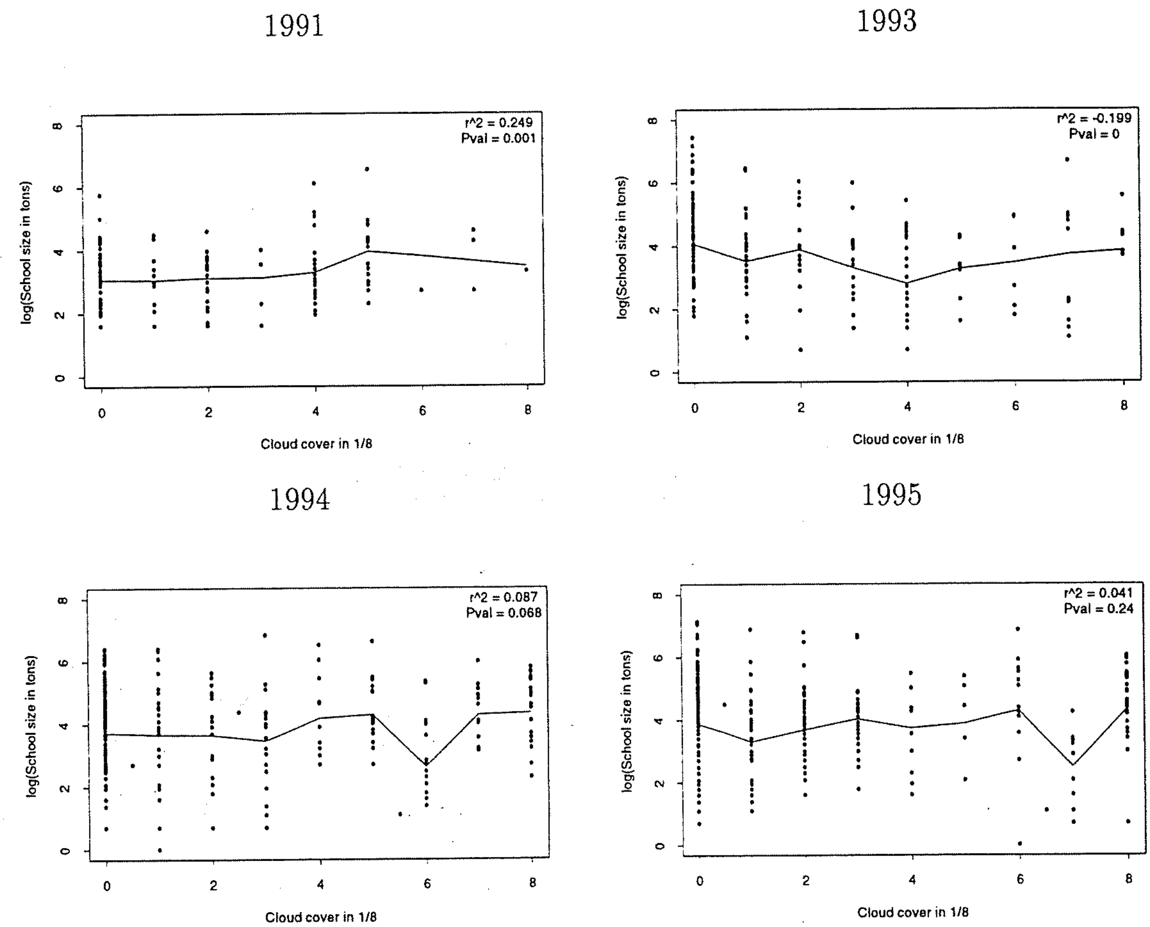


Figure A.21: Pilot's estimate of school size versus air temperature

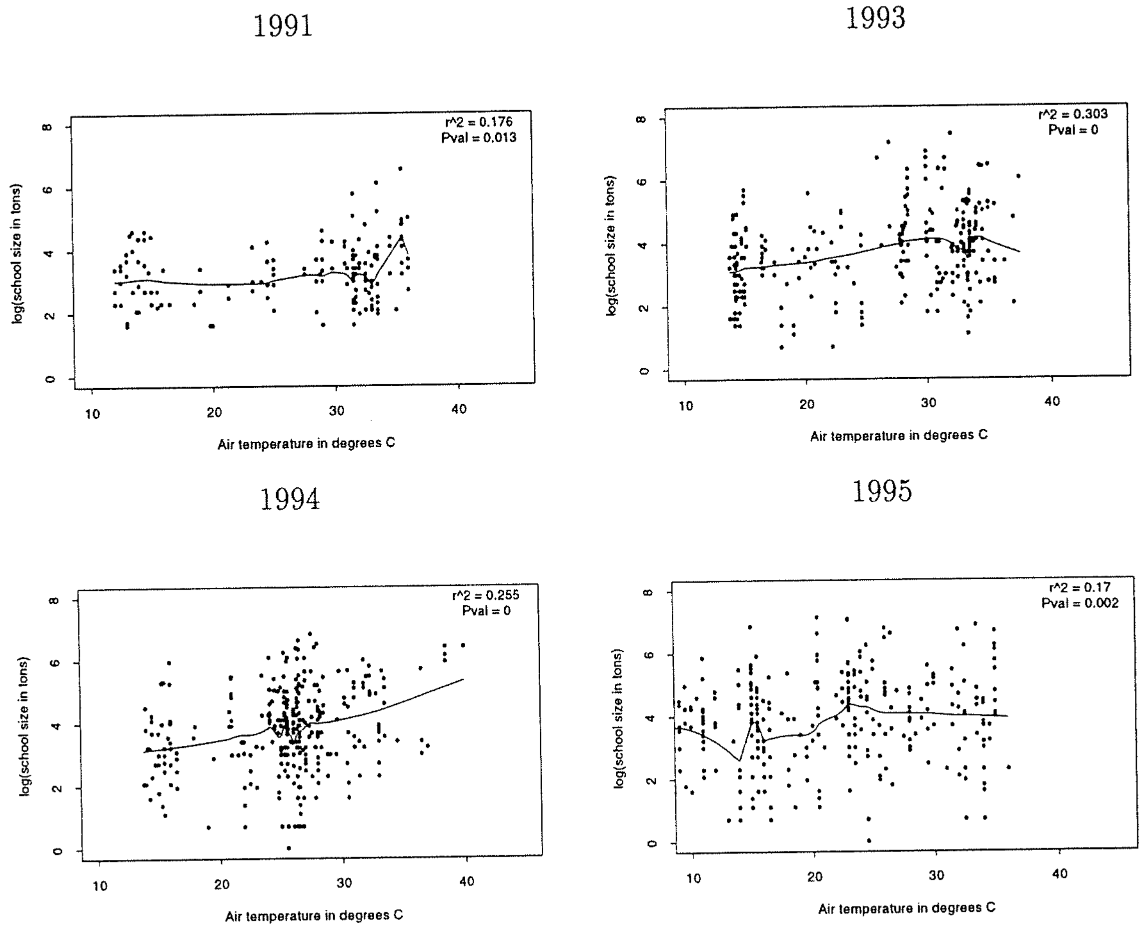


Figure A.22: Pilot's estimate of school size versus sea surface temperature