Determination of Effective Longline Effort in the Eastern Tuna and Billfish Fishery

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OBJECTIVES:

1. Determination of the depths attained by longline fishing gears deployed in the ETBF and investigation of the relationships between targeting and gear setting practices and hook depths and longline shape characteristics.
2. Investigation of the relationships between hook depth and the capture depths and associated water temperatures for the principal species caught by longline gears in the ETBF.
3. Investigation of the time-of-capture of the principal catch species caught by longline gears in the ETBF.
4. Investigation, and where necessary refinement, of the technical assumptions used in the habitat based models being used to standardise longline catch per unit effort in the WCPO.
5. Development of habitat based method for standardizing longline catch rates and application to the ETBF.
6. Investigation of the relationships between longline fishing practices, gear configurations and the incidental capture of bycatch and byproduct species in the ETBF.
7. Determination of the adequacy of information currently recorded in vessel logbooks for standardisation of longline CPUE and, where necessary, recommended changes.

NON-TECHNIQUE SUMMARY:

OUTCOMES ACHIEVED

By undertaking tthe first systematic monitoring of the fishing practices and operational characteristics of the longline gears deployed in the Eastern Tuna and Billfish Fishery (ETBF) this project has achieved a number of outcomes of direct benefit to both the fishers and the management of the fishery. In particular, these outcomes include improvements in i) our knowledge of the operational characteristics of the longline fishing gears deployed in the ETBF, ii) determination of the depths and times-of-capture of the species caught, and iii) the first application of the habitat-based method of standardising catch rates to an Australian fishery. These improvements provide the ETBF Resource Assessment Group with a greater understanding of the fishery for undertaking stock assessments and in particular the ability to construct reliable indices of stock status for the principal target species in the ETBF. As these indices are the main inputs to the harvest strategy which is being used to determine the annual TAE (or TAC) in the ETBF this is an important and ongoing benefit to the fishery. These outcomes will also help inform the science and stock assessments undertaken for the Western Central Pacific Fisheries Commission.

The harvest strategy adopted for the Eastern Tuna and Billfish Fishery (ETBF) relies on the calculation of a number of resource indicators determined from the catch and effort data collected from the fishery. In particular, standardised catch rates are used as an indicator of resource status or availability. However, the ETBF is a multi-species fishery having at least five principal target species – yellowfin, bigeye and albacore tunas, broadbill swordfish and striped marlin. As such, changes in operational practices associated with targeting different species makes it difficult to determine a metric of effective effort directed at any particular species. This in turn makes it difficult to interpret changes in catch rates as changes in resource availability. In order to help overcome this problem, the primary objective of this project was to increase our knowledge of the operational characteristics and fishing effectiveness of longline gears deployed in the ETBF so that the relationship between fishing practices and resultant catch rates of the principal target species in this fishery could be better determined. The second main objective was to apply and test the utility of the habitat based method of standardising catch rates in this fishery.

In addressing these objectives this project has achieved a number of firsts. Using Temperature-Depth Recorders (TDRs) it has undertaken the first systematic examination of the depths and temperatures fished by longlines deployed across the ETBF. A total of 2050 individual TDR recordings were obtained between August 2004 and May 2007. Furthermore, by combining these depth data with the catch-by-hook position data collected by AFMA observers, this project has achieved the first systematic understanding of the range of depths at which individual species are caught within the ETBF. Finally, by combining the observed depth-profiles of the longline hooks with observations of the depth-profiles of bigeye tuna obtained from archival tags, it has been possible for the first time to apply the habitat-based method to standardising catch rates to an Australian fishery.

The longline hooks deployed in the ETBF were observed to attain a range of depths down to around 400m. The time-at-depth profiles for sets deploying less than 10 hooks-per-float (HPF) were found to be very similar, though the depth-profiles associated with those sets deploying more than 15 HPF were considerably deeper. As most sets targeting yellowfin, bigeye or swordfish generally deploy less than 10 HPF, the depths fished by hooks targeting these species were found to be similar. On the other hand, for gear configurations deploying more than 10 HPF a near linear relationship was found in the mean depth fished across all hooks and the number of HPF. This result supports the assumptions often used in the CPUE standardisation models for longline fishing that the number of HPF is a proxy for mean fishing depth, but the former result shows that this assumption may not true for across all HPF configurations.

The most common depths fished by hooks deployed in the ETBF were found to be relatively shallow, with monitored hooks spending around 34 percent of the soak time between 40-60 meters and around 75 percent of the time at depths less than 80 meters. Hooks fished depths greater than 140 meters for only 10 percent of the time. However, the greater use of sets deploying 20 or more HPF during 2007 increased the percentage of time hooks fished below 140 meters to 20 percent and below 200 meters to 10 percent. Furthermore, the depth profiles of hooks deployed in the ETBF were found to be different to those estimated for hooks deployed from Japanese longline vessels fishing across the Western and Central Pacific Ocean.

While the depths to which hooks were observed to sink were found to be highly variable for a given HPF configuration and hook number, the mean depths attained were found to be reasonably well predicted by the longline catenary equation of Yoshihara (1951). Current-speed, HPF configuration and the use of a line shooter were found to be the main factors influencing variation from the predicted depth.

Significant differences in the catch rates of the five principal target species between gears with different HPF configurations were observed, though for each HPF configuration the relative catch rates-by-depth profiles were usually similar for these species. This indicates that the relative availability of these species with depth was similar over the range of depths fished by each gear configuration. Only for sets with 30 HPF was it observed that the catch of bigeye tuna generally occurred on deeper hooks than for the other species. Nevertheless, after combining the results across all gear configurations it was possible to discern major differences in the availability-by-depth for the five principal target species. Availability of yellowfin, swordfish and striped marlin was generally greatest in the top 40 meters, whilst availability for albacore was estimated to be relatively low in the upper parts of the water column and to be highest below 150 meters. Bigeye tuna availability was found to be more evenly distributed with depth, though with a tendency for higher availability at deeper depths. These results should be of particular interest to fishers as this knowledge will assist them better understand the factors that control the depths fished by hooks and how effective each gear configuration is at targeting a given species. Individual improvements in fishing effectiveness will, in turn, assist improving the economic efficiency of the entire fishery.

The information gained from this study on the depth distributions of the fishing gears, together with the improved understanding of the depth preferences of bigeye tuna gained through the deployment of archival tags in the ETBF in recent years, provided the opportunity to apply the habitat-based (HBS) method to standardising the catch rates of bigeye tuna in the ETBF. This method has the advantage of making direct use of the information on the depths of hooks and fish, and provides an alternative to the statistical approaches of the GLM and GAM methods. The large amount of data available for the ETBF helped to overcome a number of problems which have limited the use of this approach in other fisheries. Both the deterministic and statistical HBS models were applied and two approaches were also used to infer the spatial distribution of the habitat across the fishery. The first made use of the Ocean Global Circulation Model (OGCM) data, as used in previous application of the HBS model, whilst the second applied the depth and temperature distributions inferred from the tag-data to the entire fishery. Furthermore, the availability of information on set-time allowed the addition for the first time of a diurnal habitat component to the HBS model.

Comparison of the resulting indices of bigeye availability calculated for each model indicated that the deterministic HBS model (which relies to the greatest extent on the OGCM data) was the most dissimilar, while the results from the statistical HBS model and the two models using the tag-based depth and temperature distributions were quite similar. It is likely that deterministic HBS model is limited by the poor resolution of the OGCM data within the ETBF region while the statistical HBS model has the freedom to modify the tag-based temperature-preference profile of the fish to overcome such limitations. For smaller regional fisheries such as the ETBF this results implies that one might best avoid using the OCGM data and just assume a single habitat profile across the entire fishery based on information obtained directly from archival tags. Where such tag data is spatially extensive, it may also be possible to estimate separate profiles for each sub-region of the fishery. This approach would also be preferable for large regional fisheries such as that within the WCPO but will require a systemic program of archival tagging in order to collect the required data. This will be an important consideration for the managers of these fisheries.

The results also indicated that addition of the diurnal component to the model makes a significant improvement to the result. This is not unexpected, as it is well known that the depth and temperature preferences for bigeye tuna are significantly different between the day and night and there have been shifts over time in the proportion of sets in the ETBF deployed during the day and night.

Whilst the HBS method is able to make direct use of information to match the depths and temperatures fished by hooks with the habitat of the species of interest, it is currently limited in that it does not incorporate other factors which are known to also influence the catchability of a longline hook such as bait type, use of lightsticks, etc. As such there remains a role for the use of the more traditional statistical GLM in standardising catch rates. However, the development of a third approach, which is able to combine the use of the currently disparate data sources used by the HBS and GLM methods, would be seen as an important advance and should remain the focus of ongoing research. This is especially the situation given the central role played by standardised catch rates as indices of resource abundance in stock assessments and for the harvest strategy adopted for the ETBF.

Finally, the results of this study reaffirm the critical need to collect a range of information from the fishery on those fishing practices which influence the performance of the fishing gears and the resulting catch rates. By undertaking the first extensive survey of the depths fished by the longline gears deployed in the ETBF this study has provided a baseline against which future changes in fishing practices and changes in fishing effectiveness can be compared. This will be an important to understand changes in the fishing effectiveness and prevent biases entering the calculated indices of stock status due to effort creep.

KEYWORDS: Eastern Tuna and Billfish Fishery, longline fishing gears and targeting practices, monitoring longline fishing depths, depth and time-of-capture, habitat-based CPUE standardisation.

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Section 1: Introduction

1.1 Background

Understanding the relationship between catch rates and resource abundance or availability is of critical importance to both stock assessments and the sustainable management of fisheries. Whilst stock assessments are usually concerned with understanding the absolute abundance of a stock relative to some benchmark (for example, B_o or the abundance in some reference year), on the other hand catch rates usually only provide a relative measure of the abundance of fish available to the fishing gear. For example, if the depths at which fish are distributed in the ocean is influenced by environmental factors, then the availability of fish to longline gears can change in response to changes in these environmental factors whilst the absolute abundance of the stock remains constant. It is for this reason that catch rates are associated with providing a measure of the availability of fish to the fishing gears rather than a measure of the total abundance of the stock.

However, catch rates are influenced by a multitude of factors apart from resource availability and so interpreting changes in catch rates remains problematic. For example, catch rates are highly dependent on the operational and gear setting practices associated with the targeting of different species, whilst the performance of longline gears is also influenced by changes in prevailing oceanographic conditions (Mohri and Yasuaki 1997, Yano et al 1998, Mizuno et al 1999). However, without a detailed knowledge of how these factors influence the effective effort directed at particular species, it is not possible to account for the influence of these factors on catch rates. In turn, this makes it difficult to interpret changes in catch rates as changes in resource availability and as such limits our ability to assess the impact of the fishery on the underlying resource.

The importance of being able to adequately interpret changes in catch rates in the Eastern Tuna and Billfish Fishery (ETBF) is also highlighted by a constraint on assessing the resource status in the ETBF due to the fact that many of the species taken in this fishery are part of single stocks which occur throughout the broader western and central Pacific Ocean (WCPO). Due to this situation, it is not possible to undertake a "stock assessment" on only that portion of the stock which occurs off eastern Australia unless one has an understanding of movement rates of fish into and out of this region. While stock-wide assessment models have been developed for the principal tuna species in the WCPO (, Langley et al 2007, Langley and Hampton 2008, Langley et al 2008, Hoyle et al 2008, Kolody et al 2008) the results of these assessments still remain uncertain. Furthermore, due to uncertainties in the spatial distribution of both the resource and patterns of recruitment, it remains difficult to infer from these assessments the status of a portion of the resource in a limited region such as off eastern Australia.

Given this situation, in 2003 the Fisheries Assessment Group for the ETBF recommended that appropriate performance indicators, based on the monitoring of temporal and spatial changes in catch rates and the size of fish caught, be used to monitor the resource status and the success of fisheries management in the ETBF (Anon, 2003). Reliable indices of resource availability are also a critical input to assessment models for those stocks (such as swordfish and striped marlin) which have a more regional SW Pacific distribution. More recently, the development of robust empirical-based indicators has been given increased importance with the adoption of a CPUE and size-based harvest strategy in this fishery (Davies et al 2007).

If unbiased indicators of resource status are to be developed, it will be necessary to develop a better understanding of those factors, apart from resource availability, which influence catch rates. For example, studies have shown that factors such as current sheer (Mizuno et al 1999, Bigelow et al 2005) and gear type (Suzuki et al 1977, Yano et al 1998) can significantly affect the expected depth at which longlines fish, while the resulting fishing depths can significantly impact on the resulting catch rate (Suzuki et al 1977, Yang and Gong 1987, Boggs 1992, Mohri and Yasuaki 1997, Nakano et al 1997, Ward and Myers 2005). While methods to standardise fishing effort to account for those factors which influence catch rates have been developed and are routinely used as part of stock assessments world-wide, in most instances the success of this exercise is limited by the absence of data on many of these factors. This is particularly the case in a multi-species fishery such as the ETBF, where one needs to know not only whether there have been changes in the effectiveness of fishing gears, but whether there have been changes in the effective targeting of particular species.

In recent years, a number of developments in the ETBF have greatly improved the ability to collect and analyse the data required to characterise the effectiveness of longline effort in the ETBF. In particular:

i) An observer program commenced in July 2003 within the ETBF and provides an ongoing ability to collect verified catch and effort data and other at-sea data (such as information on fishing practices) which until now has not available.
ii) There have been promising advances in the statistical integration of fisher behaviour (their targeting practices and effective depths of longline sets) with data from archival and pop-up tags on fish habitat preferences to standardize longline effort (Hinton and Nakano 1996, Hampton et al 1997, Bigelow, et al 2002, 2003). Put simply, these methods examine the effective fishing depths of longline hooks relative to the water mass, depth, temperature, oxygen etc preferences of the fish they are targeting to standardize the effort unit. However, the approach requires detailed information on the depth distributions of both the hooks fished by longlines and the different species which are caught, and application of this approach is presenting constrained by the lack of such data.
iii) Recent advances and use of archival tags (such as the ongoing work on bigeye in the Coral Sea), together with the integration of remotely sensed data and ocean-circulation models, are greatly assisting in our ability to map the spatial habitat of target species.

In building on these developments, and following the 2003 recommendation of the ETBF Fisheries Assessment Group to develop robust empirical-based indicators of resource status, CSIRO purchased a number of longline gear monitors in order to collect and analyse the data on a number of factors which influence the operational effectiveness of longline fishing gears. The aim was to improve the interpretation of catch rates as indices of resource availability and help address a number of other related issues pertinent of the successful management of the Australian Eastern Tuna and Billfish Fishery (ETBF).

1.2 Need

The following four issues highlight the need for an improved understanding of the relationship between catch rates and resource availability within the ETBF.

1. The need to develop indicators of resource availability off eastern Australia

Current stock assessments for the principal tuna and billfish species in the Western Central Pacific Ocean contain a number of key uncertainties. In particular, uncertainties in the spatial distribution of both the resource and recruitment patterns makes it difficult to infer from these assessments the status of the resource in a limited region such as region fished by the ETBF. In order to provide an understanding of the impact of the ETBF on the fish resources which occur off eastern Australia, in 2005 the Resource Assessment Group for the ETBF identified as a high priority the need to develop a number of performance indicators for monitoring the status of these resources. These indicators were to be based on the monitoring of temporal and spatial changes in catch rates (and the sizes of fish caught) which, in turn, would require gaining a better understanding of the factors, apart from resource availability, which influence catch rates.

2. The need to improve the data and methods used to standardise catch rates.

To improve our understanding of those factors which influence catch rates, information needs to be collected on a range of operational factors which influence the effectiveness of longline fishery gears. These factors include targeting and gear setting practices, resulting hook depths, depth preferences of the target species, time-of-capture, and prevailing oceanographic conditions. Furthermore, an understanding of these relationships is crucial if one is to make use of the new habitat-based models which have been developed to standardise longline catch rates (Hampton et al 1997).

3. The need to avoid the incidental capture of important bycatch species.

Information on the fishing characteristics of longline gears in the ETBF are also needed to help address the real or perceived threat that longlining has to threatened and endangered species. An improved understanding of the factors influencing the configuration of longline fishing gears and resulting catch rates will help identify fishing practices which may be used to avoid the incidental capture of important bycatch species, such as turtles and other threatened and endangered species (Polavina et al 2003). This will be similar to the observer-based research carried out in the mid-1990s in the Coral Sea to help identify methods to avoid the capture of black marlin (Campbell et al 1997).

4. The need to improve indicators of stock status in the WCPO.

Improvements in regional stock assessments are needed to assist managers of the ETBF gain a better understanding of the status of the stocks on which the ETBF depends. While several factors contribute to the uncertainties in the WCPO assessments, improvements in the construction of indices of stock biomass based on the analysis of longline catch-per-unit-effort have been identified by the Scientific Committee for the Western Central Pacific Fisheries Commission as a critical factor and a high priority for further research (SCTB 2003). The availability of accurate indices of stock biomass will also be a critical input for the development of assessment models for those pelagic resources (such as swordfish and striped marlin) which have a more regional SW Pacific stock structure.

1.3 Project Objectives

Given the identified needs and the recent developments in the ETBF previously outlined, the present project was developed to help achieve the following specific objectives:

1. Determine the depths attained by longline fishing gears deployed in the ETBF and investigation of the relationships between targeting and gear setting practices and hook depths and longline shape characteristics.
2. Investigate the relationships between hook depth and the capture depths and associated water temperatures for the principal species caught by longline gears in the ETBF.
3. Investigation of the time-of-capture of the principal catch species caught by longline gears in the ETBF.
4. Investigate, and where necessary refine, of the technical assumptions used in the habitat based models being used to standardise longline catch per unit effort in the WCPO.
5. Develop a habitat based method for standardizing longline catch rates and application to the ETBF.
6. Investigate the relationships between longline fishing practices, gear configurations and the incidental capture of bycatch and byproduct species in the ETBF.
7. Determinate the adequacy of information currently recorded in vessel logbooks for standardisation of longline CPUE and, where necessary, recommended changes.

The project commenced in mid 2005 and was scheduled to run for two years. However, a series of delays associated with the failure of a number of the gear monitors together with the receipt of the observer data associated with the trips on which the gear monitors were deployed resulted in the completion date for the project being extended to mid-2008.

Section 2: Data Collection

2.1 Deployment of Gear Monitors

In mid-2004 CSIRO Marine and Atmospheric Research (CMAR) purchased a range of longline monitoring gears for use by the Pelagic Research Group. This initial purchase consisted of 26 Star-Oddi DST Cent-ex Temperature-Depth data recorders (TDRs) and 250 Lindgren-Pitman HT 600 Hook Timers (HTs). During the life of this project, additional TDRs were also purchased using funds provided by the project to cover ongoing losses and failures.

Deployment of the gear monitors by AFMA observers commenced in late August 2004 and continued through until May 2007. The gear monitors were divided into two batches so that up to two observers could deploy them at any one time. An instruction manual on how to best deploy the gears, including additional observer forms for recording information associated with the deployment of the TDRs and HTs, was written to facilitate the use of the gears (see Appendix A). TDRs were programmed to record temperature and depth either every half, one, two or three seconds.

A listing of observer trips during which the gear monitors were deployed is provided in Table 2.1 while a summary of the number of sets and gears deployed per trip is provided in Table 2.2. In total 52 trips were undertaken by a total of six different observers. However, not all gear monitors were deployed on all trips. Of the 329 sets deployed during all monitored trips, TDRs were deployed during 44 trips and 258 sets and HTs deployed during 36 trips on 201 sets. The number of sets where HTs were deployed was less than that for TDRs as HTs were often not deployed in rough seas as they tended to tangle in the mainline. Up to 13 TDRs (mean=8.6) were deployed during any single set and data associated with 2216 TDR-deployments was collected during the life of the project. Between 70-100 HTs were deployed on any single set.

2.2 Gear Performance and Technical Issues

Despite the large amount of data collected, a number of problems were encountered during the deployment of the gear monitors, particularly the TDRs. While on occasions a TDR would be lost this was not unexpected and these units were routinely replaced. However, many TDRs failed and had to be returned to the manufacturer resulting in considerable delays. In May 2005 due to ongoing issues with the TDRs all were returned to the manufacturer for testing. Those found to be faulty (7 of the initial batch) were replaced under warrantee. Unfortunately, the TDRs were not returned until August 2005 resulting in a loss of time for deploying them. An additional 10 TDRs were ordered from Star-Oddi in June 2005 and received in August 2005. However, most of these were found to be faulty and had to be returned to the manufacturer for replacement. Continuing problems and losses led to another 20 TDRs being ordered and these were received in September 2006.

Two further problems also limited the number of sets available for deploying the gear monitors. First, the observer coverage in the ETBF was lower than the 5.1% initially expected (often due to lengthy delays between observer trips and boats not willing to

Table 2.1. List of ETBF observer trips on which the project related gear monitors were deployed.

Trip Number	AFMA Voyage-ID	Project Type	AFMA Vessel-ID	Vessel Name	Observer	Port	Departure Date	Return Date
1	595	ECTBF	11539	Rahi Aroha	Andrew Bayne	Mooloolaba	23-Aug-04	03-Sep-04
2	598	ECTBF	11147	Samurai	Dave Penson	Mooloolaba	04-Sep-04	08-Sep-04
3	600	ECTBF	11921	Moon Shadow	Dave Penson	Mooloolaba	16-Sep-04	05-Oct-04
4	599	ECTBF	11787	Demi Maddison	Steve Hall	Mooloolaba	15-Sep-04	20-Sep-04
5	601	ECTBF	11755	Ocean Wanderer	Andrew Bayne	Mooloolaba	19-Sep-04	07-Oct-04
6	602	ECTBF	11787	Demi Maddison	Steve Hall	Mooloolaba	22-Sep-04	27-Sep-04
7	633	LLTORIPL	11672	Esbjorn	Steve Hall	Mooloolaba	15-Oct-04	05-Nov-04
8	621	LLTORIPL	309	Sarah J	Andrew Bayne	Mooloolaba	23-Oct-04	09-Nov-04
9	620	LLTORIPL	11552	Ocean Dawn	Andrew Bayne	Mooloolaba	18-Nov-04	24-Nov-04
10	650	LLTORIPL	11752	Malibu	Steve Hall	Mooloolaba	25-Nov-04	07-Dec-04
11	618	LLTORIPL	11552	Ocean Dawn	Andrew Bayne	Mooloolaba	25-Nov-04	07-Dec-04
12	613	LLTORIPL	12214	Seeker	Andrew Bayne	Mooloolaba	15-Dec-04	21-Dec-04
13	603	ECTBF	11642	Fortuna II	Andrew Bayne	Mooloolaba	27-Dec-04	06-Jan-05
14	605	ECTBF	11787	Demi Maddison	Steve Hall	Mooloolaba	16-Jan-05	18-Jan-05
15	607	LLTORIPL	11787	Demi Maddison	Steve Hall	Mooloolaba	20-Jan-05	24-Jan-05
16	608	LLTORIPL	11787	Demi Maddison	Steve Hall	Mooloolaba	29-Jan-05	06-Feb-05
17	664	LLTORIPL	12221	Megan M	Dave Penson	Mooloolaba	10-Mar-05	17-Mar-05
18	672	LLTORIPL	11642	Fortuna II	Craig Bambling	Mooloolaba	26-Mar-05	05-Apr-05
19	710	LLTORIPL	11102	Samurai	Dave Penson	Mooloolaba	12-Apr-05	19-Apr-05
20	701	LLTORIPL	11678	Ocean Wanderer	Craig Bambling	Mooloolaba	16-Apr-05	25-Apr-05
21	703	LLTORIPL	11895	Blue Mistress	Dave Penson	Mooloolaba	22-Apr-05	30-Apr-05
22	702	LLTORIPL	11678	Ocean Wanderer	Craig Bambling	Mooloolaba	26-Apr-05	03-May-05
23	818	LLTORIPL	11752	Malibu	Craig Bambling	Mooloolaba	12-Jun-05	22-Jun-05
24	815	LLTORIPL	11438	Blue Moves	Dave Penson	Mooloolaba	11-Aug-05	21-Aug-05
25	877	LLTORIPL	11678	Ocean Wanderer	Andrew Bayne	Mooloolaba	08-Aug-05	25-Aug-05
26	1064	ECTBF	12123	Ocean Odyssey	Andrew Bayne	Mooloolaba	08-Sep-05	29-Sep-05
27	829	ECTBF	12510	Mutiara II	Steve Hall	Mooloolaba	22-Sep-05	01-Oct-05
28	836	LLTORIPL	11678	Ocean Wanderer	Andrew Bayne	Mooloolaba	07-Oct-05	29-Oct-05
29	839	LLTORIPL	11678	Ocean Wanderer	Andrew Bayne	Mooloolaba	09-Nov-05	14-Nov-05
30	840	LLTORIPL	1109	Seeker	Andrew Bayne	Mooloolaba	14-Nov-05	16-Nov-05
31	841	LLTORIPL	1109	Seeker	Andrew Bayne	Mooloolaba	19-Nov-05	27-Nov-05
32	851	LLTORIPL	12510	Mutiara II	Steve Hall	Mooloolaba	13-Nov-05	26-Nov-05
33	838	LLTORIPL	11552	Ocean Dawn	Andrew Bayne	Mooloolaba	30-Nov-05	13-Dec-05
34	842	LLTORIPL	11552	Ocean Dawn	Andrew Bayne	Mooloolaba	14-Dec-05	22-Dec-05
35	898	LLTORIPL	11438	Blue Moves	Craig Bambling	Mooloolaba	07-Dec-05	15-Dec-05
36	899	LLTORIPL	11438	Blue Moves	Craig Bambling	Mooloolaba	15-Dec-05	22-Dec-05
37	859	LLTORIPL	11552	Ocean Dawn	Andrew Bayne	Mooloolaba	05-Jan-06	14-Jan-06
38	897	LLTORIPL	11102	Samurai	Craig Bambling	Mooloolaba	09-Jan-06	16-Jan-06
39	905	LLTORIPL	11102	Samurai	Craig Bambling	Mooloolaba	18-Jan-06	26-Jan-06
40	921	ECTBF	11774	Papanui	Craig Bambling	Mooloolaba	31-Jan-06	22-Feb-06
41	916	ECTBF	12179	Esbjorn	Craig Bambling	Mooloolaba	12-Apr-06	19-Apr-06
42	916	ECTBF	12179	Esbjorn	Craig Bambling	Mooloolaba	22-Apr-06	10-May-06
43	945	LLTORIPL	11438	Blue Moves	Craig Bambling	Mooloolaba	18-May-06	27-May-06
44	950	LLTORIPL	123536	Beluga	Craig Bambling	Mooloolaba	26-Jun-06	04-Jul-06
45	971	LLTORIPL	11742	Beluga	Craig Bambling	Mooloolaba	06-Jul-06	17-Jul-06
46	965	ECTBF	11147	Samurai	Nathan Bicknell	Mooloolaba	24-Jul-06	01-Aug-06
47	1021	ECTBF	281	Fortuna II	Nathan Bicknell	Mooloolaba	04-Oct-06	14-Oct-06
48	1036	ECTBF	12400	Tiwi Pearl	Craig Bambling	Brisbane	06-Nov-06	19-Nov-06
49	1047	ECTBF	6976	Star Trek	Craig Bambling	Mooloolaba	21-Nov-06	15-Dec-06
50	1065	ECTBF	12029	Straight Shooter	Matt Preston	Mooloolaba	13-Apr-07	23-Apr-07
51	1063	ECTBF	11523	Teepookana	Matt Preston	Mooloolaba	30-Apr-07	07-May-07
52	1066	ECTBF	11895	Blue Mistress	Matt Preston	Mooloolaba	21-May-07	30-May-07

take observers). Furthermore, during the winter SBT season most of the observers were required to be on vessels with SBT quota and as these vessels operated in the southern part of the fishery, and outside the project region. It was not possible to complete the monitoring during these periods. Second, due to poor economic returns from the fishery in recent years, there has been a significant decrease in the number of vessels and the number of longline sets in the fishery. Hence, it took longer than anticipated to achieve the necessary number of deployments and coverage.

Table 2.2. Listing of number of sets monitored per trip, the number sets where TDRs and Hook-Timers were deployed, and the number of

		TDR Sets			TDR Deployments				
Trip Number	Total Sets	TDR Sets	Deploy Data	TDR Data	TDRs Deployed	Deploy Data	TDR Data	HookTimer Sets	HTs Triggered
1	5	0	0	0	0	0	0	4	14
2	4	0	0	0	0	0	0	4	18
3	12	0	0	0	0	0	0	7	14
4	4	4	4	4	52	52	51	4	29
5	10	10	10	10	120	120	109	10	47
6	3	3	3	3	39	39	39	3	8
7	12	9	9	9	106	106	102	0	0
8	8	8	8	8	88	88	88	7	31
9	2	1	1	1	11	11	11	2	9
10	9	7	7	4	77	77	44	7	21
11	6	6	6	6	61	61	60	4	12
12	5	0	0	0	0	0	0	0	0
13	7	7	7	7	64	64	62	0	0
14	1	1	1	0	11	11	0	1	7
15	4	0	0	0	0	0	0	4	17
16	4	0	0	0	0	0	0	4	13
17	3	0	0	0	0	0	0	0	0
18	8	8	8	8	60	60	50	8	22
19	6	4	0	4	21	0	21	0	0
20	6	6	6	6	57	57	43	6	11
21	6	6	6	0	37	37	0	0	0
22	4	4	4	4	24	24	17	3	6
23	6	0	0	0	0	0	0	4	15
24	6	1	1	1	8	8	7	6	18
25	11	11	11	11	97	97	77	9	42
26	11	11	11	11	99	99	99	10	16
27	7	5	5	5	45	45	45	0	0
28	12	12	12	12	108	108	108	10	19
29	3	2	2	2	24	24	24	2	3
30	1	1	1	1	12	12	12	1	2
31	6	5	5	5	60	60	60	5	22
32	6	1	1	1	6	6	5	0	0
33	7	6	6	6	71	71	70	5	14
34	3	2	2	2	22	22	22	2	5
35	6	6	6	6	43	43	38	0	0
36	6	6	6	6	31	31	30	0	0
37	5	4	4	4	44	44	44	3	10
38	5	6	6	6	37	37	36	0	0
39	5	3	3	3	18	18	18	3	5
40	14	14	14	14	84	84	83	10	22
41	2	2	2	2	12	12	12	0	0
42	12	12	12	12	69	69	68	12	96
43	6	6	6	6	29	29	29	6	27
44	7	6	6	6	30	30	30	7	13
45	9	9	9	9	45	45	45	9	41
46	6	6	6	6	29	29	29	6	7
47	2	2	2	2	10	10	8	0	0
48	7	7	7	7	58	58	58	7	25
49	13	13	6	13	169	78	169	0	0
50	6	6	6	6	53	53	53	6	2
51	6	5	5	5	44	44	44	0	0
52	4	4	4	4	31	31	30	0	0
# Trips	52	44	43	42	44	43	42	36	36
Total	329	258	247	248	2216	2104	2050	201	683

2.3 Data Status

Not all of the 2216 TDR deployments resulted in usable data. Apart from the loss of several TDRs either whilst deployed or during the hauling process, as already noted many of the TDRs also failed and/or data was not able to be retrieved from the monitor. Furthermore, for the data to be used in the subsequent analyses some auxiliary data needed to be collected by the observer. In particular, details of the hook-number and the gear configuration of the longline (i.e. the number of hooks-per-float, HPF) were required, as the position of the hook on the longline has a bearing on the depths fished by the hooks. To facilitate the collection of this data an additional observer form was created and distributed to the observers before each trip (see Appendix A). Unfortunately, there were 11 sets for which this data was not collected and therefore the data associated with the related 112 TDR deployments could not be analysed as planned.

Of the 2216 TDR recordings, associated data on the deployment of the TDRs (i.e. hook-position and gear configuration) was collected for 2104 recordings, and data retrieved from the TDR for 2050 recordings. There were also occasions where there was deployment data but no TDR data and vice versa. A summary of the overall status of the TDR data collected is provided in Table 2.3. Of the 2104 recordings accompanied by the necessary observer, no TDR data were retrieved from 166 recordings, the TDR data was retrieved but erroneous for 6 recordings, retrieved but incomplete (data terminated before haul commenced) for 3 recordings. This resulted in a total of 1929 recordings with usable TDR data. For these latter recordings, there were 155 occasions when the TDR did not begin recording until after the unit had been deployed and was sinking, leaving 1774 recordings for which the recording started before deployment.

Table 2.3 Summary of the overall status of the TDR data collected.

Recording Status	Deployment data	# TDRs Deployed	# TDRs Records	Overall Status
Start Above	Yes	1774	1774	OK
	No		111	
Start Below	Yes	155	155	OK
	No		1	
Bad Recording	Yes	6	6	
No Haul	Yes	3	3	
No Recording	Yes	166		
Total		2104	2050	1929

Of the thousands of HTs which were deployed during the project 683 were triggered upon retrieval, with 385 (56%) of these being associated with the catch of a fish (note, HTs often are retrieved in a triggered state believed due to either the fish escaping from the hook or the fish taking the bait but not being hooked).

2.4 Data Coverage

2.4.1 Coverage Rate

The ETBF observer program, which commenced in July 2003, had a stated coverage rate of 5.1% of annual effort (hooks deployed). Eight observers were to be deployed within as part of the ETBF observer program and in preparatory discussions with AFMA two observers at any one time were to be assigned to this project. As such, the anticipated observer coverage level for the project was 1.275%. Given that around 12,000 sets were deployed in the ETBF during 2003, it was expected that information would be gathered from approximately 150 longline sets (155,000 hooks) per year.

Table 2.4 (a) Number of trips, longline sets and hooks monitored by observers during six-monthly periods (both trips deploying TDRs and total observed trip) together with the total number of trips, sets and hooks deployed in the ETBF, (b) monitored trips, sets and hooks as a percentage of the ETBF totals.

(a)	TRIPS			SETS			HOOKS		
Period	TDR	OBS	TOTAL	TDR	OBS	TOTAL	TDR	OBS	TOTAL
04_2	13	46	948	87	156	3,304	93,479	157,562	3,093,544
05_1	10	68	1,317	48	207	4,664	51,067	214,934	4,545,385
05_2	13	115	1,128	85	365	4,421	107,042	345,957	4,351,368
06_1	8	56	1,012	56	234	4,054	75,620	234,677	4,327,569
06_2	5	88	836	37	278	3,672	51,167	270,829	4,537,455
07_1	3	19	666	16	88	2,826	28,686	103,450	3,362,985
Overall	52	392	5,907	329	1,328	22,941	407,061	1,327,409	24,218,306

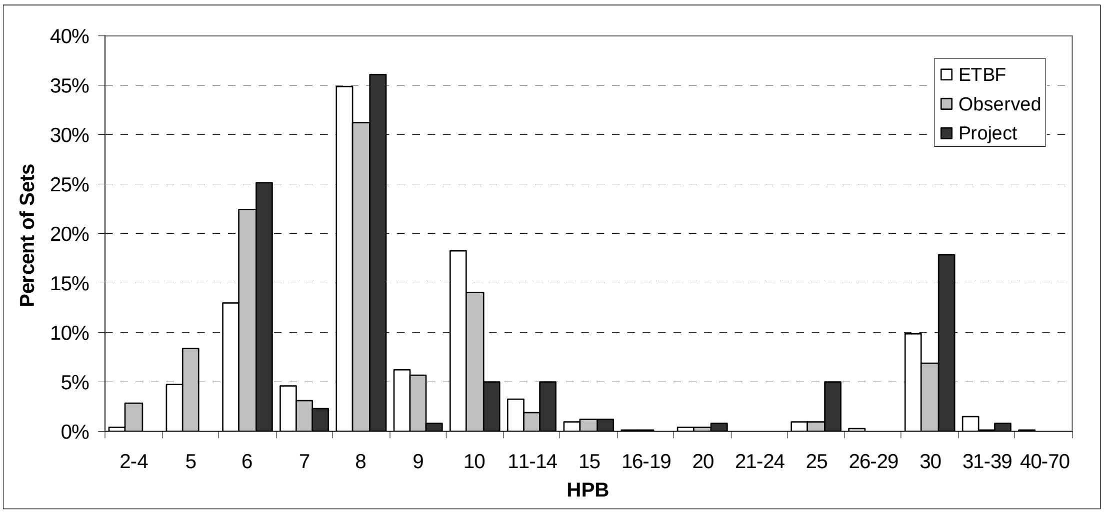
(b)	TRIPS			SETS			HOOKS		
Period	TDR	OBS	TOTAL	TDR	OBS	TOTAL	TDR	OBS	TOTAL
04_2	1.4%	4.9%		2.6%	4.7%		3.0%	5.1%	
05_1	0.8%	5.2%		1.0%	4.4%		1.1%	4.7%	
05_2	1.2%	10.2%		1.9%	8.3%		2.5%	8.0%	
06_1	0.8%	5.5%		1.4%	5.8%		1.7%	5.4%	
06_2	0.6%	10.5%		1.0%	7.6%		1.1%	6.0%	
07_1	0.5%	2.9%		0.6%	3.1%		0.9%	3.1%	
Overall	0.9%	6.6%		1.4%	5.8%		1.7%	5.5%	

A summary of the actual observer coverage achieved during each six-month period between the commencement (23 August 2005) and finish (21 May 2007) of the project is given in Table 2.4. The number of trips undertaken by observers related to this project varied between 3 and 13 during any period, whilst the number of sets varied between 16 and 87. These represented between 6% and 28% of all observed trips during any period and 18% and 55% of all observed sets during any period. Over the entire 33 month period that observers deployed the gear monitors, project trips and sets represented 13% and 25% of all observed trips and sets respectively. Whilst the percentage of project trips observed varied between 0.5% and 1.4% of all trips within the ETBF within a given period, the coverage rate of deployed effort (hooks) varied between 0.9% and 3.0%, with a mean of 1.7% over the entire period. This was greater than the 1.27% planned for in the original project design. Furthermore, whilst the coverage rate decreased in the latter half of the project, the total number of hooks observed during the project (407,000) exceeded the 310,000 in the original project design.

2.4.2 Gear Configurations

During the 33 month period of the project, AFMA logbook data indicated that 39 different HPF gear configurations were deployed by vessels operating across the entire ETBF. Of these operations, AFMA observers during this time observed the deployment of 19 different gear configurations and 15 different configurations on project-related trips. A comparison of the percent of all sets deploying each gear configuration across each type of set is shown in Figure 2.1. For all ETBF operations, seven different gear configurations accounted for around 92% of all sets, with 8 HPF being the most commonly deployed and accounting for around one-third of all sets followed, in order of decreasing use, by 10, 6, 30, 9, 5 and 7 HPF. Gear configurations with 6 and 30 HPF were over-represented in the project-specific observer data (26% versus 9% and 19% versus 10% respectively) while gear configurations with 9, 10 and 5 HPF were relatively under-represented in the project-specific data (1% versus 6%, 5% versus 18% and 0% versus 5% respectively). A chi-squared test indicated that both

Figure 2.1 Percentage of (a) all ETBF sets, (b) all observed sets, and (c) all sets monitored with TDRs during the project, deploying a given hook-per-basket configuration.



the observer and project-specific coverage of sets using different HPF configurations were significantly different (P<0.01) in their distributions to that within the entire ETBF.

The number of sets, stratified by gear configuration (hooks-per-float) and quarter, on which TDRs were deployed by the project is displayed in Table 2.5 whilst the percentage of (a) all ETBF sets, (b) all observed sets, and (c) all sets monitored with TDRs during the project, deploying a given hook-per-basket configuration within each six-monthly period of the project is shown in Figure 2.2. For project-related sets, there is seen to be a shift away for observing sets with less than 12 HPF and towards sets deploying more than 12 HPF. Indeed, only 6 (3.9%) of the 153 sets observed before 2006 had a gear configuration using more than 12 HPF, whilst after this time 62 (59%) of the 105 sets had such a gear configuration. Of the 54 sets observed during the last year of the project, more than half were sets deploying 30 HPF.

2.4.3 Hook Numbers

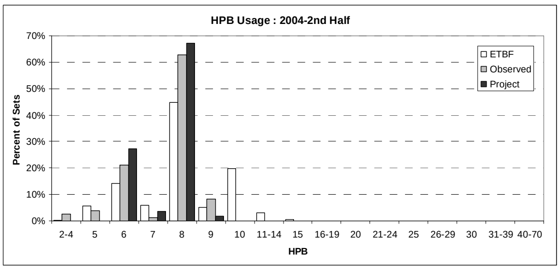
For this project each observer was requested to record the hook-number that each TDR was attached. The hook-number is the number of the branchline after the previous float. For example, the first branchline after the float has hook-number 1 and the last branchline has hook-number *N* where *N* is the number of hooks-between-floats. A listing of the number of TDRs attached to each hook-number within each observed gear configuration for the 2040 TDRs from which a usable data recording was retrieved is shown in Table 2.6 and Figure 2.2. Of the 248 sets from which TDR data was obtained, it is apparent that for many gear configurations the number of observed sets is not large (sometimes only 1) with usable TDR data from more than 10 sets only available for four different gear configurations (6, 8, 25 and 30 HPF), with these accounting for 214 (86%) of the 248 TDR-related sets.

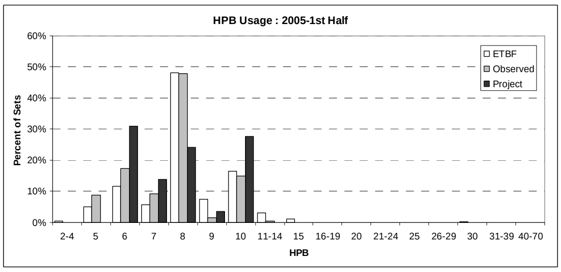
Unfortunately, for 321 TDR deployments the hook-number was not recorded and so these data could not be used in the subsequent analyses. Fortunately, however, the two gear configurations where this occurred (6 and 8 HPF) were also those from which the

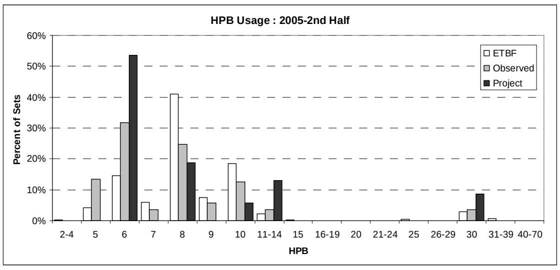
Table 2.5 Number of sets, stratified by gear configuration (hooks-per-float) and quarter, on which TDRs were deployed by the project.

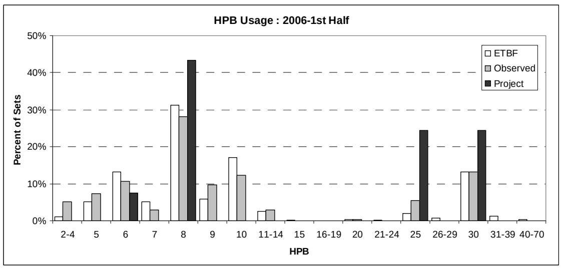
		2004		2005				2006				2007	
HPF	Total	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2
6	65	8	7		9	11	26	4					
7	6		2	3	1								
8	93	7	26	6	5	11	2	23			13		
9	2		1	1									
10	13				8		4						1
11	8						8						
12	3					1							2
13	1												1
14	1												1
15	3									3			
20	2												2
25	13								13				
30	46					5	1		11	14	7		8
32	1										1		
35	1										1		
Total	258	15	36	10	23	28	41	27	24	17	22	0	15

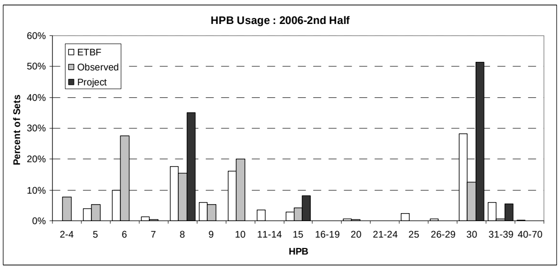
Figure 2.2. Percentage of (a) all ETBF sets, (b) all observed sets, and (c) all sets monitored with TDRs during the project, deploying a given hook-per-basket configuration within each six-monthly period of the project.











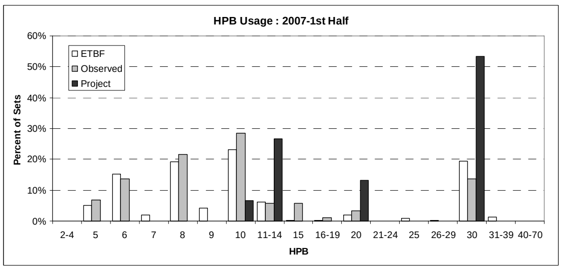


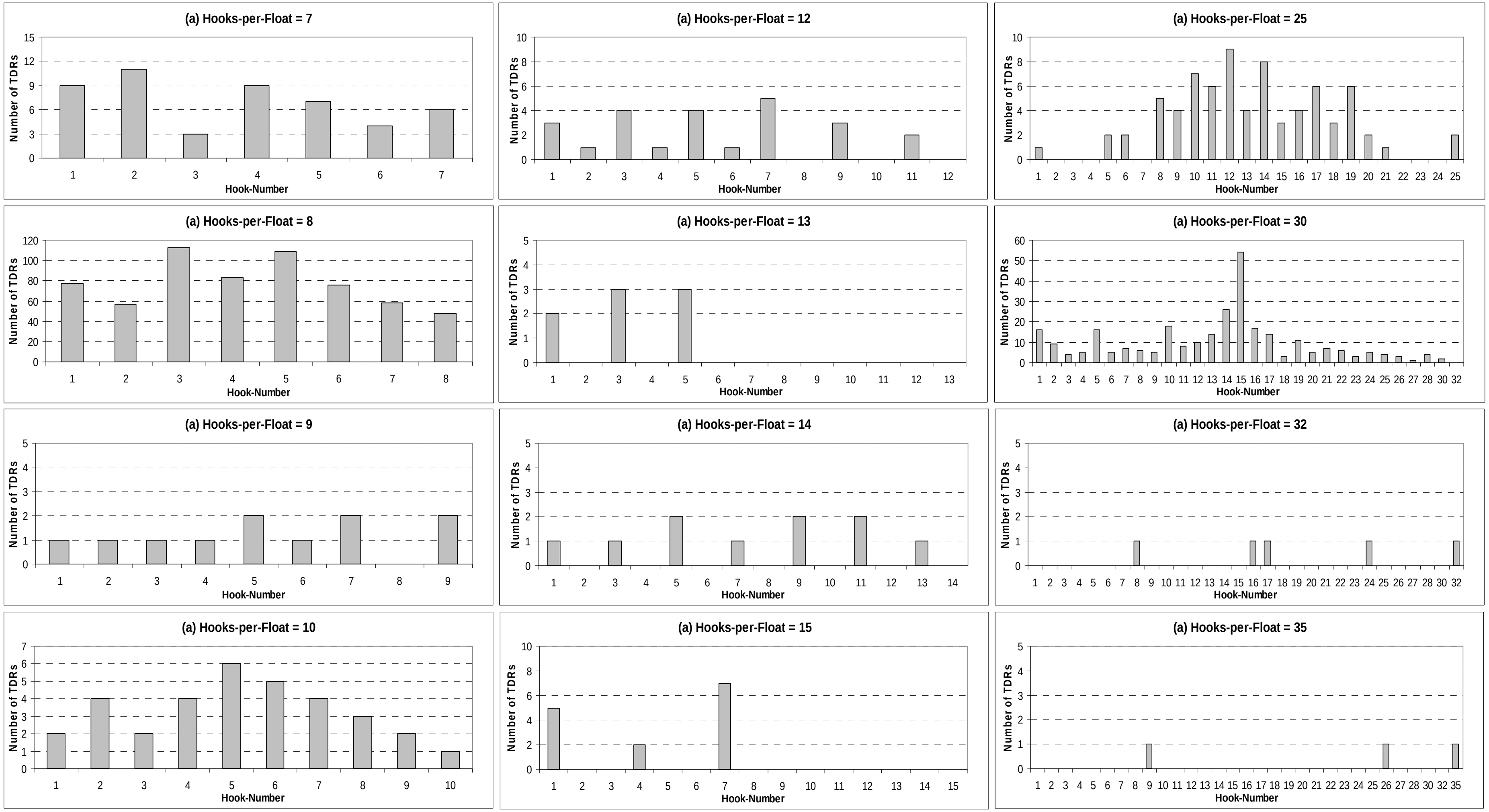
Table 2.6 Distribution of TDRs from which usable data was attained across the different hook-numbers within each observed gear configuration. (Note, ns = not specified and HN = hook number).

Hook Number	Gear Configuration (Number of Hooks-per_Float)															
	6	7	8	9	10	11	12	13	14	15	20	25	30	32	35	Total
1	88	9	77	1	2	1	3	2	1	5	4	1	16	0	0	
2	85	11	57	1	4	3	1	0	0	0	0	0	9	0	0	
3	83	3	113	1	2	3	4	3	1	0	5	0	4	0	0	
4	96	9	83	1	4	9	1	0	0	2	0	0	5	0	0	
5	73	7	109	2	6	6	4	3	2	0	3	2	16	0	0	
6	81	4	76	1	5	5	1	0	0	0	0	2	5	0	0	
7		6	58	2	4	5	5	0	1	7	5	0	7	0	0	
8			48	0	3	6	0	0	0	0	0	5	6	1	0	
9				2	2	2	3	0	2	0	5	4	5	0	1	
10					1	6	0	0	0	0	0	7	18	0	0	
11						4	2	0	2	0	0	6	8	0	0	
12							0	0	0	0	0	9	10	0	0	
13								0	1	0	0	4	14	0	0	
14									0	0	0	8	26	0	0	
15										0	0	3	54	0	0	
16											0	4	17	1	0	
17											0	6	14	1	0	
18											0	3	3	0	0	
19											0	6	11	0	0	
20											0	2	5	0	0	
21												1	7	0	0	
22												0	6	0	0	
23												0	3	0	0	
24												0	5	1	0	
25												2	4	0	0	
26													3	0	1	
27													1	0	0	
28													4	0	0	
30													2	0	0	
32														1	0	
35															1	
ns	109		212													321
Total	615	49	833	11	33	50	24	8	10	14	22	75	288	5	3	2040
With HN	506	49	621	11	33	50	24	8	10	14	22	75	288	5	3	1719
No. Sets	65	6	90	1	7	8	3	1	1	3	2	13	46	1	1	248
With HN	55	6	71	1	7	8	3	1	1	3	2	13	46	1	1	219
Sampled HNs	6	7	8	8	10	11	9	3	7	3	5	18	29	5	3	

greatest number of recordings had been collected, and as the usable number of TDR recordings for these two configurations still remained over 500 (with a good distribution across all hook-numbers) this loss did not have a significant impact on the analyses undertaken. This left a total of 1719 TDR recordings from 219 different longline sets for which complete deployment information was also available.

From Figure 2.2 it is seen that while the aggregate distribution of TDRs across each hook-number was relatively uniform for gear configurations deploying 6 HPF this was usually not the case. First, there was a preference to place TDRs on the hooks near the centre of the basket, though the hook-position closest to the float was observed for all gear configurations. Second, for gear configurations where the number of TDR sets was small not all hook-numbers had a TDR observation. Of the 15 gear configurations observed, all hook-numbers were sampled by TDRs for only five configurations (where HPF=6, 7, 8, 10, 11) whilst 75% or more hook-numbers were observed for four configurations (HPF=9, 12, 25, 30) and 50% were observed for a single configuration (HPF=14). For the other 5 gear configurations (HPF=13, 15, 20, 32, 35) the number of observed hook-numbers was less than 25%.

Figure 2.2 Number of TDRs attached at each hook-number within each gear configuration from which useful data was retrieved.



2.4.4 Spatial Coverage

All observed trips deploying the gear monitors commenced from the port of Mooloolaba. This is despite one set of gear monitors being re-deployed in early 2006 to an observer undertaking trips off southern NSW. However, due to a combination of bad weather, a general lack of fishing due to the low availability of fish, and the fact that few vessels now remain fishing in this region no observer trips were undertaken. Given the small number of vessels which now remain fishing in both the southern and northern sector of the fishery (eg operating out of Cairns) it was considered prudent to continue to deploy the gear monitors on vessels operating out of the ports in the central (eg Mooloolaba) region for the life of the project.

The spatial locations of the 242 sets from which usable TDR data were retrieved are shown in Figure 2.3. In that the sets range across the inshore to offshore regions of the main Mooloolaba grounds and the new albacore grounds, the coverage is seen to be reasonably representative across the central fishing regions of the ETBF. The locations

Figure 2.3 Start-set positions of longline sets deploying TDRs within the ETBF.

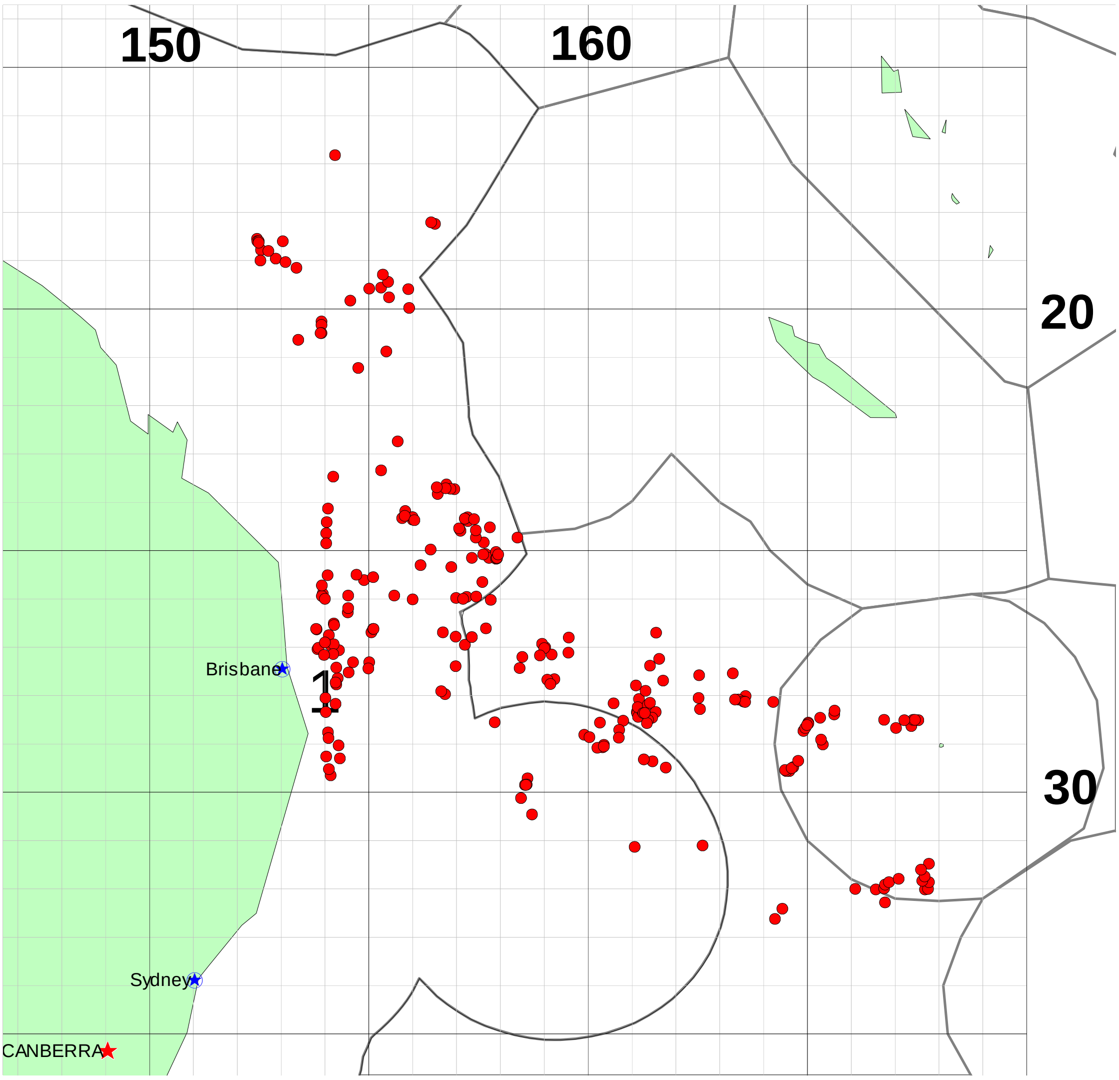
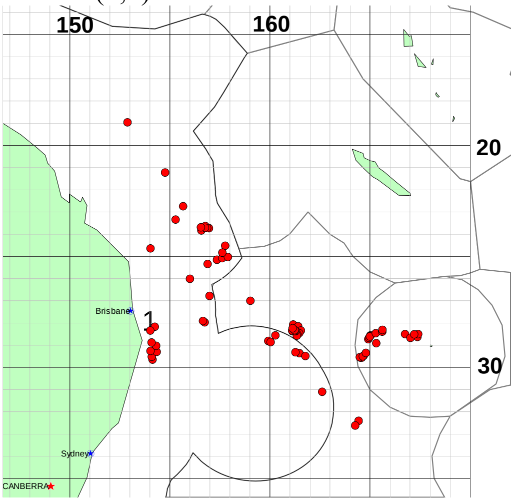
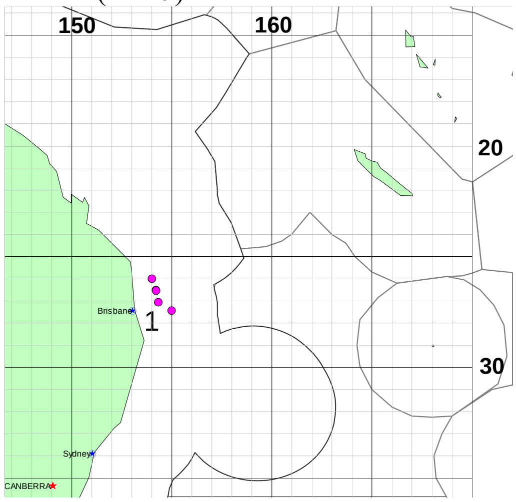


Figure 2.4 Positions of sets stratified by HPF configurations.

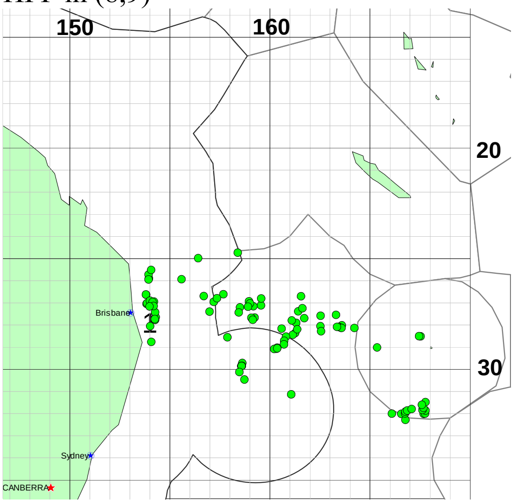
HPF in (6,7)



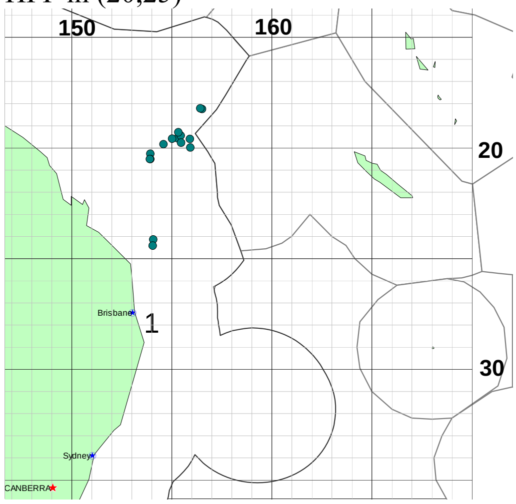
HPF in (12-15)



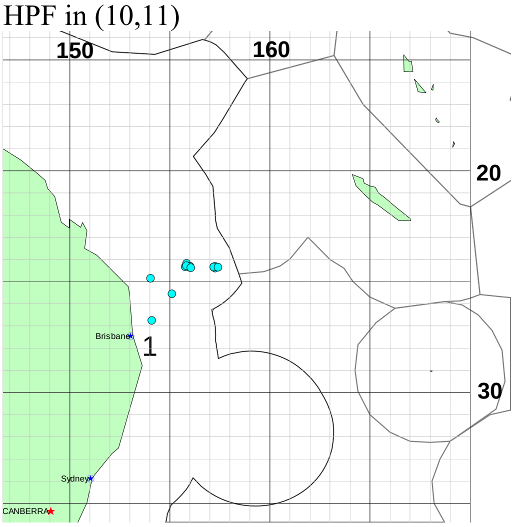
HPF in (8,9)



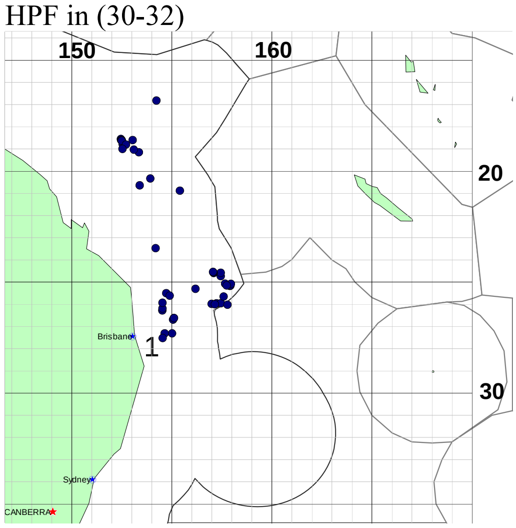
HPF in (20,25)



HPF in (10,11)



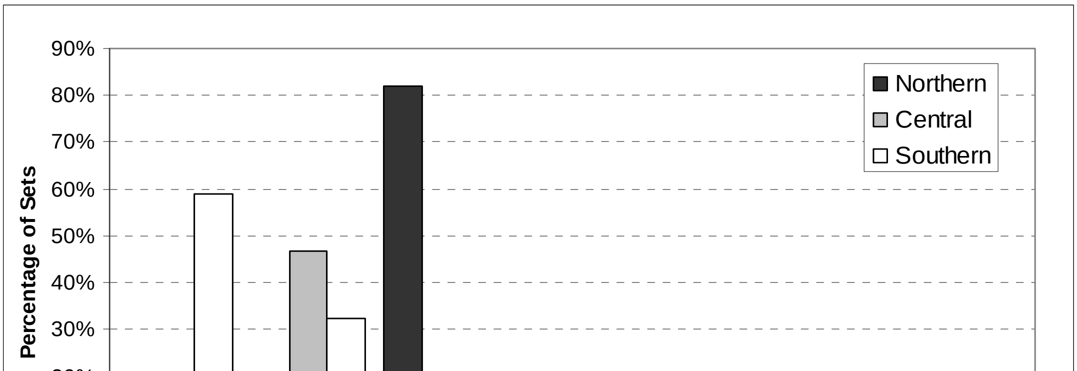
HPF in (30-32)



of the sets stratified by HPF are shown in Figure 2.4. All except one set north of 20°S deployed 20 or more HPF and this is consistent with vessels setting deep longlines whilst targeting albacore tuna in this region. Sets deploying 30 or more HPF are distributed quite broadly within the AFZ and again are consistent with the more recent targeting of albacore off-shore of Brisbane as well as further north in the Albacore Box.

The consequences of the lack of monitoring north and south of the central ETBF region can be ascertained from Figure 2.5 which displays the percentage of all sets within three regions of the ETBF during the duration of the project deploying different HPF configurations. The central region is bounded by those latitudes encompassing the monitored fishing operations (18-33°S, c.f. Figure 2.3) whilst the northern region is defined as the area of the ETBF north of 18°S and the southern region is defined as that area south of 33°S. The number of sets deployed within the northern, central and southern regions was 2838, 17,463 and 2,818 respectively. Whilst a range of gear configurations were deployed in all three regions, in the southern region most sets deployed 6 or fewer HPF (59%) whilst in the central region only 14% of sets used these gear configurations and no sets in the northern region. These observations coincide with a greater targeting of yellowfin tuna (and the associated use of shallower sets) in the southern inshore region of the ETBF. On the other hand, in the northern region most sets (82%) deployed 9 or 10 HPF while the use of such gears in the central and southern regions was 18% and 5% respectively. In both the northern and central regions around 11-13% of sets deployed 30 or more HPF whilst in the southern region only 1% of sets used such gear configurations. This coincides with the general lack of sets targeting albacore in the southern region. As the range of gears monitored in the central region cover those used in the northern region the results of this project should also be applicable to this region (unless there are other aspects in the manner in which the longlines are deployed between the two regions which result in the hooks attaining different depths). On the other hand, as there was no monitoring of sets deploying 5 HPF the results may be cover the 25% of sets using such gear configurations in the southern region of the fishery.

Figure 2.5 Percentage of all sets within three defined regions of the ETBF during the duration of the project deploying different HPF configurations. (NS= not specified).



2.4.5 Day-Night Sets

Information recorded by the observers on the start-times and end-times of deploying and hauling the hooks was used to estimate the number of hooks in the water during each hour for each set. Hooks were assumed to enter the water at a uniform rate between the start-deployment and end-deployment times and leave the water at a uniform rate between the start-haul and end-haul times. The number of hooks in the water during each hour was then summed to give the total hook-hours for the set. The proportion, P, of the total hook-hours within each of the following defined Day and Night periods was then calculated:

- Day (6am to 6pm)
- Night (6pm to 6am)

A scatter plot the proportion of the total hook-hours that occurred during the day for each set versus the start hour of the set is shown in Figure 2.6a. The majority of the sets started deployment between 2pm and 8 pm (61%) with the second most common time being between 4am and 8am (26%). Each set was then associated with one of the following three set types based on the proportion of the hook-hours occurring during the day:

1) Day-set ($P>0.66$)
2) Night set ($P<0.33$)
3) Combined set ($0.33< P <0.66$)

The proportion of all sets within each set-type stratified by gear configuration is shown in Figure 2.6b. For all sets analysed (255), the majority (46.7%) were classified as night sets, with 27.5% classified as day sets and 25.9% classified as combined sets. Only 11 (5.7%) of the 192 sets deployed with 15 HPF or less were classified as day sets, while no sets deploying 20 HPF or more were classified as night sets. As noted above with differences in the percentage of sets in each of the three regions deploying given gear settings, there are also some differences in the percentage of sets deployed at given times (cf. Figure 2.7). In particular, the majority of sets in the southern and northern regions are deployed on the morning (i.e. deployed before noon) and is likely to coincide with the greater targeting of yellowfin and bigeye tunas in this regions compared to the greater targeting of swordfish in the central region.

Figure 2.6 (a) Percent of total hook-hours occurring during the day for each set, and (b) the proportion of all sets within each set-type stratified by gear configuration (HPF). The line shown in (a) displays the mean percentage for each hour.

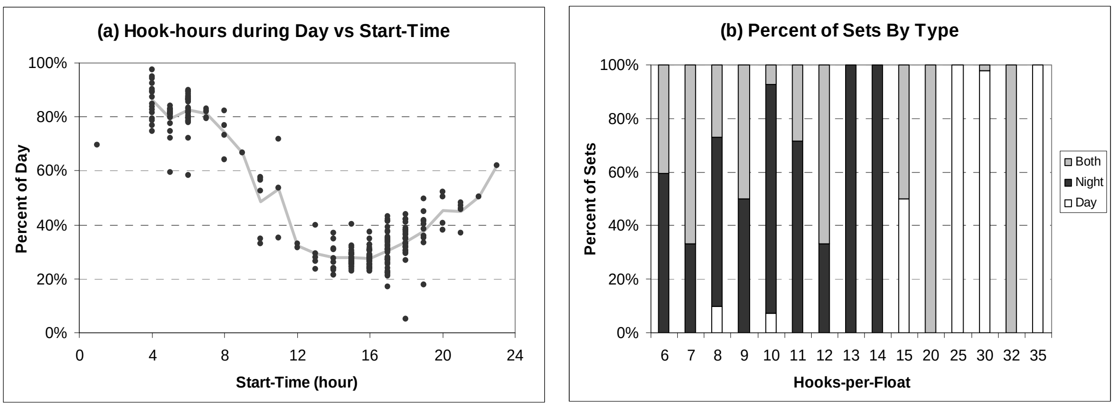
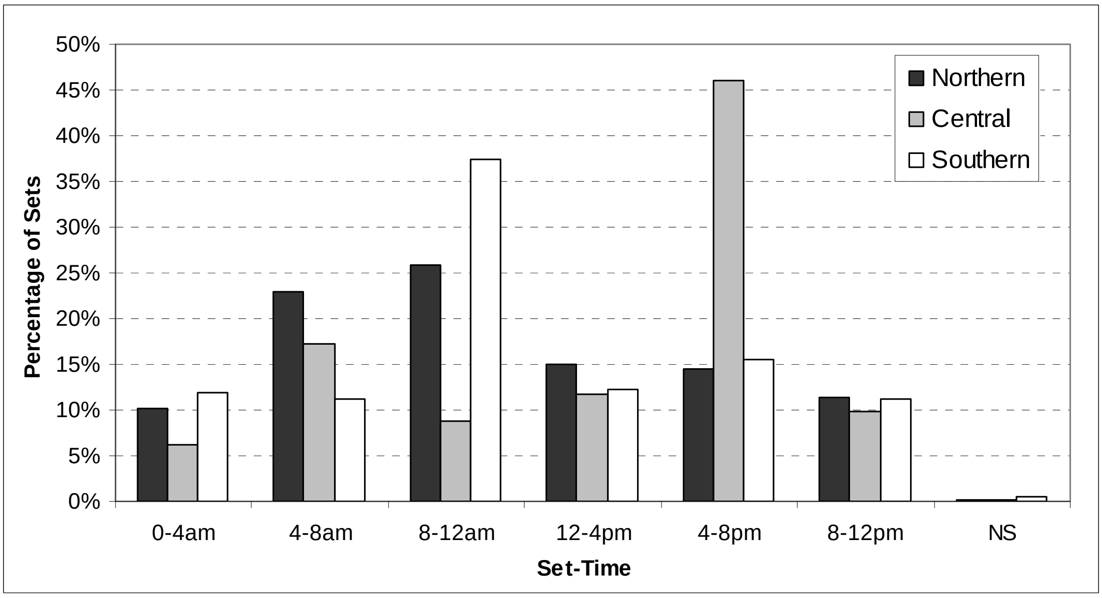


Figure 2.7 Percent of sets in each of the three regions defined in the text stratified by set-time. (NS= not specified).



2.5 Management of Project Data

2.5.1 TDR and HT data

For ease of data manipulation and to aid analysis of the data, a series of five database tables were created to store the TDR and HT data within the Pelagic ORACLE Database maintained by CMAR in Hobart. The structure of these tables is detailed in Appendix B.

A FORTRAN program was written in order to facilitate transfer of the data from the TDR format to the database tables. This program also identified the following three periods in the deployment of each TDR: 1) sinking, 2) fishing, and 3) hauling. In order to make data storage efficient, temperature and depth readings were stored at a minimum of every two minute intervals during the "fishing period" whilst every data record was stored for the sinking and hauling periods. A summary of the time-interval between measurements for the 2050 TDR from which data was retrieved, and the time-interval between data stored in the database in given in Table 2.5. The total number of individual depth-temperature records stored in the database was 790,644.

Table 2.5 Listing of the number of TDRs deployed against the time-interval between measurements for the 2050 TDR from which data was retrieved, and the time-interval between data stored in the database.

Time Interval (min)	No. TDRs	Interval between measurements in database		
		Sinking	Fishing	Hauling
0.5	236	0.5	2	0.5
1	235	1	2	1
2	707	2	2	2
3	872	3	3	3
	2050			

2.5.2 AFMA Observer data

AFMA observers collect an extensive set of data detailing the gears used and the catch for each observed set. A full description of the data collected, and the manner in which it is collected, is provided in the manual provided to observers (Westlake 2006). In order to relate the data collected by the TDRs and HTs to the observer data for each associated set a copy of all observer data for ETBF longline vessels was obtained from AFMA and stored in the Pelagic Database. Unfortunately there were considerable delays in the provision of this data from AFMA and for several trips the complete data required for the analysis was not obtained. No data were available for one trip consisting of 6 sets.

As part of related projects, CSIRO have been working closely with the AFMA data centre to resolve these issues (in process and AFMA data structure) so that these delays can be avoided in the future and the AFMA data structures and systems for the various ETBF data sources are efficient, timely and provide secure long-term maintenance of these important data sets.

Section 3: Description of Depths and Temperatures fished by Longline Gears

3.1 Definition of Hook-Deployment Periods

In this section we provide a detailed summary of the depths fished by the monitored longline gears and investigate some of the factors that influence them. A more detailed examination of the depths at which fish are caught by the hooks is given in Section 4.

For the purposes of analyzing the TDR data, the deployment of each monitor was stratified into the following three periods:

a) the period the TDR took to sink to its initial fishing depth,
b) the period the TDR took to be hauled,
c) the period the TDR was "fishing" (i.e. not sinking or being hauled).

Each of these three periods will mimic similar behaviour for each hook deployed. It is important to separately identify each of these three periods so that the actual fishing depths attained by the TDR can be correctly indentified. It needs to be noted, however, that the longline has the potential to catch fish for the entire duration that hooks are in the water (i.e. during the sinking and hauling periods as well as the "fishing" period defined above).

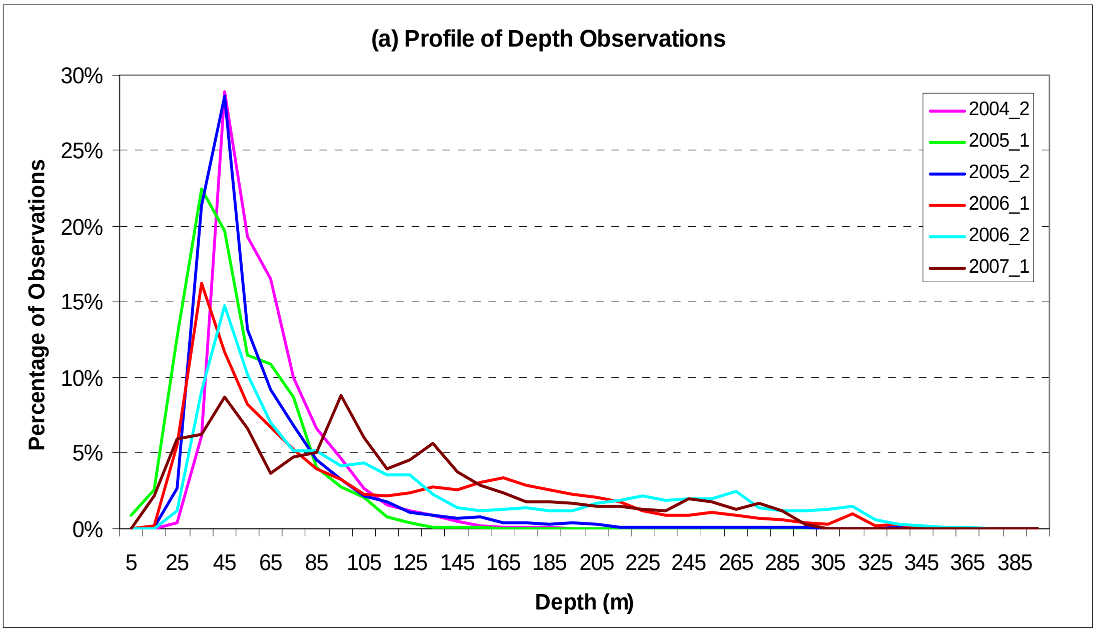
After deployment, a TDR was considered to be sinking when each consecutive depth reading was greater than the previous. Identifying the start of the haul was more difficult, however, due to the fact that there can be large changes in depths of the TDR whilst "fishing". The method adopted was based on identifying the sequence of large changes in depth (decreases due to the line being pulled when hauled, and possible increases when the line may sink again due to processing delays) working back from the time that the TDR was retrieved. A FORTRAN program was written to read the data from each TDR deployment and to identify each of these periods. At the same time, the average depth and temperature was then calculated for the period the TDR was "fishing".

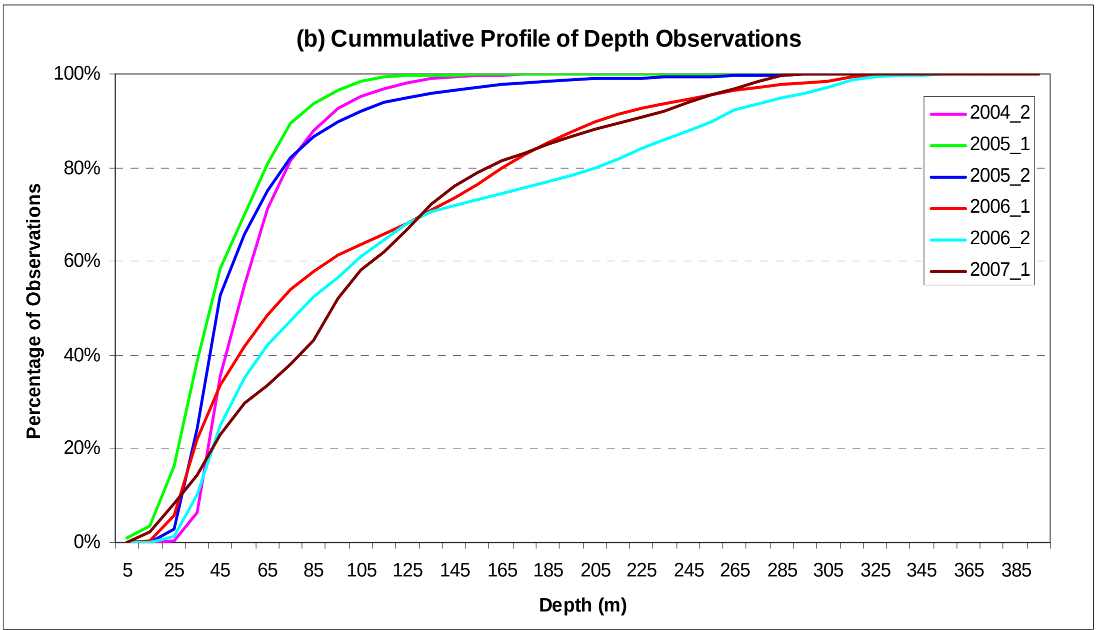
3.2 Aggregate Fishing Depth and Temperature Profiles

3.2.1 Overall Observations

The aggregate time-at-depth profiles combining all the 1924 usable TDR recordings (c.f. Table 2.3) are shown in Figures 3.1a-b. The six profiles shown in each figure are based on the observations recorded during each of the different six monthly sampling periods. The pre-2006 depth profiles display a similar pattern with nearly all hooks fishing above 120m, whilst the 2006 and 2007 profiles show that, on average, hooks spent a significant proportion of their time fishing at depths down to 300m or more (with the deepest recorded depth being 397m). This change is quite dramatic and is related to the increased targeting of albacore tuna by vessels in the fishery and the concomitant setting of deeper longlines (using 20-40 HPF). On the other hand, during all periods hooks spent little time in depths less than 20m. The cumulative plots indicate that of the sets observed in 2004 the hooks spent 50% of the time at depths less than 60 meters and only 5% of the time at depths greater than 100 meters. During both periods of 2005 hooks spent 50% of the time at depths less than 50 meters and

Figure 3.1. (a) Time-at-depth profiles and (b) cumulative profiles of fishing depths attained by hooks recorded by TDRs for sets monitored during each six month period of the year shown (1=Jan-Jun, 2=July-Dec).

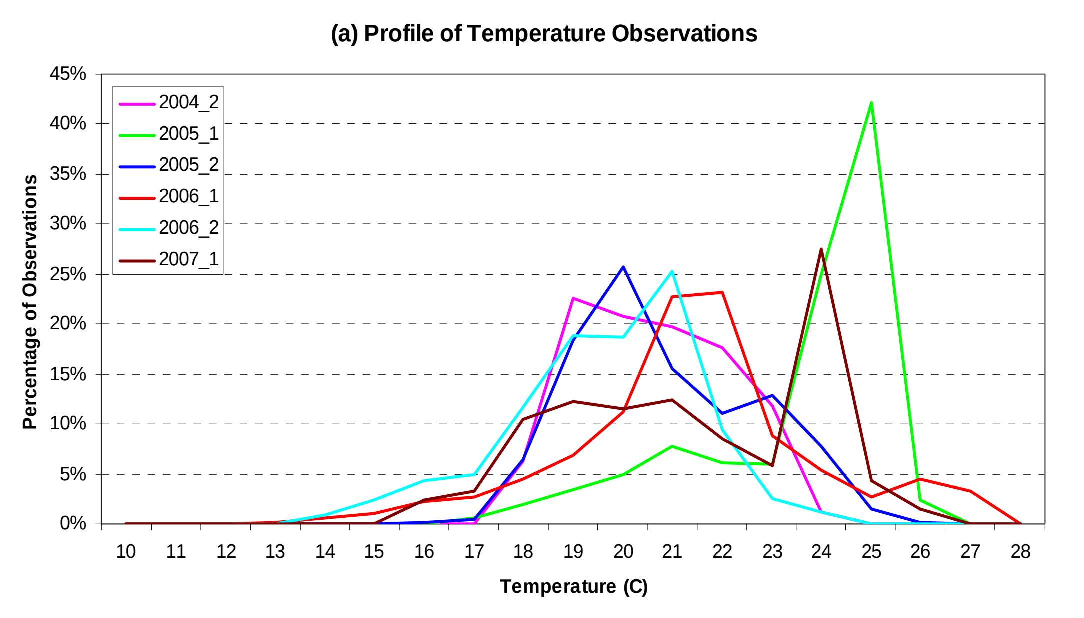


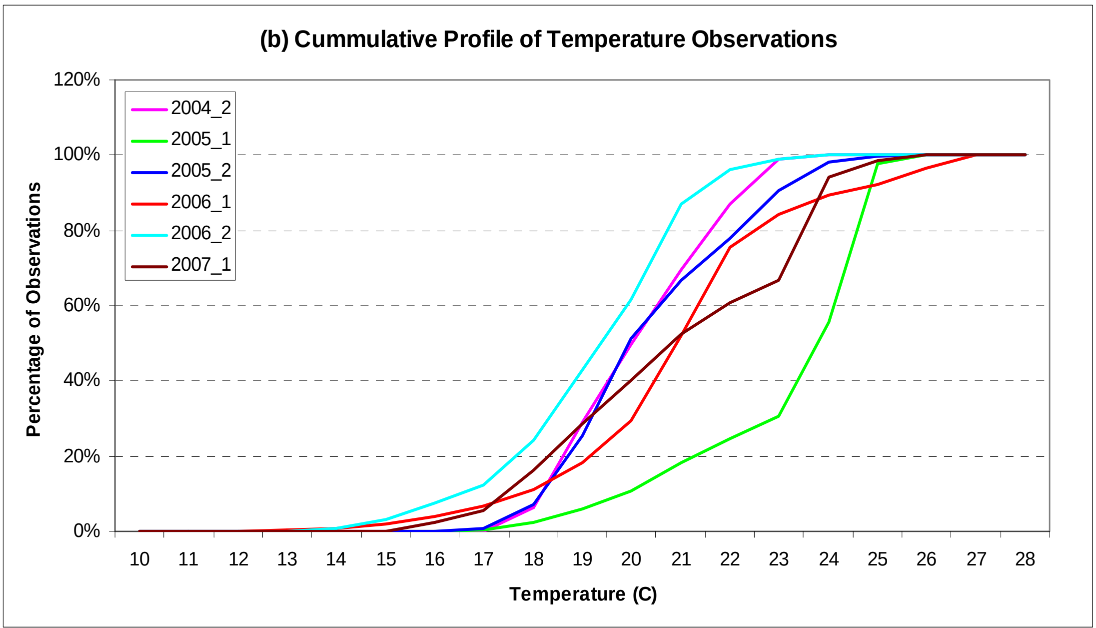


only 2% and 8% of the time at depths greater than 100 meters. Over the remaining three periods this changed considerably, with hooks spending 50% of the time at depths less than 80 m, 90 m and 100m respectively and greater than 100 m for 36-42% of the time.

Similar time-at-temperature profiles of the water temperatures fished by hooks recorded by TDRs for sets monitored during each period are shown in Figure 3.2. The six profiles display more seasonal changes than that observed for the depth profiles, indicating that there were significant changes in the temperature-at-depth between seasons. For example, the hooks spent a greater proportion of time in relatively higher

Figure 3.2. (a) Time-at-temperature profiles and (b) cumulative profiles of water temperatures fished by hooks recorded by TDRs for sets monitored during each six month period of the year shown (1=Jan-Jun, 2=July-Dec).





temperatures during the first half of 2005 compared to the second half of the year despite the fact that the profiles of hooks-at-depth were similar. For hooks monitored in 2005 the most common water temperatures fished were 19-23^{o}C (accounting for 92% of all time-at-temperature) whilst over successive periods this time spent in this temperature range was 28%, 83%, 73%, 75% and 50% respectively. Before 2006, the time spent within water temperature 18^{o}C or less was less than 7% while with the advent of deeper longlining after 2006 this varied between 11% and 24%.

3.2.2 By Primary Target Species

Observers are instructed to record the primary target species as informed by the skipper for each observed set and it is informative to compare differences in depth profiles across sets targeting different species. The aggregate time-at-depth profiles over all years stratified by primary target species are shown in Figure 3.3a. The profile for yellowfin tuna shows a strong unimodal distribution with hooks spending, on average, 90% of their time between 20 and 110 meters. Hooks targeting bigeye tuna and broadbill swordfish display very similar unimodal distributions, with hooks spending 90% of their time between 20-100m and 30-110m respectively. Alternatively, hooks targeting albacore tuna display a significantly different and much flatter distribution, with hooks spending 90% of their time between 50 and 290m.

The profiles for each six-month period of observations (shown in Figure 3.3b) display a similar overall pattern. However, it is worth noting a shift in this pattern towards deeper sets during 2007 for yellowfin, bigeye and swordfish. This is consistent with reports from fishers about a broader shift to fishing deeper that is not just associated with albacore fishing but "mixed fishing" where the target is a mix of large high value bigeye and yellowfin plus the larger export quality albacore Not withstanding this shift, these results appear to indicate that there is little difference in depths fished by the hooks when targeting yellowfin, bigeye or swordfish but, as noted previously, considerably deeper depths are targeted when fishing for albacore. Whether or not the lack of difference in depths fished for those sets which do not target albacore is by choice or whether fishers cannot target depths on a fine-scale level remains uncertain

In comparison, the time-at-temperature profiles stratified by primary target species are shown in Figure 3.4 and display a greater degree of difference for each of the four species shown. Hooks targeting bigeye tuna generally fish in the warmest waters (21-25°C) while hooks targeting yellowfin and swordfish where observed to generally fish

Figure 3.3a Time-at-depth profiles of fishing depths attained by hooks recorded by TDRs stratified by the primary target species recorded by the observer.

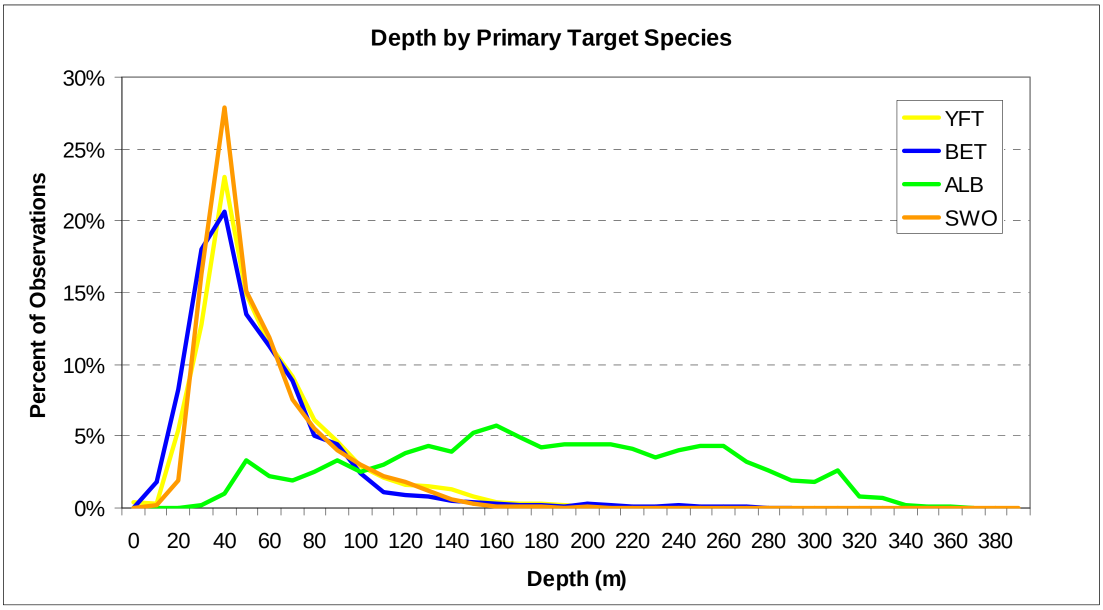


Figure 3.3b Time-at-depth profiles of fishing depths attained by hooks recorded by TDRs stratified by the primary target species recorded by the observer and the six-month period during which the observations were made.

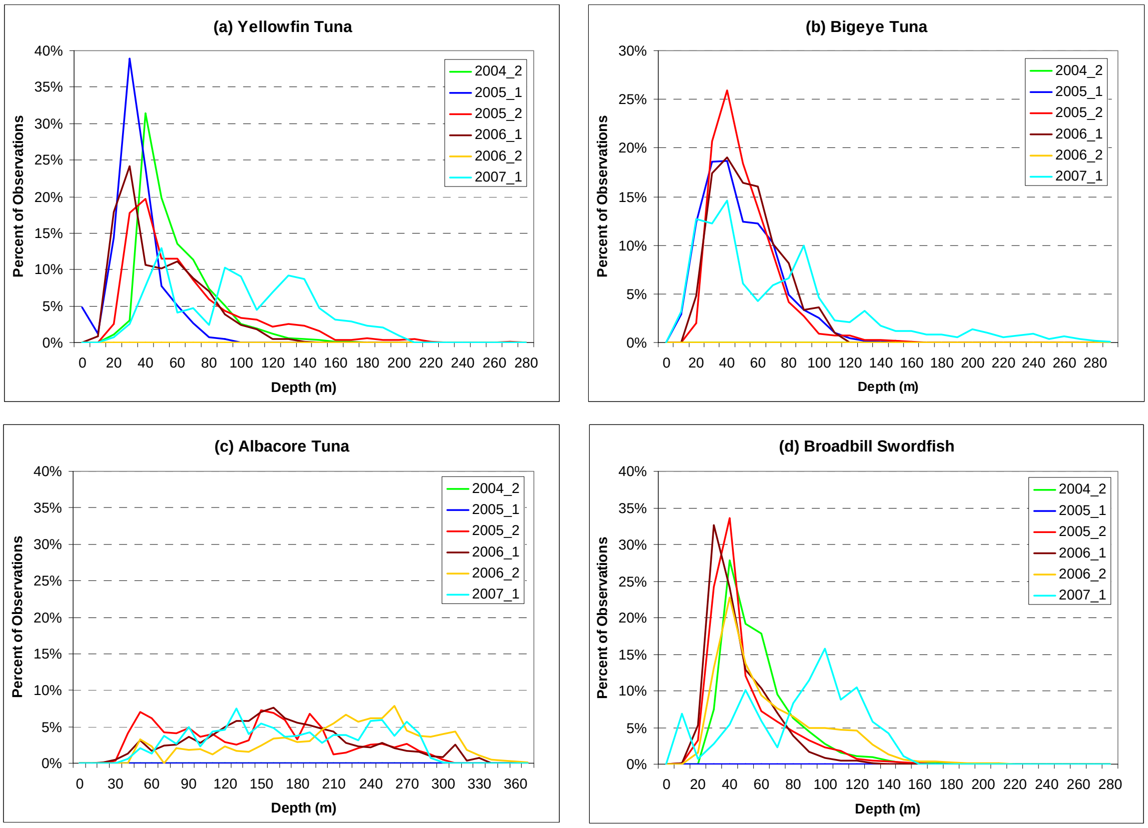
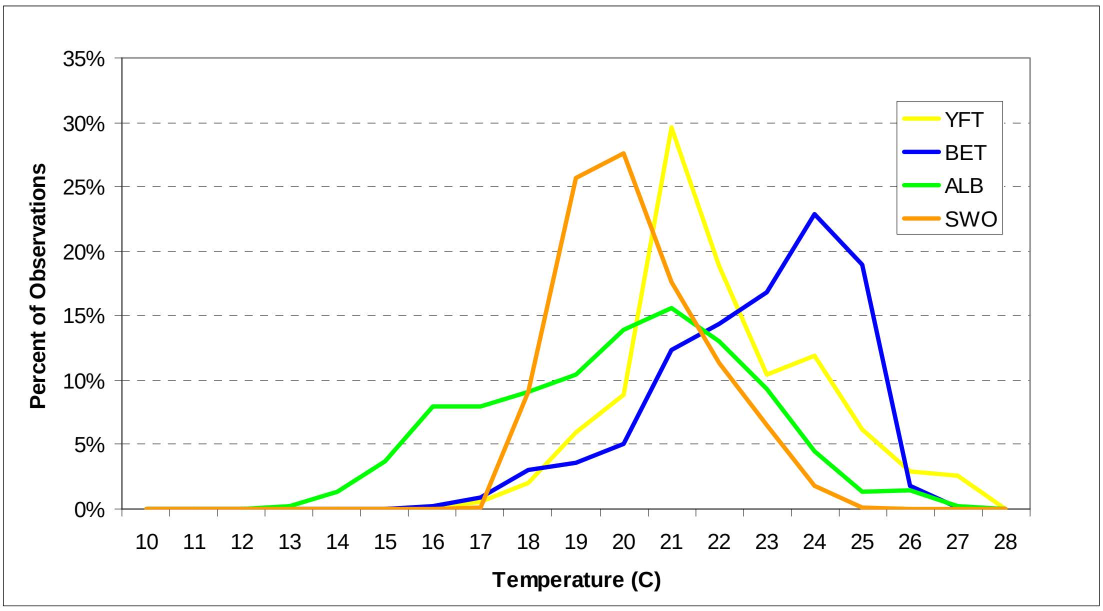


Figure 3.4 Time-at-temperature profiles of water temperature fished by hooks recorded by TDRs stratified by the primary target species recorded by the observer.



within water temperatures of waters (20-24°C) and waters (18-23°C) respectively. Hooks targeting albacore fish the greatest range of water temperatures, and are generally being in the range 15-23°C.

3.2.3 By Hooks-per-Float

Historically, Japanese longliners changed the number of hooks-between-a-float in order to change the depth profile of the hooks whilst fishing. Generally, deeper depths were reached by setting more hooks-between-floats. Historically Japanese longliners generally deployed shallow sets (deploying around 5 HPF) and targeted those species generally available in the upper 100 meters of the water column (such as yellowfin tuna and southern bluefin tuna). However, with the knowledge that the valuable species such as bigeye tuna generally occurred at deeper depths there was a significant shift in the targeting practices of Japanese longlines from the mid-1970s onwards towards deploying deeper longlines. These changes generally underlined the initial attempts to standardize the Japanese longline CPUE data often used in tuna stock assessments.

The practice of deploying different number of hooks- between-floats has also been used by the ETBF longline fleet, but given the variation in other factors influencing the deployment of the gears a good understanding between depths fished and the hooks-between-float configuration of the longline has been missing for this fleet. Using the data collected during this project, the depth profile of hooks stratified by the number of hooks-between-floats is shown in Figure 3.5a. The profiles for those configurations using 6 to 11 hooks-between-floats are seen to be quite similar indicating that the depths fished by these hooks must be dependent upon other factors apart from the number of hooks-between-floats. On the other hand, the depth profiles of hooks when 25 and 30 hooks-between-floats are deployed do show the expected increase in depth profile, with the latter reaching depths in excess of 300m.

Figure 3.5a Time-at-depth profiles of fishing depths attained by hooks recorded by TDRs stratified by the number of hooks-per-float as recorded by the observer.

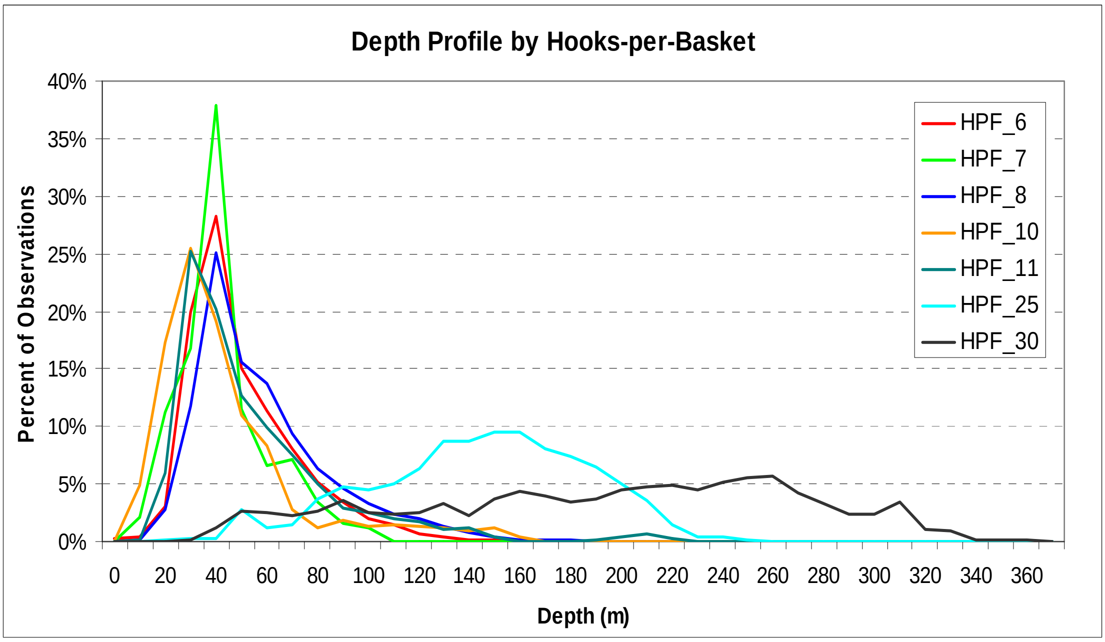
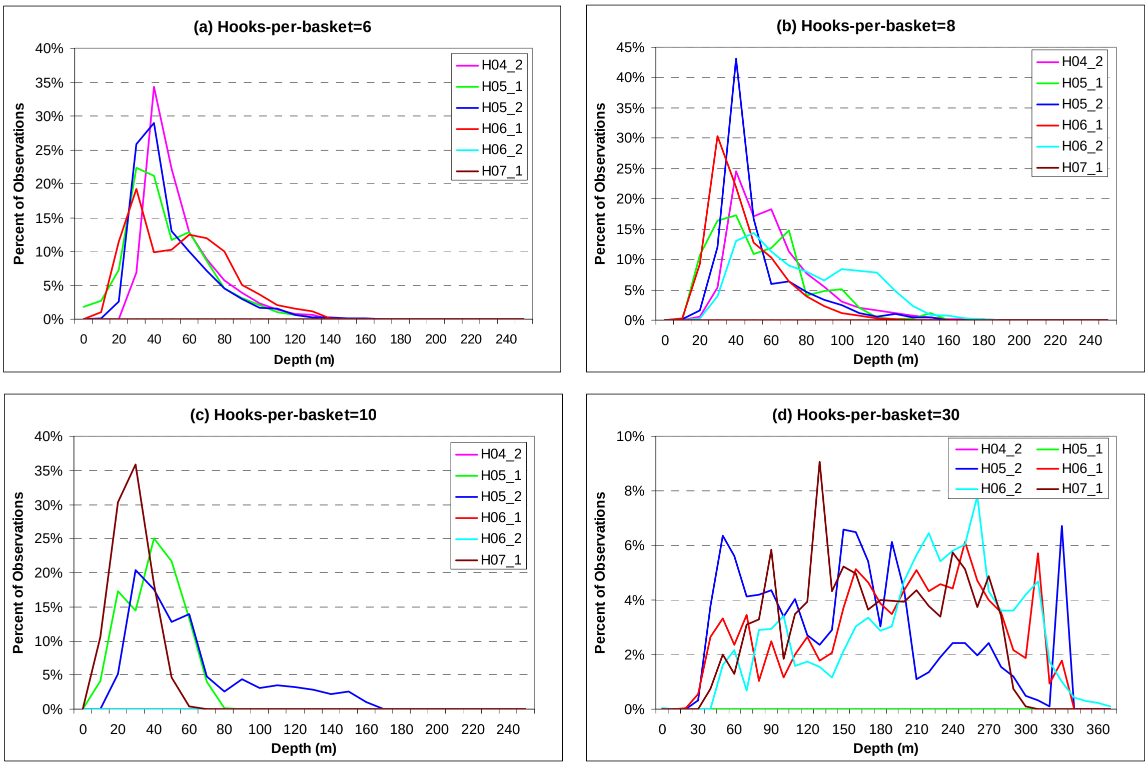


Figure 3.5b Time-at-depth profiles of fishing depths attained by hooks recorded by TDRs stratified by the number of hooks-per-float and the six-month period during which the observations were made.



3.3 Sink Depths and Times

As described previously, the period during which each TDR sank to its initial fishing depth was separately identified in the initial reading of each TDR data. From this data we can ascertain the initial depths that hooks descend to and the time taken, and from this information the rate at which the hook/TDR sank can also be determined. The depths reached by the TDRs at different hook-positions within longlines having similar gear configurations (i.e. similar HPF) can also be used to ascertain the initial shape of the line between the two floats when the gear reaches its fishing depths. However, together with the TDR data one also needs the associated deployment information on hook-number and HPF. This combined information was available for 1608 TDR data recordings collected from 216 longline sets. The distribution of these TDR data across each hook-number within each HPF configuration is shown in Table 3.1. All hook-numbers were sampled for gear configurations with 6-11 HPF with more than 75% of hook-numbers also sampled for configurations with 12, 25 and 30 HPF. In total 131 different hook-number/HPF configurations were observed.

A plot of the observed depth that each TDR sank, stratified by hook-number and HPF, is shown for the six gear configurations with the greatest number of observations in Figure 3.6. A relatively large range of depths are noted for each gear configuration and hook-number and indicates that the depths attained are obviously influenced by a large number of factors other than the number of HPF. On average, for gears with 6 HPF there is no difference in the depth at which the TDRs sank for each of the six different

Table 3.1 Distribution of TDRs from which usable data was attained across the different hook-numbers within each observed gear configuration. (Note, ns = not specified and HN = hook number).

Hook	Gear Configuration (Number of Hooks-per_Float)														
Number	6	7	8	9	10	11	12	13	14	15	20	25	30	32	35	Total
1	84	6	73	1	2	1	3	2	1	5	4	1	16	0	0	
2	78	8	53	1	4	3	1	0	0	0	0	0	6	0	0	
3	74	1	107	1	2	3	4	3	1	0	5	0	4	0	0	
4	86	4	80	1	4	9	1	0	0	2	0	0	4	0	0	
5	66	5	105	2	6	6	4	3	2	0	3	2	12	0	0	
6	77	3	74	1	5	5	1	0	0	0	0	2	4	0	0	
7		3	57	2	3	5	4	0	1	7	5	0	7	0	0	
8			48	0	3	6	0	0	0	0	0	5	5	1	0	
9				2	2	2	3	0	2	0	5	4	5	0	1	
10					1	6	0	0	0	0	0	7	14	0	0	
11						4	2	0	2	0	0	6	7	0	0	
12							0	0	0	0	0	9	9	0	0	
13								0	1	0	0	4	14	0	0	
14									0	0	0	8	25	0	0	
15										0	0	3	49	0	0	
16											0	4	17	1	0	
17											0	6	14	1	0	
18											0	3	3	0	0	
19											0	6	11	0	0	
20											0	2	4	0	0	
21												1	7	0	0	
22												0	5	0	0	
23												0	3	0	0	
24												0	5	0	0	
25												2	4	0	0	
26													3	0	1	
27													1	0	0	
28													4	0	0	
30													2	0	0	
32														1	0	
35															1	
Total	465	30	597	11	32	50	23	8	10	14	22	75	264	4	3	1608
No. Sets	54	5	71	1	7	8	3	1	1	3	2	13	45	1	1	216
Sampled HNs	6	7	8	8	10	11	9	3	7	3	5	18	29	4	3	131

hook-numbers, while for gears with 8 HPF only the hooks closest to the floats are slightly shallower. However, there is a general tendency for the middle hook to attain a greater depth than the two end hooks as the number of HPF increases. Indeed, the shape of the line for 25 and 30 HPF gears appears to approximate the catenary shape expected for a line hanging under the influence of gravity.

The mean and standard deviation of the sink depths for each hook-number and HPF configuration are shown in Figures 3.7. For gears configurations with 6 HPF the range (68.1 to 73.7m) and average (71.3m) of the mean depths across all hook-numbers was similar to those for configurations with 8 HPF (range = 62 to 78.6m, average=71.1m). Sink depths for gear configurations with 10 HPF were shallower, with a range of 17 to 59.6m and average of 45.3m. On the other hand, gear configurations with 25 and 30 HPF displayed a much greater range of depths. For both situations the shallowest hooks were those closest to the floats, having mean sink depths of 60m and 73m respectively, and the deepest hooks were those near the middle, having mean sink depths of 201m and 295m respectively.

Figure 3.6 Initial sink-depth for each TDR observation by hook-position and hook-per-basket configuration. The black lines indicate a fitted line of best fit (cubic).

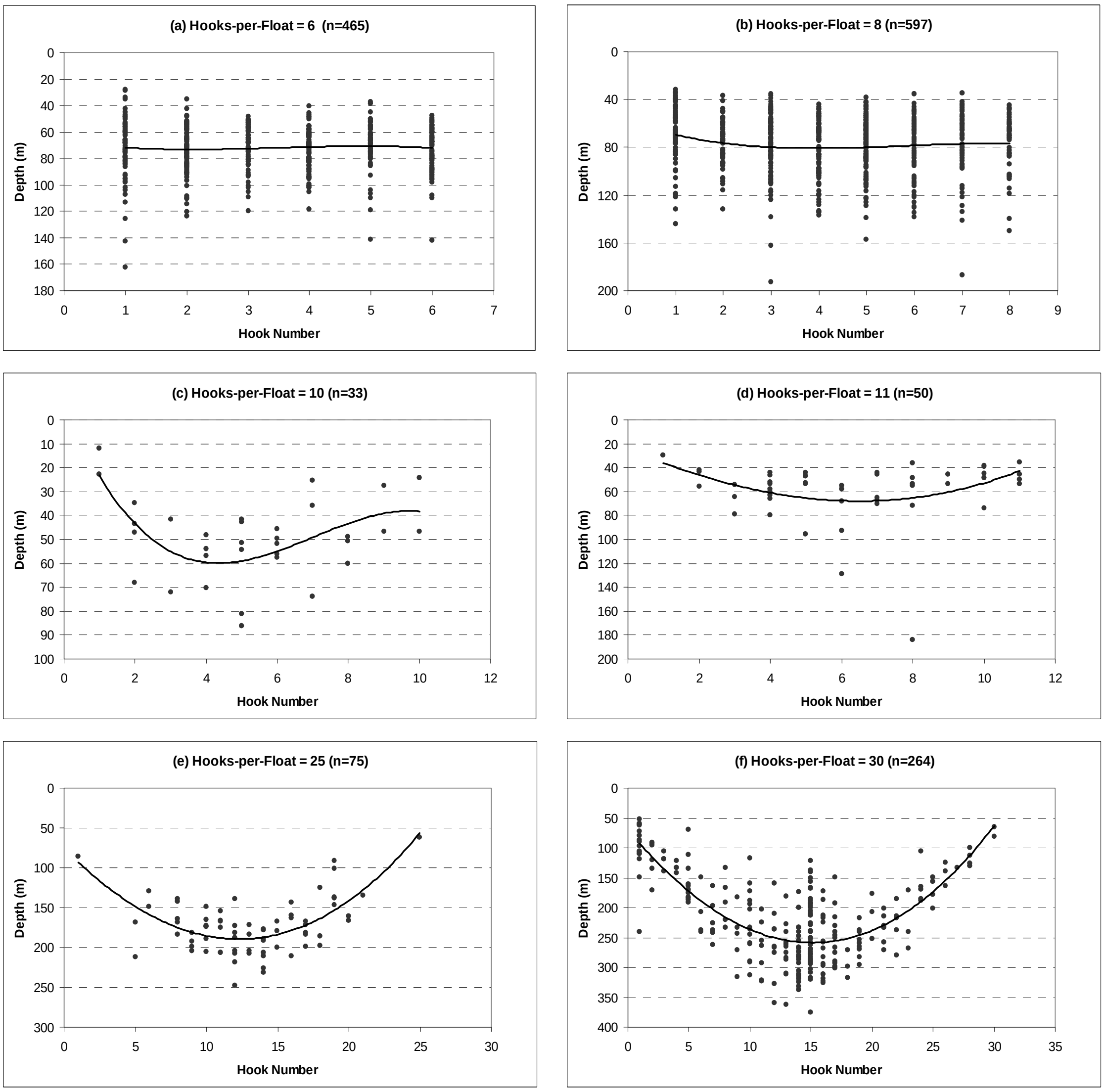
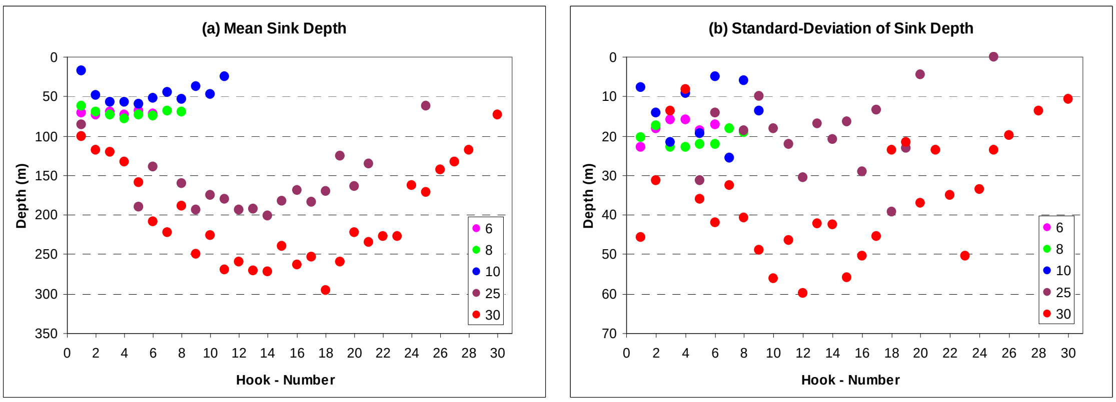
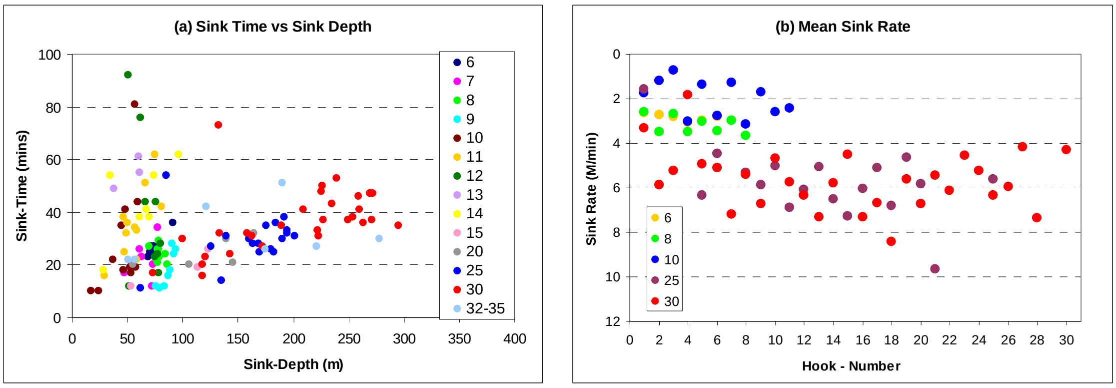


Figure 3.7 Mean and standard deviation of the sink depths attained by TDRs stratified by hook-number and HPF configuration.



The mean sink-time versus mean sink depth for the 131 different hook-number/HPF configurations observed is shown in Figure 3.8a. For the large group of observations with a sink depth of between 50-80m there is a large range of sink times, indicating that the rate at which the TDR sank was quite variable. On the other hand, for most observations where the sink depth was greater than 100m there appears to be a greater degree of linearity between depth reached and time taken. The mean sink rates for each hook-number for those HPF configurations having the greatest number of observations are shown in Figure 3.8b. Rates for configurations with 6, 8 and 10 HPF are between 0.7 m/s and 3.7 m/s with averages of 2.8, 3.2 and 2.0 m/s respectively, whilst rates for configurations with 25 and 30 HPF are generally greater, ranging between 1.6 m/s and 9.7 m/s and having averages of 5.8 and 5.7 m/s respectively. The reasons for these differences remains unclear, but it is likely that the sink rate of any TDR or hook is constrained by the attached gears with these constraining influences being greater the smaller the number of HPF.

Figure 3.8 Scatterplot of (a) mean sink time versus mean sink depth for all observed hook-number and HPF configurations and (b) mean sink rate versus hook-number for selected HPF configurations.

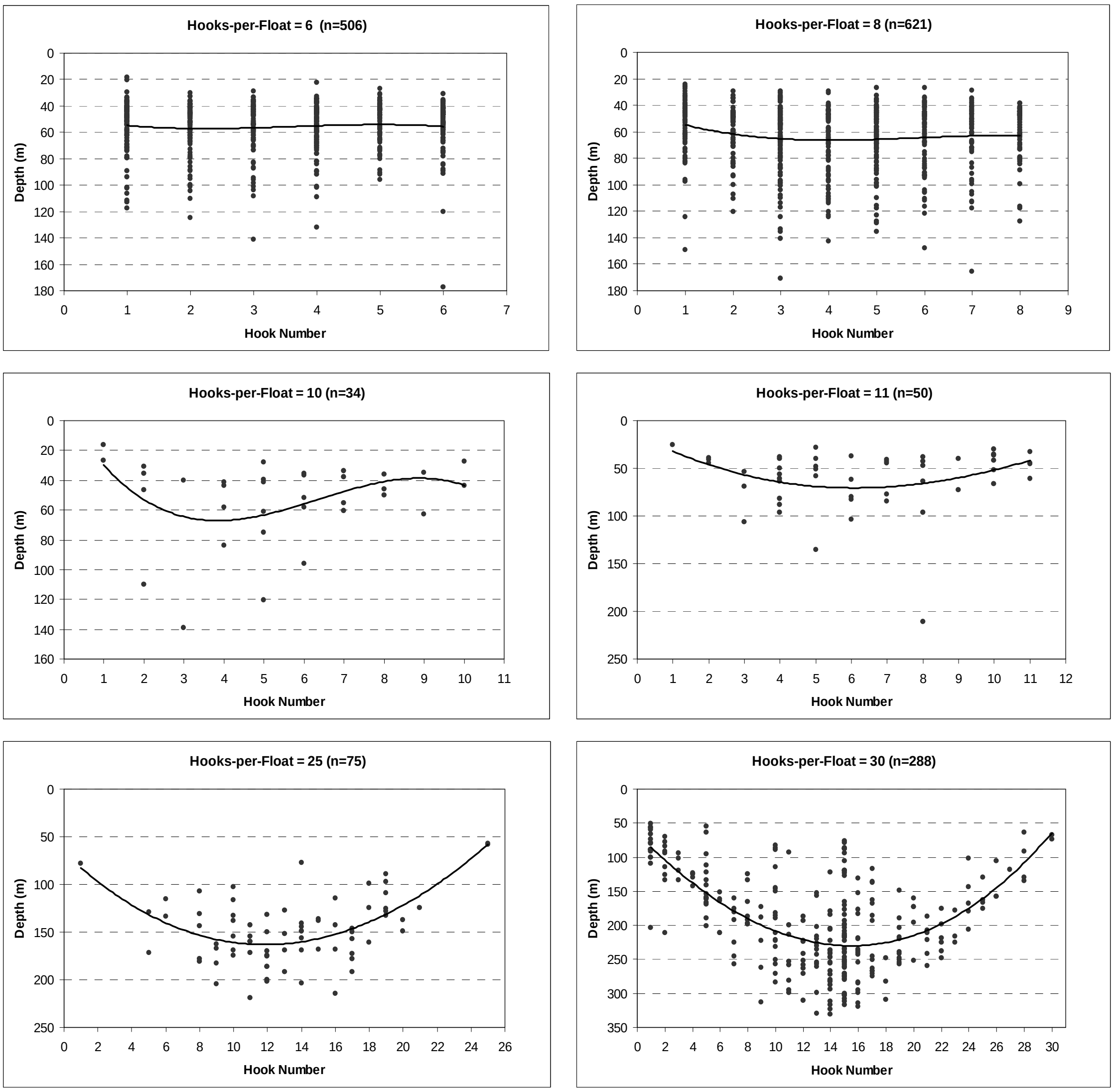


3.4 Fishing Depths versus Hook-Number

After sinking to its fishing depth, and before being hauled, the TDR provides data on the depths which would be fished by a baited hook. For the 1719 TDR readings with associated hook-number and HPF information, the average depth fished during this period was calculated and is shown in Figure 3.9 for each observed hook-number/HPF combination. As noted with the sink depth information, there is a large range of depths associated with each set of hook-number/HPF observations. The results also indicate that the mean depths fished by different hook-numbers between floats are similar for line configurations with only 6-8 HPF but take on the expected catenary shape (with the middle hooks fishing deeper than the end hooks) as the number of HPF increases.

In order to summarise the time-series of fishing depths for each of the 1719 TDR recordings, the following statistics were calculated for each TDR recording: (a) mean, (b) range, (c) standard deviation (SD) and (d) coefficient of variation (CV=SD/Mean). However, as the curves of best fit shown in Figure 3.9 indicated that the shape of the line between floats is approximately symmetrical, indicating that the depth of hooks at the same hook-position (i.e. the hook-number from the nearest float) are similar, the

Figure 3.9 Plot of the mean of the depths recorded by each TDR during the associated fishing period, for each observed hook-position and hook-per-basket configuration,. The black lines indicate a fitted line of best fit (cubic).



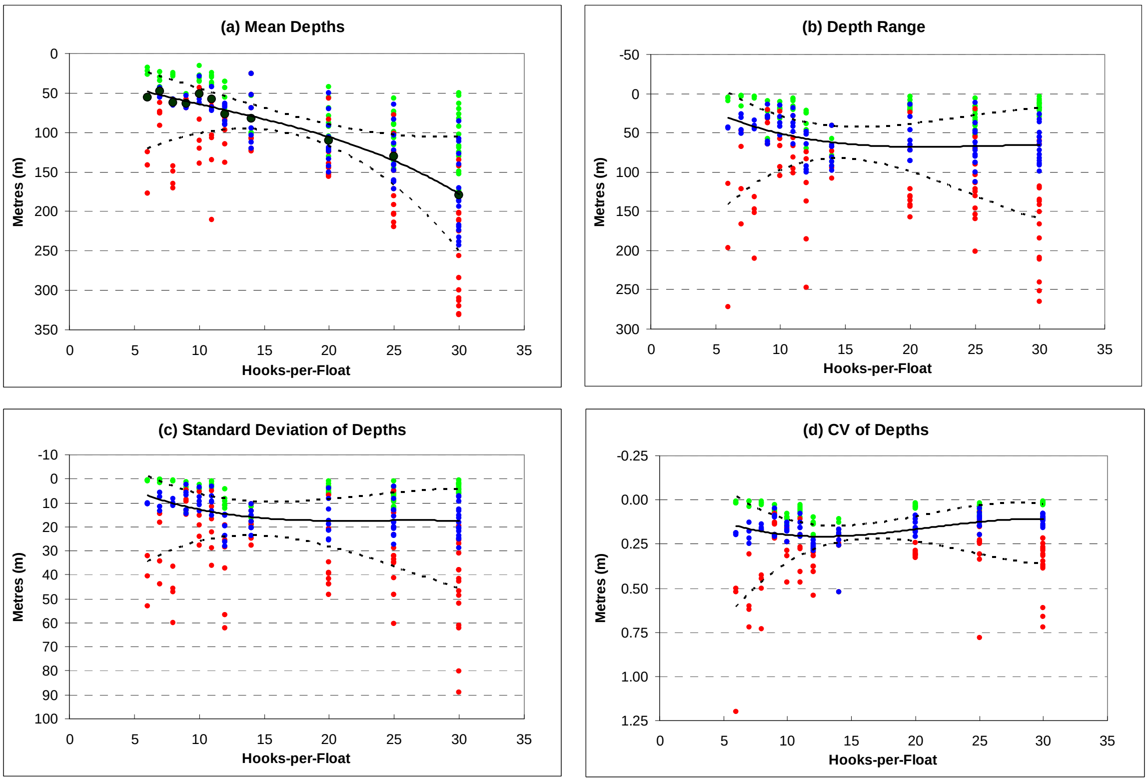
results were summarised by hook-position only instead of the greater number of hook-numbers. For each hook-position within each HPF configuration, the average, minimum and maximum of the four statistics calculated for each TDR were then tabulated. Finally, to provide a single "Indicative Depth" for each gear configuration, the mean of the average observed depth across each hook-number was calculated. The results for gear configurations with 6-12, 14, 20, 25 and 30 HPF are shown in Table 3.2 and Figure 3.10. Note, there were no TDR-based results for 9 of the 79 hook-position/HPF combinations shown in this Table and for these positions an estimate based on a linear interpolation of the results from adjacent hook-positions with observations were used.

An advantage of the summary provided in Table 3.2 is that there is a single set of results for each hook-position/HPF combination. This ensures that the lines of best fit shown in Figure 3.10 are based on an evenly weighted mean across each (and all) hook-position within each HPF configuration, for if such a curve had been fitted to all 1719 observations then the fit would have been unduly weighted by the non-uniform

Table 3.2 Summary statistics relating to the fishing depths for each hook position and HPF configuration. Hook positions highlighted in grey indicate those statistics which are based on interpolation between the adjacent positions.

	Hook	Number	Mean Depths			Std Deviation			CV			Range			Indicative
HPF	Position	TDRs	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Depth
6	1	169	55.2	18.0	177.1	10.3	1.0	32.3	0.19	0.02	0.52	43.3	9.2	197.2	
6	2	158	55.5	27.0	124.6	10.7	0.8	40.4	0.19	0.02	0.50	43.7	6.3	114.4	
6	3	179	55.9	22.0	141.4	10.7	0.5	53.0	0.20	0.01	1.20	42.8	5.4	272.5	55.5
7	1	15	44.2	23.0	73.5	5.7	0.4	14.5	0.13	0.01	0.31	26.0	3.3	47.9	
7	2	15	55.5	35.0	90.9	11.8	0.4	43.8	0.22	0.01	0.72	46.6	2.5	166.4	
7	3	10	43.8	30.0	75.7	7.5	0.5	18.4	0.18	0.01	0.60	31.2	2.9	67.6	
7	4	9	52.2	42.0	62.5	13.4	1.7	34.2	0.25	0.04	0.62	51.1	15.9	121.9	48.5
8	1	125	58.1	24.0	149.0	8.3	0.6	60.2	0.14	0.01	0.73	34.0	4.1	210.2	
8	2	115	62.2	29.0	165.4	10.0	1.0	36.7	0.16	0.02	0.45	40.4	3.9	147.1	
8	3	189	64.7	27.0	170.9	11.0	1.1	47.2	0.17	0.03	0.50	43.7	6.1	151.6	
8	4	192	66.2	27.0	142.4	11.2	1.0	45.9	0.17	0.02	0.43	44.9	4.4	132.1	62.8
9	1	3	53.9	51.0	57.6	2.6	1.5	4.6	0.05	0.03	0.08	13.6	9.3	20.6	
9	2	1	66.7	67.0	66.7	13.1	13.1	13.1	0.20	0.20	0.20	64.6	64.6	64.6	
9	3	3	61.9	60.0	64.4	5.7	3.7	9.3	0.09	0.06	0.14	28.5	23.0	37.8	
9	4	2	68.9	68.0	69.5	14.6	14.3	15.0	0.21	0.21	0.22	61.1	58.2	64.0	
9	5	2	64.5	64.0	64.8	6.7	4.8	8.6	0.10	0.07	0.13	30.4	28.3	32.4	63.0
10	1	3	28.8	16.0	43.6	3.6	2.5	5.5	0.13	0.10	0.16	14.9	10.8	22.7	
10	2	6	53.5	31.0	109.9	7.5	4.4	15.3	0.15	0.08	0.24	30.1	18.5	58.0	
10	3	5	62.3	36.0	138.9	10.9	4.0	24.2	0.17	0.11	0.29	41.9	20.8	93.2	
10	4	8	51.8	34.0	83.9	9.4	4.3	19.5	0.18	0.10	0.32	37.9	20.1	66.8	
10	5	11	58.5	28.0	120.3	13.3	5.6	27.6	0.24	0.14	0.47	53.3	32.1	104.5	51.0
11	1	5	41.8	25.0	60.9	3.3	1.1	4.9	0.08	0.03	0.11	18.0	6.2	28.9	
11	2	9	42.8	30.0	66.7	7.1	1.3	11.6	0.16	0.04	0.28	28.8	6.9	56.8	
11	3	5	68.4	40.0	106.7	9.4	2.6	16.8	0.13	0.07	0.20	37.5	9.3	67.1	
11	4	15	71.7	38.0	210.6	13.3	3.2	36.0	0.20	0.05	0.41	49.0	16.5	101.7	
11	5	11	59.0	28.0	135.2	9.7	4.0	22.4	0.16	0.10	0.27	41.8	19.8	81.2	
11	6	5	73.0	37.0	103.2	15.4	2.4	28.8	0.21	0.06	0.47	64.3	20.9	96.2	58.2
12	1	3	66.0	36.0	81.6	15.0	9.3	25.4	0.23	0.13	0.32	48.9	24.8	83.0	
12	2	3	63.5	36.0	90.0	15.4	8.5	19.3	0.25	0.21	0.30	52.6	24.0	74.8	
12	3	4	89.7	71.0	114.9	26.3	11.2	62.4	0.27	0.14	0.54	100.8	46.7	246.8	
12	4	4	67.7	56.0	85.1	19.6	11.0	28.4	0.28	0.20	0.38	64.6	38.3	114.1	
12	5	4	90.8	85.0	97.0	23.7	12.2	37.3	0.26	0.14	0.38	97.2	69.8	136.9	
12	6	6	86.3	44.0	138.3	28.0	4.4	56.9	0.29	0.10	0.41	92.3	21.7	185.7	77.3
14	1	1	25.8	26.0	25.8	13.4	13.4	13.4	0.52	0.52	0.52	81.1	81.1	81.1	
14	2	1	52.7	53.0	52.7	10.4	10.5	10.5	0.20	0.20	0.20	41.2	41.2	41.2	
14	3	1	69.0	69.0	69.0	17.8	17.8	17.8	0.26	0.26	0.26	67.5	67.5	67.5	
14	4	2	95.1	84.0	106.7	15.3	11.6	19.0	0.17	0.11	0.23	65.6	58.1	73.1	
14	5	2	104.0	100.0	107.6	23.6	19.4	27.8	0.23	0.19	0.26	97.8	87.0	108.7	
14	6	2	112.7	101.0	124.0	20.5	16.2	24.9	0.19	0.13	0.25	87.1	79.3	94.9	
14	7	1	120.7	121.0	120.7	20.3	20.3	20.3	0.17	0.17	0.17	92.9	92.9	92.9	82.9
20	1	4	50.2	42.0	57.0	4.0	1.0	7.0	0.09	0.02	0.17	14.1	4.3	23.6	
20	2	0	70.8	55.5	83.2	8.3	2.0	20.8	0.11	0.03	0.25	30.2	8.3	72.6	
20	3	5	91.3	69.0	109.3	12.6	3.1	34.6	0.13	0.03	0.32	46.2	12.3	121.5	
20	4	0	105.4	87.5	124.3	19.2	3.6	39.2	0.17	0.04	0.32	65.8	14.2	131.7	
20	5	3	119.5	106.0	139.3	25.7	4.1	43.8	0.21	0.04	0.31	85.3	16.0	141.9	
20	6	0	121.6	92.5	145.3	21.6	4.9	41.6	0.19	0.04	0.30	72.5	18.4	136.2	
20	7	5	123.7	79.0	151.2	17.5	5.8	39.4	0.16	0.04	0.29	59.7	20.8	130.4	
20	8	0	133.4	104.5	153.4	21.4	6.2	43.8	0.17	0.05	0.31	72.7	21.1	143.8	
20	9	5	143.1	130.0	155.5	25.3	6.6	48.2	0.18	0.05	0.33	85.7	21.3	157.1	
20	10	0	150.0												110.9
25	1	3	64.5	57.0	78.5	3.2	1.0	5.2	0.05	0.02	0.07	11.9	5.8	20.1	
25	2	0	83.8	73.8	101.9	8.2	3.7	14.2	0.08	0.04	0.11	37.2	21.9	55.0	
25	3	0	103.2	90.5	125.3	13.2	6.4	23.2	0.10	0.06	0.16	62.5	38.0	89.8	
25	4	0	122.5	107.3	148.6	18.2	9.0	32.3	0.13	0.07	0.20	87.8	54.1	124.7	
25	5	3	141.8	124.0	172.0	23.2	11.7	41.3	0.15	0.09	0.24	113.1	70.2	159.5	
25	6	4	133.9	116.0	148.8	13.2	7.3	20.3	0.10	0.06	0.15	50.3	34.4	69.8	
25	7	6	113.7	89.0	132.6	13.0	3.2	28.8	0.11	0.04	0.23	48.0	16.0	103.9	
25	8	8	140.6	99.0	180.9	20.0	9.4	33.5	0.15	0.07	0.31	77.7	40.4	121.9	
25	9	10	171.3	146.0	204.3	15.5	6.5	34.9	0.09	0.04	0.24	68.0	30.3	146.1	
25	10	11	148.0	102.0	214.5	17.9	5.6	34.8	0.13	0.03	0.34	72.5	25.8	130.1	
25	11	9	161.2	136.0	219.5	20.9	12.1	32.2	0.13	0.07	0.24	79.7	46.6	113.6	
25	12	17	162.7	77.0	203.3	27.3	9.0	60.3	0.20	0.04	0.78	100.7	53.0	201.0	
25	13	4	160.1	127.0	191.8	23.9	12.8	48.1	0.15	0.08	0.25	87.9	51.1	153.7	130.2
30	1	18	85.5	50.0	203.3	7.5	0.8	31.0	0.08	0.01	0.39	33.0	4.2	118.7	
30	2	9	111.5	70.0	210.8	9.3	1.7	25.4	0.10	0.02	0.37	36.4	7.3	64.6	
30	3	8	108.5	64.0	134.5	7.3	2.2	19.6	0.08	0.02	0.31	26.5	10.0	60.2	
30	4	6	127.4	119.0	142.5	12.9	2.9	26.9	0.10	0.02	0.22	55.1	12.8	141.8	
30	5	19	140.4	54.0	201.5	13.5	2.0	37.9	0.11	0.01	0.28	50.1	12.8	120.4	
30	6	9	170.6	130.0	211.8	20.4	4.4	52.1	0.12	0.03	0.32	78.1	20.6	211.9	
30	7	12	186.5	102.0	256.6	15.4	2.5	41.7	0.09	0.02	0.29	55.4	12.2	135.0	
30	8	9	187.3	125.0	225.0	20.7	6.0	48.8	0.11	0.03	0.25	72.2	27.6	183.9	
30	9	11	224.2	174.0	313.5	16.4	4.7	37.9	0.08	0.02	0.22	60.7	18.6	166.9	
30	10	25	194.5	83.0	283.8	18.3	3.4	42.7	0.12	0.02	0.38	65.0	15.1	137.7	
30	11	13	219.2	93.0	299.6	24.8	5.9	61.0	0.14	0.02	0.66	89.1	18.6	209.0	
30	12	21	233.3	149.0	310.4	23.6	6.3	62.1	0.11	0.02	0.35	91.7	29.4	240.7	
30	13	17	242.7	153.0	330.2	21.9	4.6	46.9	0.10	0.02	0.27	82.1	16.9	150.3	
30	14	40	238.7	117.0	330.5	28.8	5.5	80.4	0.15	0.02	0.61	99.6	21.7	251.9	
30	15	71	217.9	77.0	319.4	25.2	4.4	89.0	0.16	0.02	0.72	85.5	18.7	264.7	179.2

Figure 3.10. Average (blue), minimum (green) and maximum (red) of the indicated depth statistics across all TDR observations for each hook position and HPF configuration. Cubic splines are fitted to each set of data, with the solid line indicating the fit to the averages. The “Indicative Depths” for each gear configuration are also shown in (a) as large black dots.



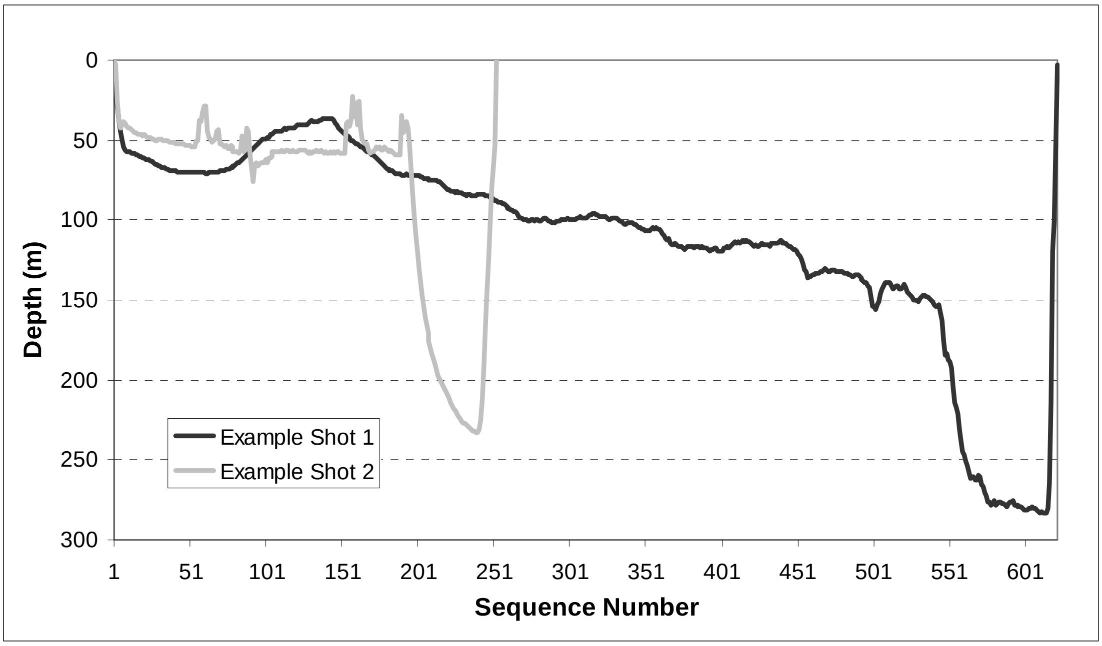
distributions of TDR observations across each hook-position.

The results for each depth statistic shown in Figure 3.10 indicate:

- There is a general monotonic increase in the mean depth of hooks as the number of HPF increases from 6 to 30. This result supports the assumption often used in the CPUE standardisation models for longline fishing that the number of HPF can be used as a proxy for fishing depth. However, Figure 3.10a also indicates that for the group of gear configurations with 6-11 HPF the “Indicative Depths” are very similar in which case the above relation does not hold true.
- The mean of the depth range of hooks within a configuration of 6-7 HPF is around 40m and asymptotes to around 70m for hooks within a configuration of 25-30 HPF.
- The mean of the standard deviation of hook depths within a configuration of 6-7 HPF is around 10m and asymptotes to around 17m for hooks within a configuration of 25-30 HPF.
- Due to the approximate linear increase in the mean and asymptotic behaviour of the standard deviation, the mean CV of hook depths decreases with increasing HPF (from around 0.2 to 0.11).

The results for the maximum values of each depth statistic indicate that the depths attained by hooks in any individual set can be quite large and varied. Also, the

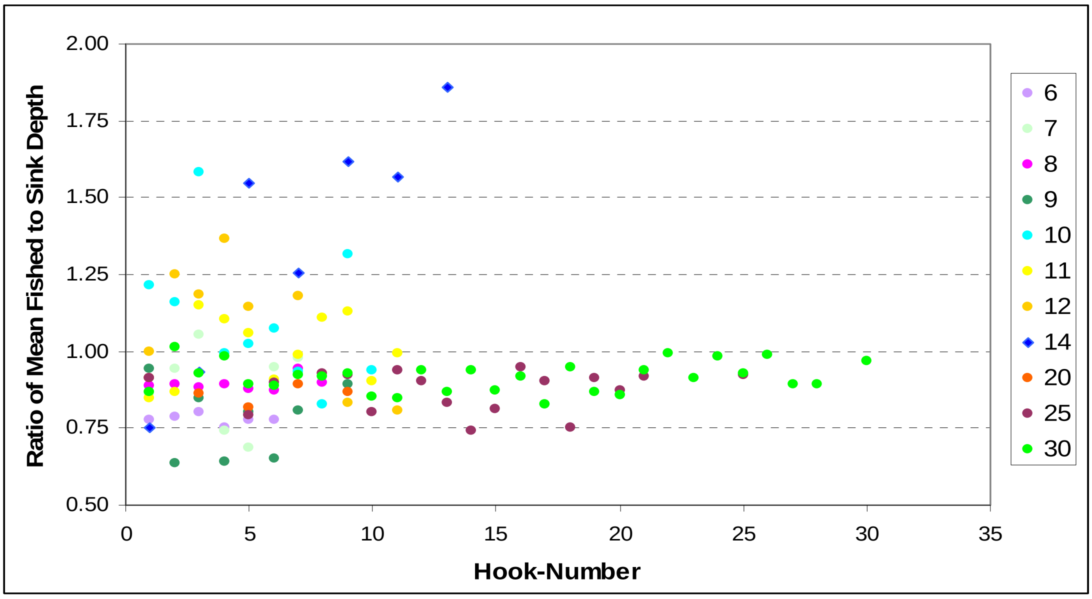
Figure 3.11 Two example time-series of depths for TDR recording of fishing depths with a depth range greater than 200m,



maximum values for the range and standard-deviations in depths can be similar across the different HPF configurations. (Note, the smaller maximums seen for both the 14 HPF and 20 HPF configurations are likely to be influenced by the corresponding smaller number of observations). In order to investigate the time-series of depths for TDR recordings of fishing depths with a depth range greater than 200m, two examples are shown in Figure 3.11. In both instances, there is a significant drop in the depths fished towards the end of the time-series followed by a quick ascent corresponding to the haul of the line. The reason for this behaviour remains uncertain but it may be associated with some break in the hauling of the line which results in the line sagging significantly in the water. Significant variation in the depths of a particular hook may also be due to the movement associated with a fish captured on that or a nearby hook.

The above results indicate that the individual gear configurations can be combined into three groups. The first group consist of those deploying less than 12 HPF and for which the "Indicative Depths" fished is similar for all HPF configurations. This group coincides with "Shallow" or "Surface" fishing where the depths fished are generally less than 100 m. Of the 1860 monitored sets for which the principal target species was recorded, the majority (91% and 81% respectively) of sets that targeted yellowfin and bigeye occurred within this group, as did almost all (99%) sets targeting swordfish. On the other hand, no sets in this group targeted albacore. The second group consists of those gear configurations deploying more than 25 HPF and for which the depths fished are generally greater than 100 m. These "Deep" sets comprise all sets recorded as targeting albacore and 5% of the bigeye targeted sets. A third "Intermediate" group consists of those sets which deploy between 12 and 20 HPF and generally fish depths between 50 and 150 meters - overlapping with the deeper depths of the first group and the shallower depths of the second group. These sets target a range of species and comprised 9%, 13% and 1% of the yellowfin, bigeye and swordfish targeted sets respectively.

Figure 3.12 Average ratio of the mean fishing depth to the sink depth for all TDR recordings for each hook-number and HPF configuration.



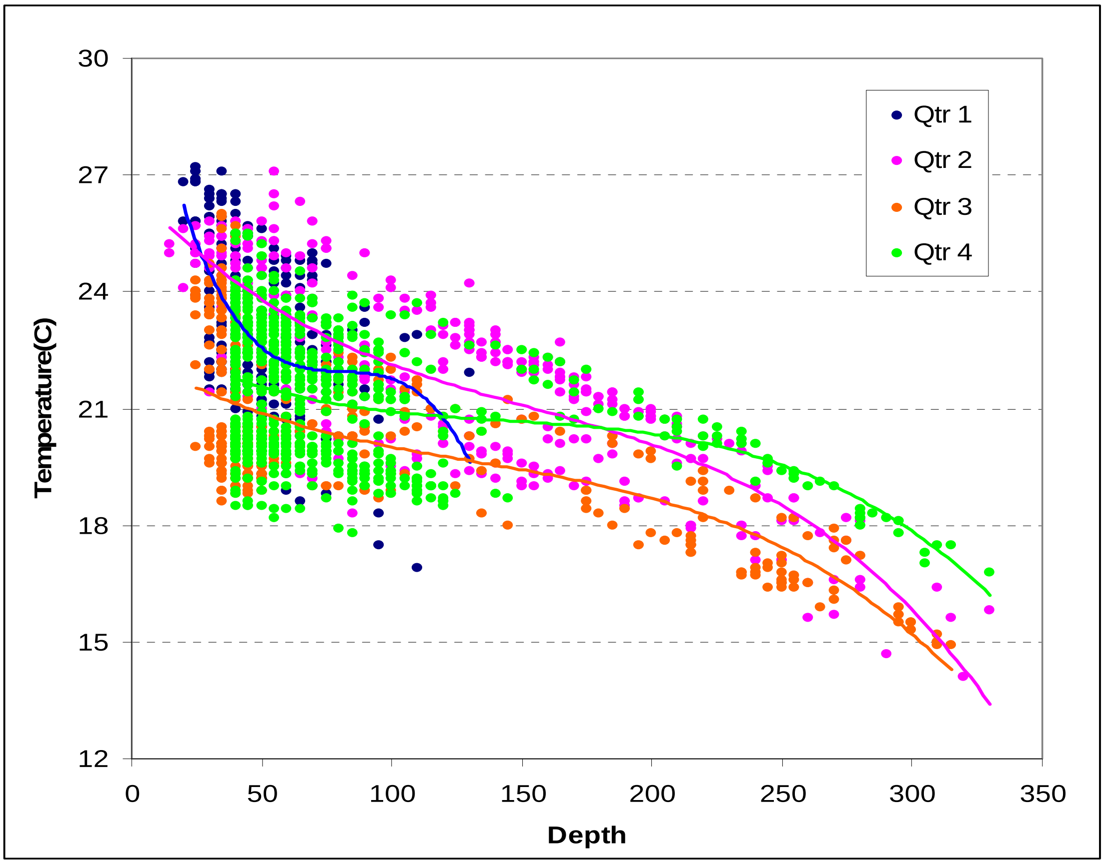
Finally, in order to investigate any change in mean depths whilst fishing compared to the initial sink depth we calculated the ratio of the two statistics, and the mean ratio across all recordings for each hook-number/HPF combination is shown in Figure 3.12. Of the 124 hook-number/HPF combination observed, 97 had a mean ratio less than 1 and 26 had a mean ratio greater than 1, indicating that on average the hook depths decreased during the fishing period, with the average ratio of depths fished to initial sink depth being around 87% when this occurs. The reason for this behaviour may be due to the floats drifting slightly further apart due to the action of the current thus lifting the line and the hooks. Of course, an increase in depth fished may be due to the currents moving the floats closer together.

3.5 Fishing Temperatures versus Hook-Number

As the relation between depths fished and hook-number was found to be highly variable for each gear configuration, so one would expect the relation between water temperatures fished and hook number. This relationship is made more complex by the fact that water temperature-at-depth will vary throughout the year due to seasonal cycles of warming and cooling of the oceans and changes in the depth of the thermocline. There can also be significant changes in temperature-at-depth on an interannual basis as well.

A plot of the mean temperature recorded by each TDR versus the associated mean depth fished stratified by each quarter of the year is shown in Figure 3.13. Cubic splines of best fit for each quarter are also shown. Within each quarter, water temperatures-at-depth are seen to be highly variable within the top 100 meters of the water column, below which the relation between temperature and depth appears to be more defined. This variation may be influenced by the spatial variations in water temperature associated with the different locations of the observed sets within each quarter as well as changes across years. Water temperatures are seen to be generally highest in the first and second quarters, lowest in the third quarter and intermediate in

Figure 3.13 Scatterplot of the mean temperature recorded by TDR versus mean depth fished stratified by quarter of the year. Cubic splines of best fit for each quarter are also shown.

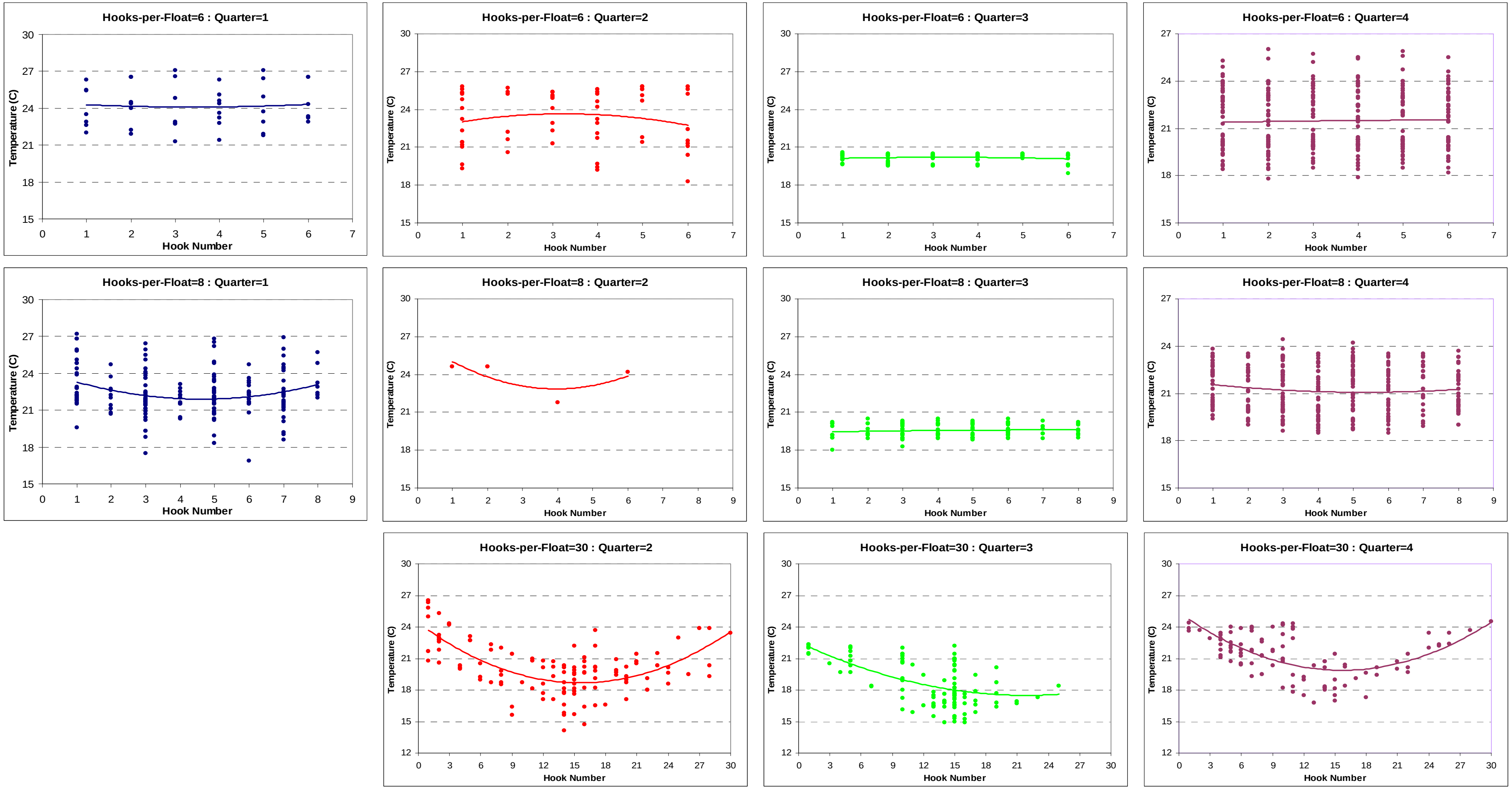


the third quarter, though the highest temperatures below 200 meters where observed during this latter quarter.

Plots of the mean fishing temperatures recorded by each TDR stratified by hook-position, hook-per-basket configuration and by quarter are shown in Figure 3.14 for those configurations with adequate samples. As with the observations of depths fished, there is again a relatively large range of temperatures fished across all observations for each hook-number/HPF configuration and discernible differences between hook-numbers only for higher HPF configurations. For observations with 6 HPF the temperatures fished during the first quarter ranged from 21-27C with a mean around 24C. This mean decreases to around 20C in the third quarter (though the sample size is small) and 21.5C during the fourth quarter. On the other hand, the temperatures fished by the deepest hooks for configurations deploying 30 HPF ranged down to around 14-15C during the second and third quarters, increasing a few degrees in the fourth quarter.

Temperatures-at-depth can be highly variable between years and are dependent on a number of oceanographic features beyond the control of the fishery. Indeed, there appears to have been discernible differences in general water temperatures in the ETBF during several sampling period (c.f. Figure 3.2). As such, without stratifying the data by sampling period, it remains unclear as to how temperatures fished vary solely

Figure 3.14 Average fishing temperatures for each TDR record by hook-position for a selection of hook-per-basket configurations and quarters. The black lines indicate a fitted line of best fit (quadratic).



due to differences in gear configuration and not to shifts in water temperatures themselves. Because of this fact the further analyse of the TDR data will be primarily limited to the analysis of the depth data as it remains unclear as to how well temperatures alone can be used as an indicator of gear-setting practices and targeting practices.

Section 4: Prediction of Longline Configuration

4.1 Longline Configuration

The name of the curve attained by a heavy uniform cable suspended vertically between two points under the influence of gravity alone is a catenary. In the absence of other oceanographic (e.g. currents) and environmental influences (e.g. wind) a similar configuration is often assumed for the length of mainline between two adjacent float lines when suspended in the water column. In this situation, the depth of the *j-th* hook along the longline between the floats is given by (Yoshihara 1951):

$$d(j) = F + B + \frac{L}{2}\left\{\left[1+\cot^2\theta\right]^{1/2} - \left[\left(2\frac{j}{N+1}-1\right)^2 + \cot^2\theta\right]^{1/2}\right\} \qquad (1)$$

where: F is the length of the float line
B is the length of the branchline
L is the length of the mainline between the floats
N is the number of hooks-deployed between the floats
and θ is the angle subtended by the horizontal and the tangent to the longline at the point of attachment at the end of the floatline.

As the paper cited above is in Japanese and generally not available, and as the derivation of the above catenary equation is generally not available elsewhere, the full derivation of this equation is outlined in Appendix C.

From a practical perspective, while information on most parameters in equation (1) are readily available, information on the angle θ, often known as the sag angle, is more difficult to obtain. However, as shown in Appendix C, the sag angle is related the sag ratio *SR* as follows:

$$SR = \frac{H}{L} = \cot\theta.\sinh^{-1}(\tan\theta) = \cot\theta.\ln(\tan\theta + \sec\theta) \qquad (2)$$

where H is the horizontal distance between two adjacent attachment points at the end of the floatlines (and if the floatlines hang vertically can be considered equivalent to the horizontal distance between two adjacent floats). Information on the sag ratio can then be used to provide an estimate of the sag angle. Furthermore, if it is assumed that the sag ratio is the same for all baskets, and that the entire longline is deployed in a straight line, then the sag ratio is equivalent to the ratio of the horizontal distance between the first and last float and the overall length of the mainline deployed, i.e.

$$SR = \frac{D}{M}$$

where D is the horizontal distance between the start-set position and the end-set position
M is the length of the deployed mainline.

There are several means by which information on D and M can be collected. The most obvious is to collect this data directly, i.e. record the start-set and end-set positions and calculate D, and record the length of the deployed mainline, M. However, there are often situations where this information is not available, and when this occurs other information is needed to estimate these two parameters.

4. 2 Observer Data and Cross-Validation

As already noted, observers record a large amount of data concerning the longline gears deployed during each trip and each set. For the purposes of calculating the depths attained by the hooks using equation (1) the list of gear settings shown in Table 4.1 were used. For each of these gear settings, histograms of those settings used in the 219 sets for which usable TDR data is also available are shown in Figure 4.1. Also shown, when available, are the corresponding histograms based on the gear setting information recorded in vessel logbooks. For these situations, a measure of the dissimilarity between the observer-recorded and logbook-recorded data is also shown. This measure is based on calculating the statistic:

$$R = \text{observer-data/logbook-data}$$

for each set for which both sets of data are available and then determining the number of such sets within each bin of width 0.1. The number of sets where $0.95 < R < 1.05$ is shown in Table 4.1

Table 4.1 Listing of data recorded by observers and logbooks used to help derive the longline configuration.

Gear Setting	Frequency of Recording	Observer Data		Logbook Data	
		Number of Sets			
		With Data	No Data	With Data	0.95 <R< 1.05
1. Floatline Length	Trip	219	0	0	na
2. Branchline Length	Trip	219	0	0	na
3. Mainline Length	Trip	80	139	209	3
4. Number of Hooks deployed	Set	219	0	210	198
5. Number of Hooks-per-Float	Set	219	0	213	204
6. Start-set and End-set Times	Set	218	1	215	178
7. Distance between Branchlines	Set	210	9	0	na
8. Time between Branchlines	Set	55	164	0	na
9. Line Shooter Speed	Set	56	163	0	na
10. Vessel Setting Speed	Set	206	13	0	na
11. Start-set and End-set Positions	Set	219	0	0	na

Figure 4.1 Histograms of the gear settings used in the 219 sets for which usable TDR data was obtained.

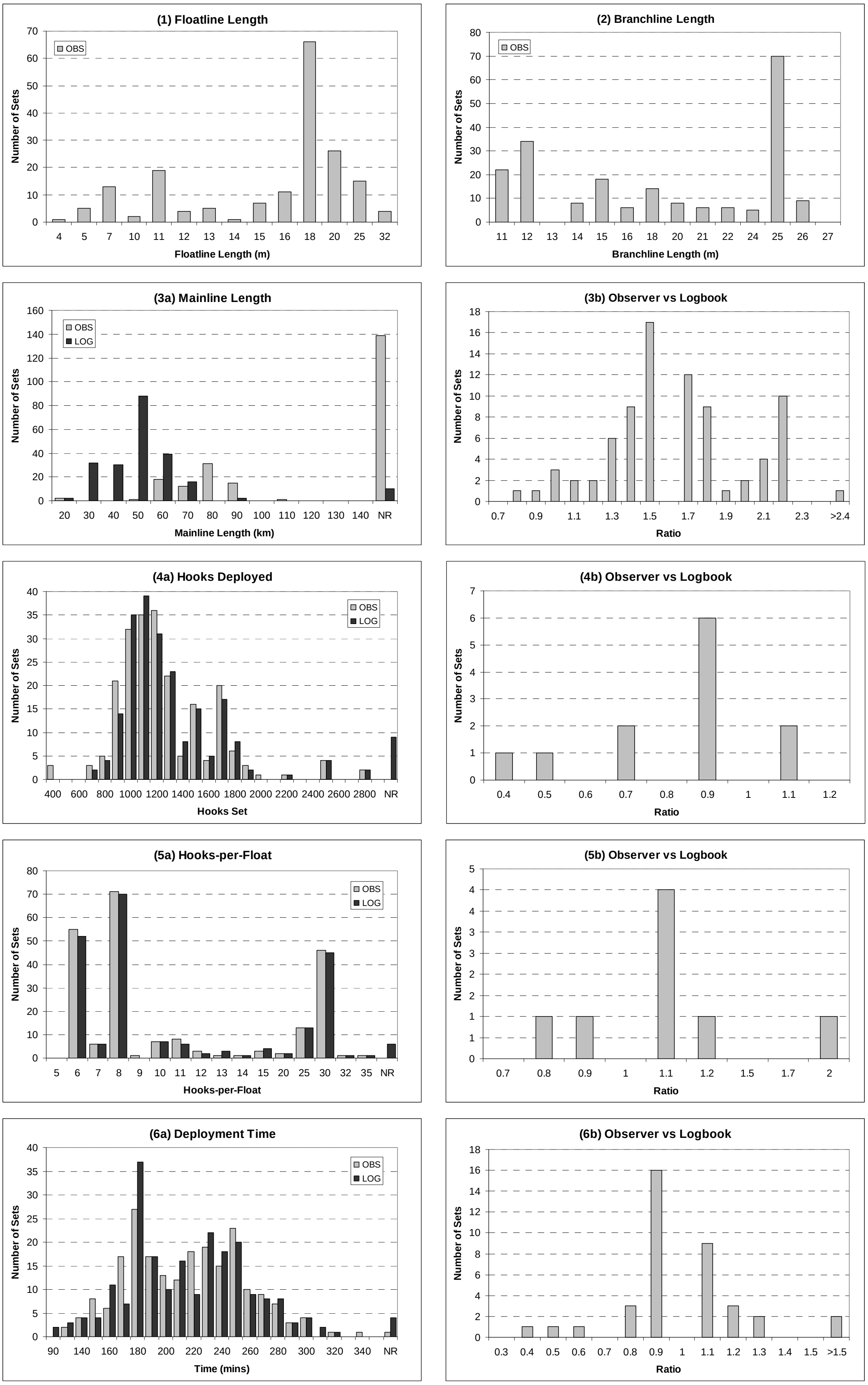
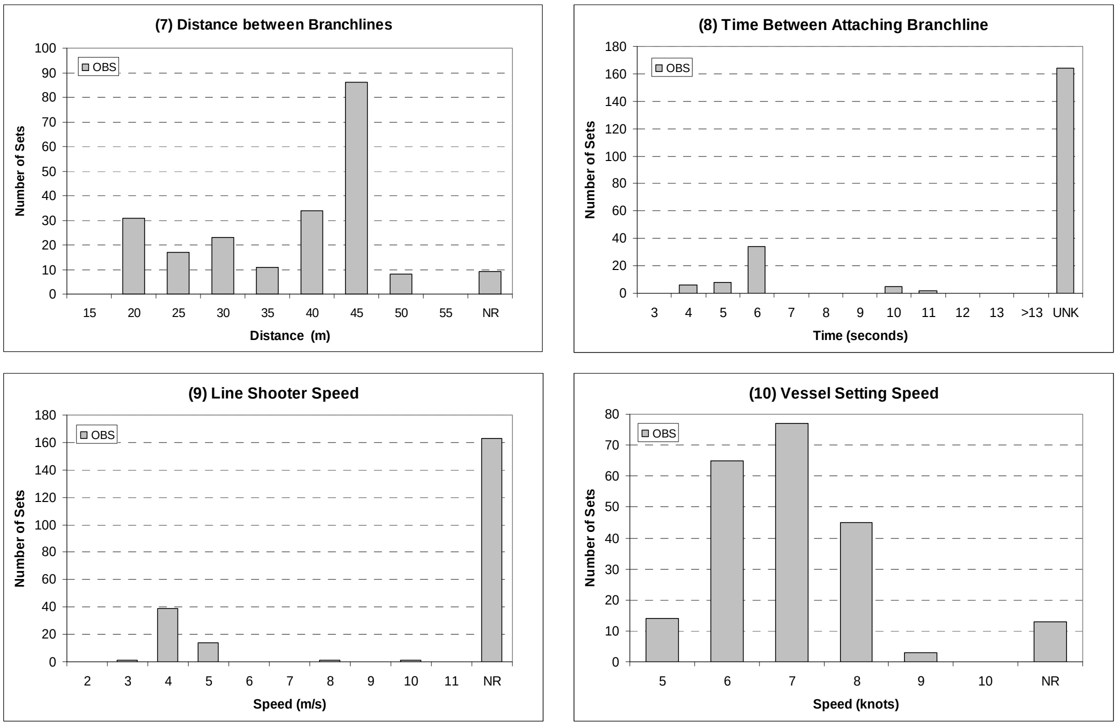


Figure 4.1 (cont'd) Histograms of the gears settings used in the 219 sets for which usable TDR data was obtained.



Given the range of data collected by observers, it is possible in some circumstances to cross-validate some of the data. This was undertaken in the following circumstances:

1) Distance between branchlines, $d_{Derived}$

a) Using the observed-recorded length of the mainline, M_{obs}, in kilometers, then:

$$d_{Derived}(1) = \frac{1000.M_{obs}.HPF}{N.(HPF+1)} \text{ m}$$

b) Using the logbook-recorded length of the mainline M_{log} in kilometers, then:

$$d_{Derived}(2) = \frac{1000.M_{\log}.HPF}{N.(HPF+1)} \text{ m}$$

c) Using the line shooter speed, S, m/s and the time between the attachment of branchlines Δt seconds, then:

$$d_{Derived}(3) = \Delta t.S \text{ m}$$

2) Time between attaching branchlines, $\Delta t_{Derived}$

a) Using the total time to deploy the mainline, T, minutes, consisting of (N/HPF) baskets each containing ($HPF+1$) branch sections, the time between attaching each branchline is given by

$$\Delta t_{Derived}(1) = \frac{60.T.HPF}{N.(HPF+1)} \text{ seconds}$$

b) Using the distance between branchline, d, and the speed of the line shooter S, the time between attaching each branchline is given by:

$$\Delta t_{Derived}(2) = \frac{d}{S} \text{ seconds}$$

3) Line shooter speed, $S_{Derived}$

   a) Using the total length of mainline deployed, *M* kilometers, and the total time to deployed the mainline, *T,* minutes, the line shooter speed is given by:

$$S_{Derived}(1) = \frac{1000.M}{60.T} \text{ meters per seconds}$$

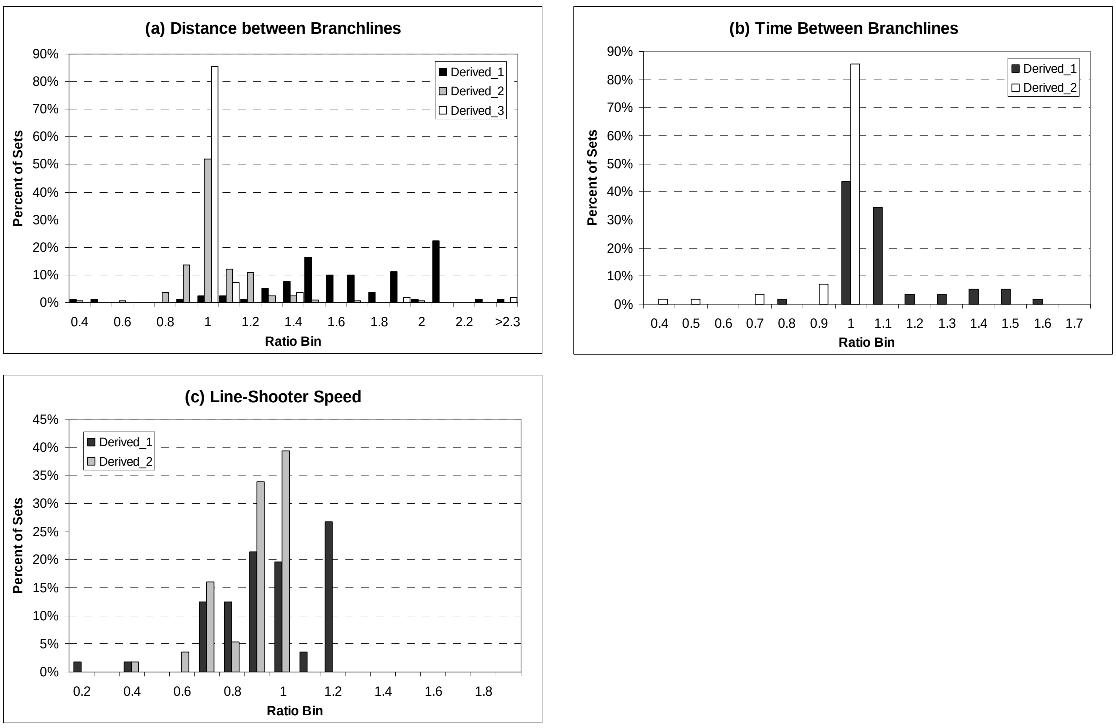
   b) Using the estimate for the mainline length given by $M_{est}(1)$ and the total time to deployed the mainline, *T,* minutes, the line shooter speed is given by:

$$S_{Derived}(2) = \frac{d.N.(HPF+1)}{1000.T.HPF} \text{ meters per seconds}$$

For each derived parameter, the ratio with the corresponding observer-recorded value was calculated and the histogram of these ratios, rounded to the nearest 0.1, are shown in Figure 4.2.

For the distance between branchlines, the values of $d_{Derived}(1)$ correlate poorly with the observer-recorded values. If one believes that the number of hooks deployed and the number of hooks-per-float are reasonably accurately recorded, then this result indicates that either the length of the mainline, M_{obs}, or the distance between branchlines, *d,* as recorded by the observer are in error. On the other hand, the values of $d_{Derived}(2)$ correspond more closely with the observer-recorded values, and as this only parameter which changed between these two results is the recorded mainline length, this indicates that the logbook-recorded length may be a better estimate of the

Figure 4. 2 Histograms of the ratio of the derived-to-observed parameters.



mainline length than the observer-recorded length. Finally, there is a good correlation between the values of $d_{Derived}(3)$ nd the observer-recorded values. Although these parameters were only provided for around one-quarter of the sets, there is a large degree of consistency between these values. This is probably not surprising, as the line-shooter speed and the timer are most likely used to derive the distance *d*. The good correspondence between the values of $\Delta t_{Derived}(2)$ and the observer recorded values n Figure 4.2b supports this conclusion. However, the poorer correspondence between $\Delta t_{Derived}(1)$ and the observer recorded values may indicate that there is a bias in the value of Δt or that the total time to deploy the line.

4.3 Estimation of the Sag Ratio

4.3.1 Definitions

From Table 4.1 it is apparent that the mainline length was not recorded by observers for the majority of sets, though the length of the mainline on the vessel during the trip is available from the majority of logbook data. Furthermore, not all sets are deployed in a straight line and so the horizontal distance between the set-start and set-end positions does not provide a correct measure of the horizontal distance between the first and last float. However, this distance can be estimated by multiplying the vessel setting speed by the total time to deploy the line (though the actual distance is likely to be influence by current speed). Given these data limitations, the following approach was used to estimate the parameters *D* and *M* required to calculate the sag ratio, *SR*.

A. Estimation of *D*, the horizontal distance between first and last float.

1) Great-circle distance, D_{GC}

   Where the start-set and end-set positions are known, the great-circle distance between these two positions was calculated (Anon, 2008):

$$D_{GC} = 2R_e.\arcsin(\sqrt{\sin^2\left(\frac{\beta_e - \beta_s}{2}\right) + \cos\beta_s \cos\beta_e \sin^2\left(\frac{\lambda_e - \lambda_s}{2}\right)} \; kms$$

   where (β_s, λ_s) and (β_e, λ_e) are the respective latitude and longitudes of the start and end positions and R_e=6372.795 km is the spherical radius of the earth.

2) Distance travelled, D_{DT}

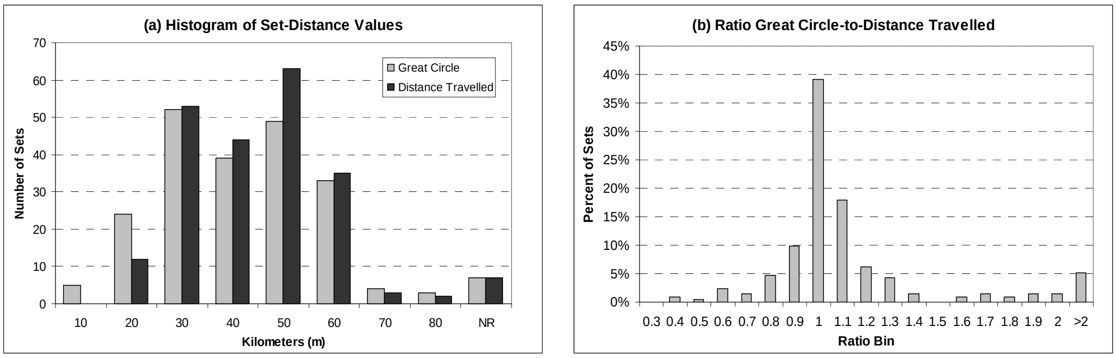
   Where the vessel setting speed and the total time to deploy the line are known, the distance steamed between the start and end of the set was calculated:

$$D_{DT} = \frac{1.852.V.T}{60} \; kms$$

   where V = setting speed of vessel (knots)
   T = total time to deploy longline (mins)

Both D_{GC} and D_{DT} were calculated for 212 of the 219 TDR sets and the histograms of the two calculated set-distances are shown in Figure 4.3a. As one would expect if mainlines are not deployed in a straight line, the great-circle distances are generally smaller than the distances travelled. However, the histogram of the ratio of D_{GC} to D_{DT}, shown in Figure 4.3b, indicates that for many sets $D_{GC} > D_{DT}$ so that it is likely

Figure 4.3 (a) Histograms of the two estimates of the horizontal distance between first and last float across the 219 TDR sets, and (b) histogram of the ratio of D_{GC} to D_{DT} for the 212 sets with data.



that the actual horizontal distance between first and last float is likely to be poorly estimated.

B. Estimation of M, the length of the deployed mainline

Together with the observer-recorded, M_{obs}, and logbook-recorded, M_{log}, mainline lengths, the following three derived estimates were also used:

1) If one assumes that the distance between a float and a branchline is the same as the distance between adjacent branchlines, and that this distance d is a constant, then the length of the mainlines between adjacent floats is $d.(HPF+1)$. If N is the number of hooks deployed, then the number of float sections (baskets) deployed is N/HPF and the total length of mainline deployed is given by:

$$M_{Derived}(1) = \frac{d.N.(HPF+1)}{1000.HPF} \quad kms$$

2) If a line-shooter is used to deploy the mainline at a speed of S m/s and the total time to deploy the line is T minutes, then the total length of mainline deployed is given by:

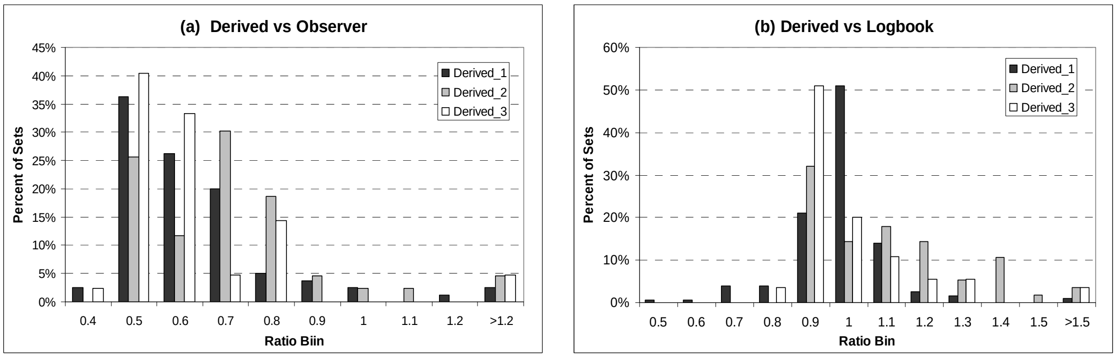
$$M_{Derived}(2) = \frac{60.S.T}{1000} \quad kms$$

3) If a line-shooter is used to deploy the mainline at a speed of S m/s and the time between attaching each branchine or float is Δt seconds, then the length of one float section is $\Delta t.S.$(HPF+1) and the total length of the deployed mainline is given by:

$$M_{Derived}(3) = \frac{\Delta t.S.(HPF+1).N}{1000.HPF} \quad kms$$

Based on the availability of data values of $M_{Derived}$(1,2,3) were calculated for 210, 56 and 56 sets respectively, and comparisons with the observer-recorded value were possible for 80, 43 and 42 sets while comparisons with the logbook-recorded value were possible for 200, 56 and 55 sets. Where comparisons were possible, the percentage of sets versus the ratio of the derived value of the length of the deployed mainline to both the observer-recorded and the logbook-recorded values are shown in Figure 4.4. The results indicates that the three derived values are in most situations

Figure 4.4 Ratio of the three derived values of the length of the deployed mainline to (a) the observer-recorded value (b) the logbook-recorded value.



less than the length recorded by the observer, while the derived values have a better correlation with the logbook-recorded value. For this latter comparison, the first derived value is seen to have the highest degree of correlation, with $M_{Derived}(1)$~M_{log} for 102 of the 200 comparisons (i.e. being within the ratio bin=1.0).

With up to five possible values of the mainline length *M* (the two recorded values and the three derived values), and the two estimates of the horizontal distance between the first and last floats *D*, it is possible to derive up to 10 estimates of the sag ratio for each set. However, the above results indicate that the observed-recorded values of *M* are likely to be unreliable and so these values were not used further. The definitions of the eight Sag-ratios potentially calculated for each set are provided in Table 4.2. Pair-wise comparisons of the Sag-ratio values where the same definition of *M* were used are shown in Figure 4.5 whilst the distributions of Sag-ratios for all eight definitions are shown in Table 4.3.

Theoretically, the Sag-ratio can take on a value between 0 and 1, with the former value depicting a situation with the line is deployed vertically (i.e. horizontal distance is zero) and the latter value depicting a situation where the line is deployed taut with no sag (i.e. horizontal distance = length of line). However, the distributions shown in Table 4.3 indicate a number of cases where the estimated Sag-ratio is greater than 1. The reasons for this are likely to be an over-estimation of the horizontal distance *D* or an under-estimation of the mainline length *M* (or both). All estimates of the Sag-ratio

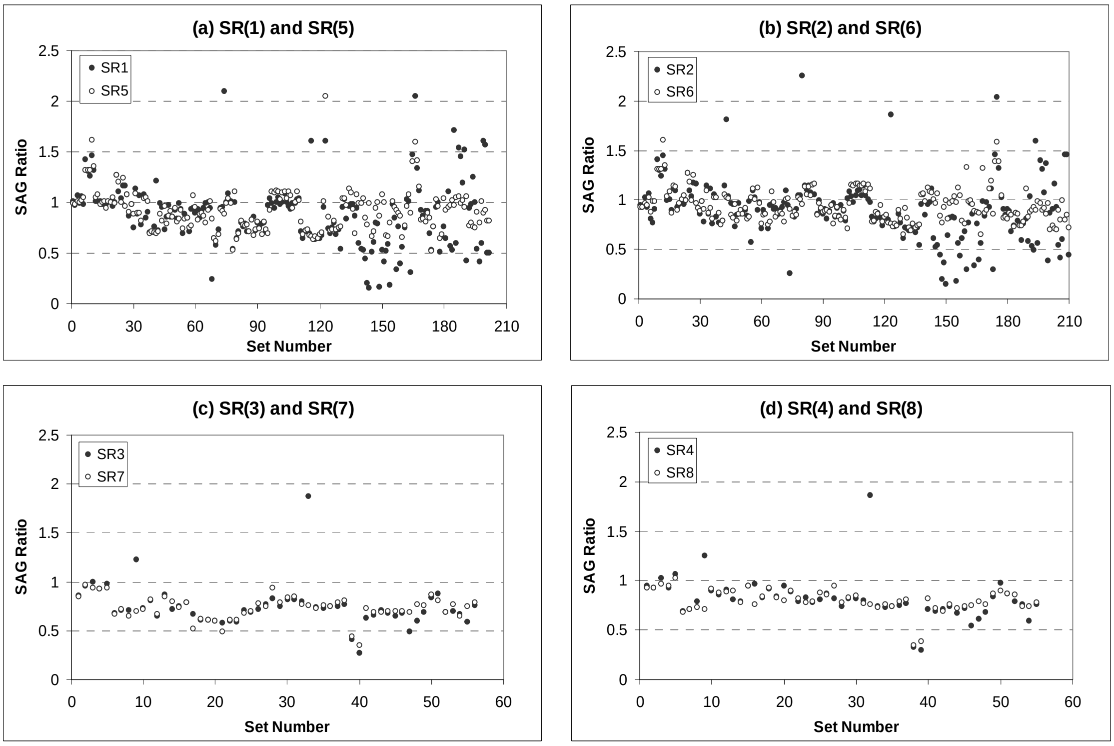
Table 4.2 Definitions of the eight estimates of the sag ratio, *SR*, and the number of sets for which each value was calculated based on availability of data.

	Horizontal Distance, D		Mainline Length, M		Sag Ratio,SR
SR	Definition	No. Sets	Definition	No. Sets	No. Sets
1	Great-Circle	212	Logbook-recorded	209	202
2	Great-Circle	212	M-Derived (1)	210	210
3	Great-Circle	212	M-Derived (2)	56	56
4	Great-Circle	212	M-Derived (3)	55	55
5	Distance Travelled	212	Logbook-recorded	209	202
6	Distance Travelled	212	M-Derived (1)	210	210
7	Distance Travelled	212	M-Derived (2)	56	56
8	Distance Travelled	212	M-Derived (3)	55	55

Table 4.3 Histograms of the number of sets against the mid-point bin values of each calculate Sag-ratio.

	Great Circle Distance				Distance Travelled			
Midpoint	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8
0.1								
0.2	5	3						
0.3	2	4	1	2				1
0.4	5	7	1				2	1
0.5	12	6	1	1	2		2	
0.6	16	11	9	2	6	1	5	
0.7	25	17	25	13	34	16	21	12
0.8	21	34	10	19	36	47	18	22
0.9	32	46	4	12	34	55	7	17
1	50	39	3	3	52	46	1	2
1.1	11	21		1	26	25		
1.2	5	5	1		2	9		
1.3	5	5		1	4	7		
1.4	1	4			3	2		
1.5	5	3						
1.6	4	1			2	2		
1.7	1							
1.8		1						
1.9		1	1	1				
2		1						
2.1	2				1			
2.2		1						
Total	202	210	56	55	202	210	56	55
Null	17	9	163	164	17	9	163	164
Total	219	219	219	219	219	219	219	219

Figure 4.5 Pair-wise comparison of the calculated Sag-ratios having the same estimate of mainline length. Sets between the two vertical line where recorded as having a U-bend or zig-zag configuration, those to left in a straight line and those to the right an unrecorded configuration.



are obviously highly dependent on the accuracy of the data used in making these calculations. In particular, where direct estimates of *D* are made, recordings of the start and end positions and times and the vessel-setting speed need to be accurate. Where derived estimates are used, obviously the most crucial information required are the number of hooks, the number of HPF, the distance between attached branch-lines, the line-shooter speed and the time between attached branch-lines. Which of these data are easiest to record and of the highest accuracy presently remains unknown but it should be possible to record each relatively accurately.

One-situation which would introduce bias in the calculation of the Sag-ratio based on the great-circle calculation of *D* is when the mainline is not deployed in a straight line. When this occurs, the distance between the start and end-positions will be less than the horizontal distance steamed whilst setting the line. Observers are requested to record the configuration of the line on deployment as either (a) in a straight line, (b) in a U-bend, or (c) in a zig-zag. Comparisons of the estimated Sag-ratios in these situations is shown in Figure 4.5 and indicates that where the line is deployed in a straight line the Sag-ratios based on either the great-circle method or the distance-travelled method are in general agreement. On the other-hand, when the line is not deployed in a straight-line, the estimated Sag-ratio based on the great-circle method is less than that based on the distance-travelled method.

4.3.2 Selection of Sets

Due to the likelihood that many data values in both the logbook and observer data may be of limited accuracy, only those sets where the data satisfied the following criteria were selected for further analysis.

$$0.9 < Ratio < 1.1$$

where the value of *Ratio* is one of the following:

1. (derived-value of *d*) / (observer-recorded value of *d*)
2. (derived-value of *S*) / (observer-recorded value of *S*)
3. (derived-value of Δt) / (observer-recorded value of Δt)
4. (Logbook-value of *T*) / (observer-recorded value of *T*)

Application of this criteria resulted in the selection of 56 sets for further analysis and comparison of the eight calculated Sag-ratios for these sets is shown in Figure 4.6. Unfortunately, this did not eliminate all unrealistic Sag-ratio values, with 33 (7.3%) of the 448 values still being greater than 1. Half these values were associated with the values of *SR1* and *SR5*. The ratio $R=D_{GC}/D_{DT}$ of the two measures of the horizontal distance was also checked with 45 of the 56 sets having a value between 0.9 and 1.1.

In order to calculate a single 'best-estimate' of the Sag-ratio for each test, a simple average over all estimates with a value less than 1 was taken. This 'best-estimate' was also compared with (i) the mean of *SR1* and *SR5* and (ii) the mean of *SR2, SR3, SR4*, *SR6, SR7 and SR8* and a comparison of these calculated values is shown in Figure 4.7. The Avg(1,5) values show the greatest degree of difference compared to the other average values and suggests that *SR1* and *SR5* are the most unreliable of the eight Sag-ratio estimates. Indeed, both rely on the logbook-recorded value of the mainline length. As there did not appear to be any systematic difference between sets with no recorded set-configuration and those sets where the ratio $R=D_{GC}/D_{DT}$ was less than 0.9 or greater than 1.1, all sets where included in the further analyses.

Figure 4.6 Comparison of the eight calculated Sag-ratios for the 56 sets selected as having the most reliable data. Lines to the left of the vertical line denote sets deployed in a straight line, whilst those to the right denote those where the set configuration was not recorded. Within each section, sets are ordered in an ascending value of the ratio $R=D_{GC}/D_{DT.}$ Sets where $0.9<R<1.1$ are within the drawn boxes.

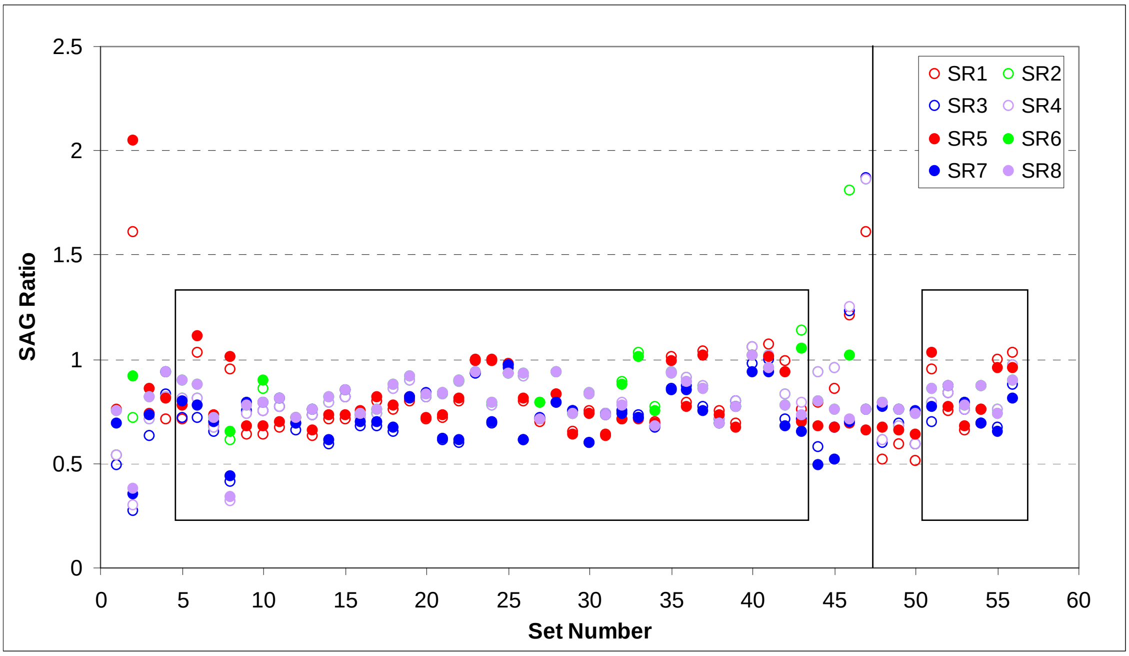
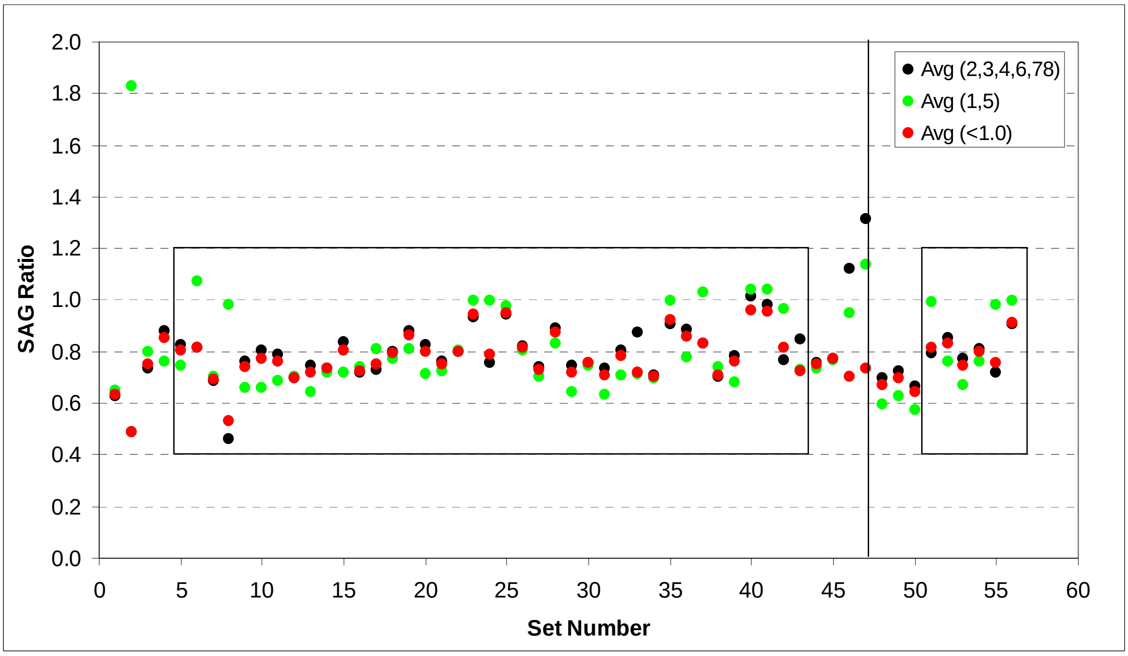


Figure 4.7. Average of the Sag-ratios shown in Figure 4.6 for each set using three different criteria for which values were included. Lines to the left of the vertical line denote sets deployed in a straight line, whilst those to the right denote those where the set configuration was not recorded. Within each section, sets are ordered in an ascending value of the ratio $R=D_{GC}/D_{DT.}$ Sets where $0.9<R<1.1$ are within the drawn boxes.



4.3.3 Estimates of Sag-Ratio and Sag-Angle

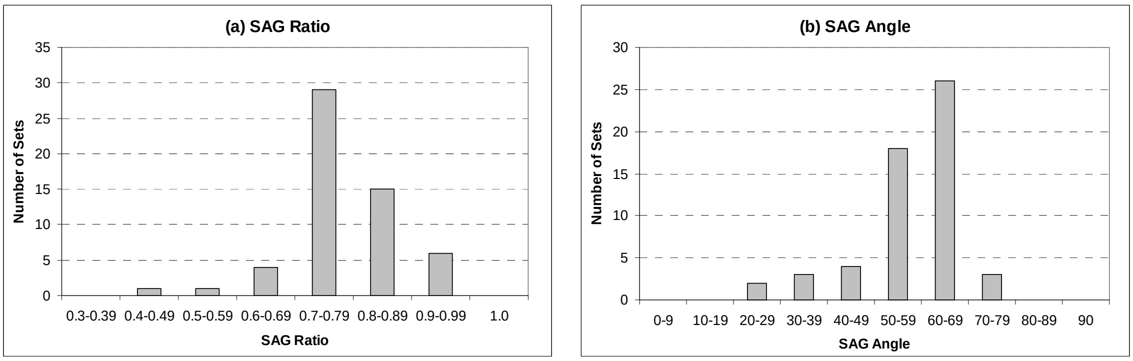
For the 56 selected sets, a histogram of the 'best-estimate' of the Sag-ratio is shown in Figure 4.8a. The most common values are between 0.7-0.79, accounting for 29 (52%) of the 56 sets. The minimum, maximum and mean values are 0.49, 0.96 and 0.77 respectively.

The Sag ratio was also used to determine the sag-angle (the angle subtended by the mainline and the horizontal at the point of attachment) by solving the following equation (c.f. equation (2)).

$$SR = \cot\theta . \ln(\tan\theta + \sec\theta)$$

A histogram of these values is shown in Figure 4.8b. The most common values are between 60-69 degrees, accounting for 26 (46%) of the 56 sets, with a further 18 (32%) having a sag angle between 50-59 degrees. The minimum, maximum and mean values of the sag angle are 24, 78 and 57 degrees respectively.

Figure 4.8 Estimated Sag-ratio and sag-angles for the 56 selected sets.

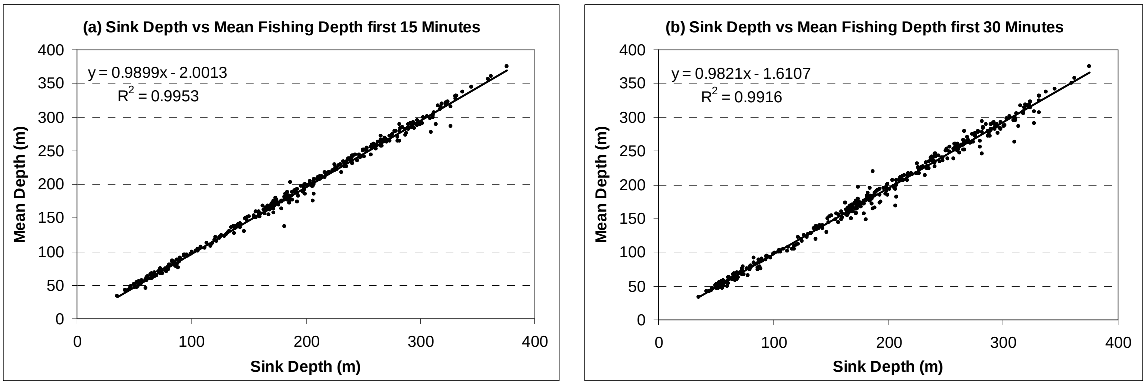


4.4 Predicted versus Measure Depths

With an estimate of the sag-angle, it is now possible to use equation (1) to make predictions about the hook depths for each longline set. These predictions can then be compared with the observed depths as measured by the TDRs. For the 56 selected sets, there were a total of 357 TDR observations which can be used for this purpose. However, due to the well-established fact that the depth of a hook can change considerably during the time spent fishing, two definitions of measured depth were used for comparative purposes. The first is the estimated sink depth of the TDR (c.f. section 3.4), while the second is the average of the depths during the first 15 and 30 minutes of the fishing period (i.e. the initial, and hopefully relatively stable, period after the longline has initially settled). A comparison of the sink depth with each of the two fishing depths is shown in Figure 4.9.

The first plot shows a high degree of correlation between the sink depth and the average depth in the first 15 minutes (Pearson correlation, R^2=0.995) and suggests that (a) the sink depths were accurately estimated, and (b) there is little change in depth during the first 15 minutes. The comparison between the sink depths and average depths over the first 30 minutes also shows a high degree of correlation (R^2=0.991), again indicating that there is no significant shift in the depths of hooks during this

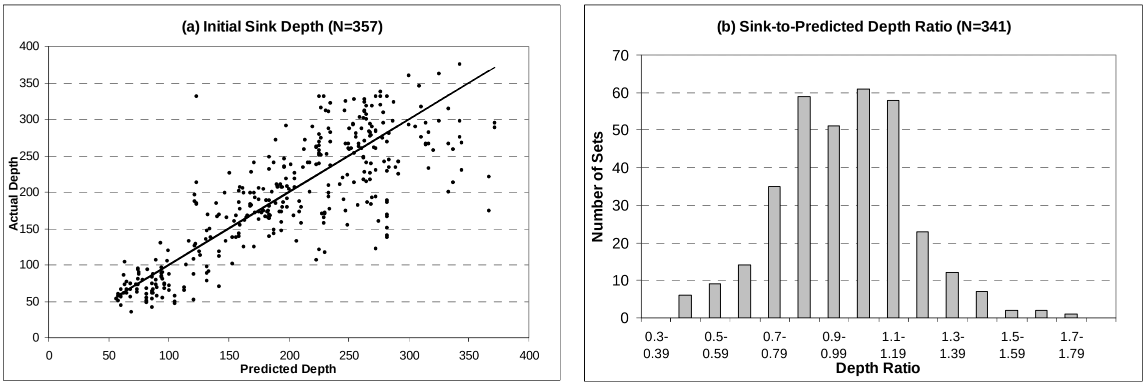
Figure 4.9 Comparison of the sink depth of a TDR, with the mean depth fishing by that TDR during (a) the first 15 minutes, and (b) the first 30 minutes.



time. A comparison of the two fishing depths (not shown) was also highly correlated (R^2=0.998). The sink depth was used in the ongoing analyses.

A comparison of the predicted depths, *P*, for the 357 deployed TDRs based on the configuration equation (1) and the recorded TDR sink depth, *A*, is shown in Figure 4.10a. There is a large scatter of points indicating that the actual recorded sink depth is often significantly different from the predicted depth. Actual depths varied between 0.35 and 1.72 times the predicted depth, with 90 percent of actual depths being within 37 percent of the predicted depth. However, a closer examination of the results indicated 16 observations where the actual depth was greater than the theoretically greatest possible depth (i.e. the depth predicted for a vertical longline with a Sag-ratio equal to 0). As this is likely to be based on a data error these observations were excluded from further analysis. With these observations excluded, there was found to be a slight preference for the predicted depth to be greater than the actual depth, with A<P for 174 observations and A>P for 167 observation, however there is little overall difference in actual and predicted depths with the mean of the ratio (*R=A/P*) being 0.99 (and 0.97 using the ratio with the mean depth during the first 15 minutes). (Note: a Wilcoxon matched-pairs signed rank test accepts the hypothesis of no overall difference with p=0.078). Based on this result, it would appear that the catenary equation is a good predictor of overall mean sink depth, but not a good predictor for any single hook.

Figure 4.10 (a) Scatterplot of the actual and predicted depths for the 357 TDR observations, and (b) histogram of the ratio of depths (*R=Actual/Predicted*) for the 341 selected TDR observations.



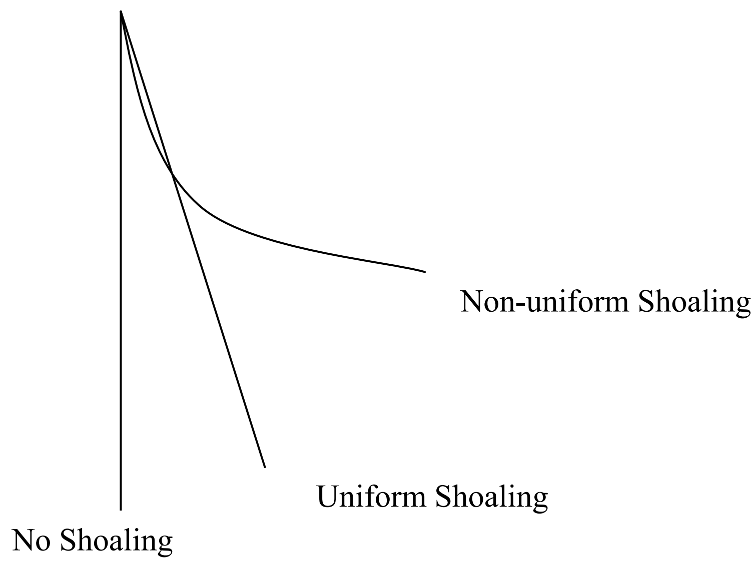
4.5 Factors Influencing Hook Depth

4.5.1 Shoaling of the Longline

The large variation in the predicted depth and the actual depth attained by a hook is likely to be due to a number of factors such as water currents and surface waves. A number of studies have indicated that currents can shoal the longline resulting in the hooks fishing at shallower depths than those predicted from application of the catenary equation. However, currents do not necessarily affect the longline gear in a uniform manner, with the result that different parts of the longline may be shoaled to differing degrees.

For example, if the degree of shoaling is influenced by the weight of the gear hanging below each point, then the profile of the gear in the vertical plane will be curvilinear (instead of a straight line if the shoaling is uniform). Such a situation is depicted in Figure 4.11. In this latter situation, the difference between the actual and predicted depths will vary with hook-position, being less for hooks near the attachment point of the mainline to the float line and greater for hooks near the middle of the basket.

Figure 4.11 Schematic of the vertical profile of a longline indicated a shape of the line under no shoaling, uniform shoaling and two examples of non-uniform shoaling.



Evidence for such non-uniform shoaling was investigated in the TDR data by classifying the hook-number associated with each TDR as a Middle-hook, an End-hook (i.e. next to the attachment point of the mainline and the float line) or as an Other-hook and then comparing the ratio of the actual and predicted depths for each hook-type. The results, shown in Table 4.4, indicate that the actual-to-predicted depth ratio decreases as the hook-position changes from the start to the middle of a basket, as expected for non-uniform shoaling. The same result is obtained using the ratio of the absolute difference between the actual to predicted depths to the predicted depth and the estimated Sag-ratio based on the actual depth (and assuming no shoaling). In this situation, the actual difference between the two depths is again seen to increases as the hook-position changes from the start to the middle of a basket.

Table 4.4 Mean statistics measuring the difference between the actual and predicted depths of a hook stratified by hook-type.

		Hook_type			
		Middle	Other	End	All
Initial Sink Depth	Estimated SAG Ratio	0.78	0.70	0.62	0.71
	Actual/Predicted Depth	91.0%	101.6%	106.4%	99.4%
	ABS(Act-Pred)/Pred	21.6%	17.1%	13.7%	17.9%
Mean Depth 15 Minutes	Estimated SAG Ratio	0.79	0.72	0.68	0.73
	Actual/Predicted Depth	89.4%	99.2%	103.0%	97.1%
	ABS(Act-Pred)/Pred	22.0%	16.8%	13.9%	17.8%

4.5.2 Factors influencing Recorded Sink Depth

As the above example demonstrates, the manner in which oceanographic and other environmental factors influence the depth attained by hooks may depend on the relative position of the hook in relation to the configuration of the longline, and perhaps in relation to the overall configuration of the longline itself. In this section, we make use of data collected by observers on oceanographic conditions and the configuration of the gears to investigate the manner in which these factors may influence the depth attained by hooks.

Together with information on the gears used in any longline set (and summarised previously), observers also recorded information on the oceanographic and environmental conditions prevailing during the deployment of the longline. In particular, observers recorded the following:

1) *Sea Height (SH)*
2) *Wind Speed (WD)*
3) *Beaufort Scale (BS)*

Information on surface water currents was not recorded *in situ*, but was obtained later using model estimates provided by CSIRO (J. Hartog, *pers comm*.).

A General Linear Model (GLM), assuming a log-normal error distribution, was used to estimate the influence of these factors on the variation between the actual and predicted depths as measured by the ratio, $R=A/P$. Hook-position (*HP*, defined as the proportion of the total distance between floats such that $HP=n/(HPF+1)$ where n=hook-number and $HP=1-HP$ where $HP>0.5$), the number of HPF and information on the use of a line shooter (*LS*) were also included to model the influence of gear configuration. All oceanographic variables were fitted as a cubic, *HP* was fitted as a quadratic, whilst *HPF* and *LS* were fitted as categorical variables. Due to potential confounding of the three factors *Sea-Height*, *Wind-Speed* and *Beaufort-Scale* each was fitted separately, resulting in the following thee models being fitted.

Model 1 $Log(Ratio) = I+SH + SH^2 + SH^3 +CS + CS^2 + CS^3 +HP + HP^2 + HPF + LS$

Model 2 $Log(Ratio) = I+WS + WS^2 + WS^3 +CS + CS^2 + CS^3 +HP + HP^2 + HPF + LS$

Model 3 $Log(Ratio) = I+ CS + CS^2 + CS^3 +HP + HP^2 + HPF + BS + LS$

Table 4.5 Statistics associated with fitting a GLM to ascertain factors influencing the differences in the recorded sink depth and the predicted depth.

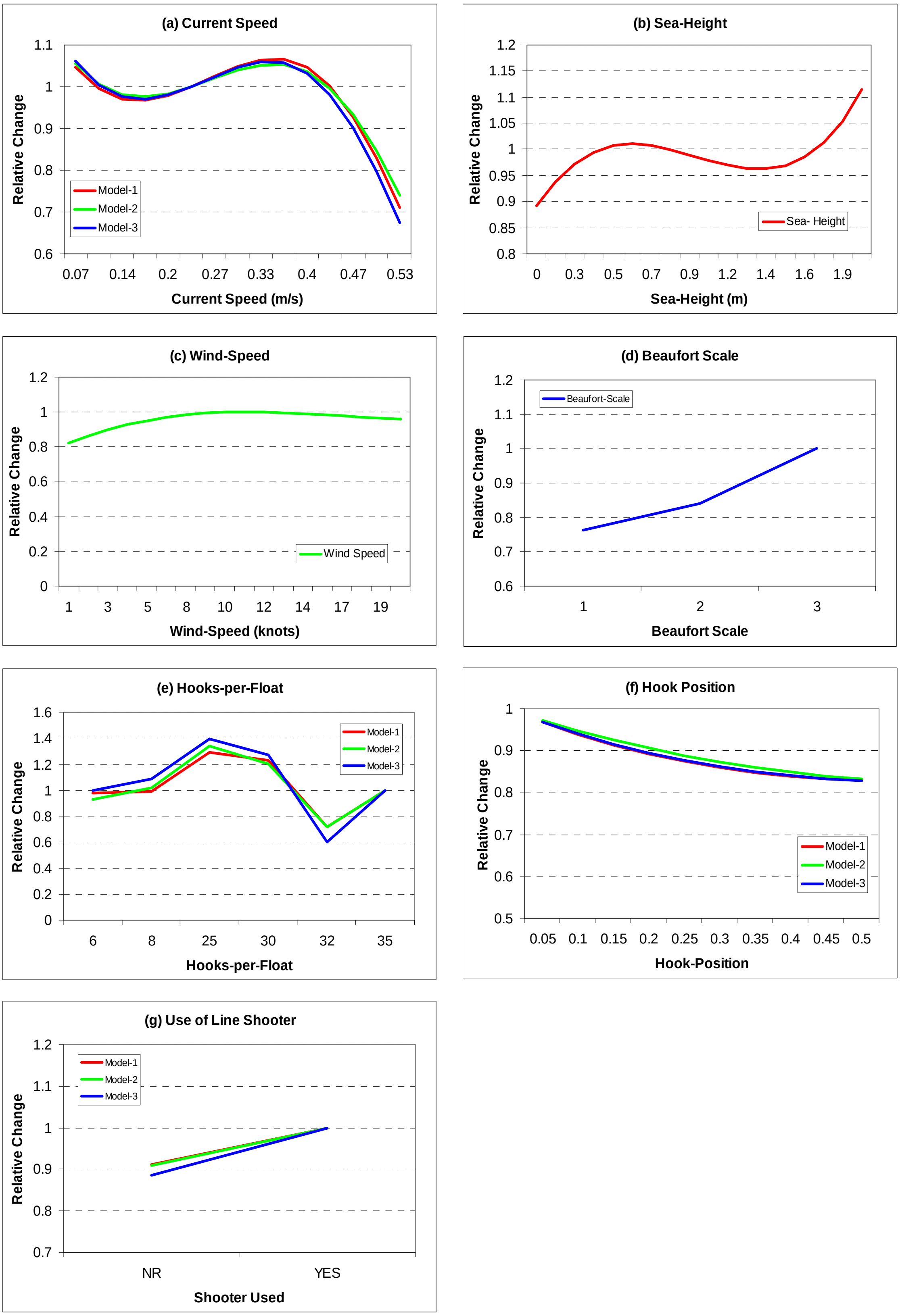
	Model 1		Model 2		Model 3	
Parameter	F-value	Pr > F	F-value	Pr > F	F-value	Pr > F
SeaHt	1.88	0.1713				
SeaHt-2	0.92	0.3372				
SeaHt-3	3.78	0.0528				
Wind			0.28	0.6003		
Wind-2			5.78	0.0167		
Wind-3			0.44	0.507		
Current	10.21	0.0015	6.63	0.0105	10.42	0.0014
Current-2	1.92	0.1672	2.1	0.148	2.25	0.1344
Current-3	22.12	<.0001	16.19	<.0001	25.19	<.0001
Hook	2.47	0.1168	1.73	0.1893	2.44	0.1196
Hook-2	0.77	0.3804	0.33	0.566	0.7	0.403
HPF	11.1	<.0001	11.98	<.0001	14.06	<.0001
Beaufort					7.93	0.0004
Shooter	8.69	0.0034	9.4	0.0024	14.96	0.0001
Model df		14		14		13
Model F		8.47		8.95		10.35
R-sq		26.7%		27.8%		29.1%

The results of fitting each model are summarised in Table 4.5, while the relative influence of each factor included in each model is shown in Figure 4. 12.

Current-speed, HPF and the use of a line shooter were found to be significant in all models, with the former explaining the greatest amount of model variance. Of the three related factors, both sea-height and wind-speed were found to be of marginal significance while the Beaufort-Scale had the greatest significance (and explains the best fit for Model 3). Hook-position was not found to be significant in any of the models. Each model explained between 26-29% of the overall model variance with Model 3 giving the best overall fit (highest F-value, lowest degrees of freedom) and all further discussion is based on the results for this model.

The influence of current-speed on depths is seen to be small for speeds less than 0.4 m/s but for higher speeds the ratio of the actual depths attained by the hooks to the predicted depth is seen to decrease considerably. For a current-speed of around 0.5 m/s the depth of the line is reduced by around 25 percent from its predicted depth. This result supports the shoaling of the longline reported in other studies. The results also indicate that the ratio of the sink-to-predicted depth increases with an increase in the influence of the wind (as measured by sea-height, wind-speed and the Beaufort-scale, with the latter two suggesting around a 20 percent increase in actual depth with scale 3 winds compared to weak winds). The reasons for this increase remain uncertain, but may be due to the fact that the floats are pushed together in strong winds, thus increasing the sag in the line and the depth of the hooks. The use of a line shooter is also seen to increase the depths attained relative to the situation where no line shooter is used, and again this is likely to be associated with the greater sag in the line. The decrease in depth ratio with hook-position is seen to be similar to the previous analysis, but as identified above this result was not found to be significant. Finally, the

Figure 4.12 Influence of each factor included in each GLM model on the dependent variable, *R=Sink/Predicted* depths.



reasons for a change in relative depths associated with the use of different HPF remains uncertain. However, there is only a single set each associated with sets with 6, 32 and 35 HPF and so this result may reflect differences associated with the manner in which gear was deployed by different fishers.

4.5.3 Factors influencing Recorded Fishing Depth

The factors influencing the sink depth of the mainline are also likely to influence the line for the remainder of the soak. As previously discussed (c.f. section 3.3) the depths of the hooks can change considerably during the soak and a plot of the mean depth fished to the sink depth for the 341 selected TDR observations is shown in Figure 4.13. It is seen that the line can either decrease or increase in depth during the soak, though on average the depths were observed to decrease as the mean ratio of the mean depth fished to sink depth over these observations was 0.88. A similar result was found comparing the mean-depths fished to the predicted depths.

A similar analysis as described in the previous section was undertaken to ascertain the factors that may influence the difference (expressed as the ratio) between the mean observed depth and the predicted depth for each deployed TDR. The results are given in Table 4.6. Again, Model 3 was found to provide the best fit to the data (explaining around 32 percent of the variance) and the nature of the influence of each factor is seen to be similar (c.f. Figure 4.14). However, there are a number of differences. First, unlike the previous result the use of the line shooter was not found to be significant and suggests that the influence of this factor may diminish during the soak as a result of changes due to the actions of the currents and other factors. Second, the influence of high current speeds is greater, with currents greater than 0.5 m/s reducing the depths fished by up to 40% from the predicted depths. This result indicates that the action of the currents tend to raise the line further during the soak. Third, unlike the previous result the influence of hook-position is now found to be significant, with the depth of the middle hook being reduced by up to 25 percent from its predicted depth (relative to the end of the basket). The greater influence of hook-position compared to the result for the sink depth is again likely to be due to the greater time the currents have to influence to configuration of the line.

Figure 4.13 Plot of the mean depth fished against the sink depth for the 341 selected TDR observations.

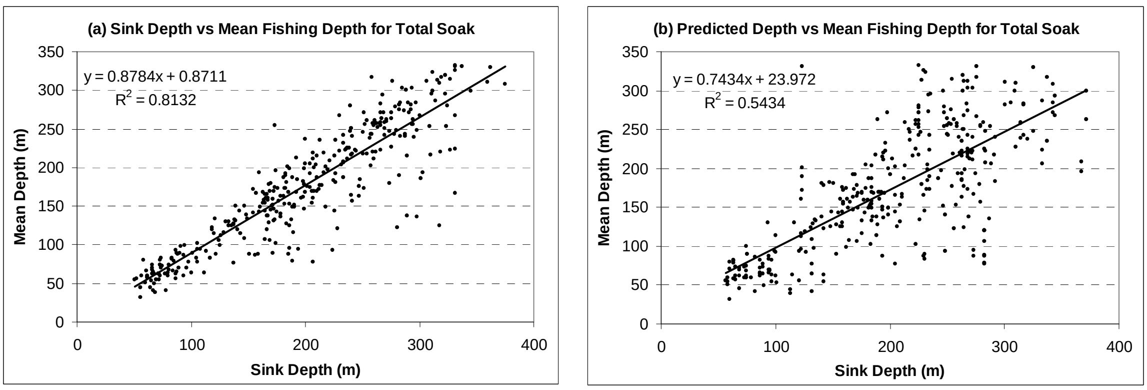
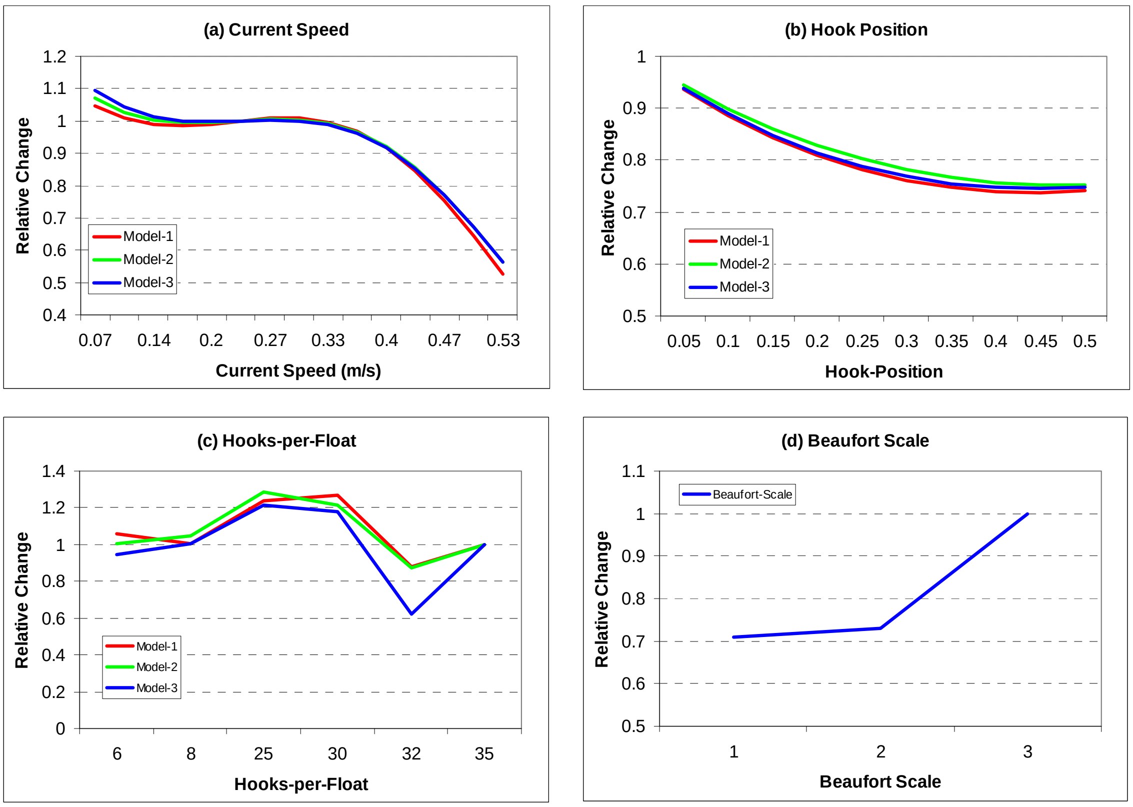


Table 4.6 Statistics associated with fitting a GLM to ascertain factors influencing the differences in the mean recorded fishing depth and the predicted depth.

	Model 1		Model 2		Model 3	
Parameter	F-value	Pr > F	F-value	Pr > F	F-value	Pr > F
SeaHt	4.61	0.0326				
SeaHt-2	0.57	0.4492				
SeaHt-3	5.69	0.0176				
Wind			0.49	0.4862		
Wind-2			6.48	0.0114		
Wind-3			2.34	0.1272		
Current	0.97	0.3245	0.33	0.5681	0.12	0.7338
Current-2	0.2	0.6578	0.03	0.8668	0	0.9844
Current-3	11.71	0.0007	9.19	0.0026	9.64	0.0021
Hook	5.71	0.0175	4.31	0.0387	5.44	0.0203
Hook-2	2.64	0.1055	1.66	0.1982	2.48	0.1165
HPF	4.12	0.0012	3.46	0.0047	5.62	<.0001
Beaufort					6.35	0.002
Shooter	1.85	0.1752	1.71	0.1914	3.78	0.0528
Model df		14		14		13
Model F		10.19		10.51		11.64
R-sq		30.4%		31.1%		31.6%

Figure 4.14 Influence of each factor included in each GLM model on the dependent variable, *R=Mean-Depth-Fished/Predicted-Depth*.



Section 5: Capture Depths and Temperatures of Principal Target Species

5.1 Information Required

Information on the depths that any species is caught on a longline can be used to infer the depth profile of the availability of this species within the water column to the fishing gears. Such information is useful to help the fisher decide the depths at which hooks should be deployed in order to optimise the catch of this target species. In a similar fashion, such information can be used to inform the fisher of depths to avoid if the aim is also to minimise the capture of threatened, endangered or protected (TEP) species such as turtles. However, unless a fish is caught on a hook with an attached depth monitor, information of the depth that a fish is caught needs to be inferred from a number of different data sources. In the analyses outlined in this section, the following procedure was followed to ascertain capture depth.

1. The information collected from the TDRs was used to determine the average depth fished by each hook number within each gear configuration.
2. The information collected by AFMA observers on the hook number associated with the catch of individual species.
3. The distribution of the number of fish caught by hook number was then matched with the information on the mean depth of each hook-number to provide an estimate of the distribution of capture depth of individual species.

5.2 Selection of Observer data

Examination of the observer data indicated that the detailed catch information required for these analyses were available from a total of 2,522 longline sets in the ETBF. However, no information on hook-number was available for 101 of these sets and no information on HPF was available for 249 sets. Furthermore, in order to avoid data recording errors a number of filters were used to select the observer data to be used in the analyses. These filters included:

- Not using 382 sets where more than one HPF configuration was used within the set.
- Not using 720 sets where the number of hooks deployed was not recorded.
- Not using 67 sets where the observer recorded number of hooks deployed did not match the logbook recorder number of hooks.

Not all these excluded sets are mutually exclusive, such that the final number of sets used in the analysis was 1,690 (or 7.4% of all sets in the ETBF during the period of monitoring, c.f. Table 2.4) on which 65,763 fish were caught.

5.3 Capture by Hook-Number

In most instances, the hook-number of each fish caught and retrieved on the longline is recorded by the on-board observer together with the species identification of the fish. The hook-number is defined as the number of the hook after a float, with hook-number 1 being the first hook after the float and hook number k being the k^{th} hook after the float. For any given longline configuration, hook number will range between

Table 5.1 Number of observed fish caught on all observed trips for which a) a valid hook-number was recoded, or (b) an invalid hook number was recorded or not recorded. The percentage shown is the proportion of fish observed for that gear configuration for which the hook-number was or was not recorded.

(a) Valid Hook-Number recorded

HPF	All Fish	%	YFT	BET	ALB	SWO	STM	SBT
4	2019	81.8%	1411	32	439	8	13	0
5	6558	70.1%	3081	179	1313	78	90	215
6	13319	86.6%	4230	415	2575	954	151	232
7	2234	88.9%	406	136	435	153	18	17
8	19965	97.7%	4348	1274	3613	2723	229	172
9	1870	96.4%	381	142	125	264	16	0
10	4865	91.1%	1657	512	500	262	34	0
11	166	99.4%	9	5	14	40	0	0
12	232	95.5%	43	19	53	13	1	0
13	17	89.5%	3	5	1	3	0	0
14	32	94.1%	2	5	1	7	0	0
15	281	64.7%	85	4	8	6	2	0
16	3	7.0%	0	1	0	0	0	0
20	172	93.5%	15	37	27	7	0	0
25	2091	99.6%	229	10	1047	3	3	0
30	3942	77.7%	254	150	2061	10	3	0
	57766	87.9%						

(b) Invalid Hook-Number or Not Recorded

HPF	All Fish	%	YFT	BET	ALB	SWO	STM	SBT
4	448	18.2%	313	6	58	8	9	16
5	2798	29.9%	1186	93	686	79	41	213
6	2069	13.4%	731	121	324	174	25	153
7	279	11.1%	26	7	126	7	1	0
8	468	2.3%	74	30	37	110	7	8
9	69	3.6%	26	16	7	12	0	0
10	475	8.9%	158	126	42	17	2	16
11	1	0.6%	0	0	0	1	0	0
12	11	4.5%	2	0	0	1	0	0
13	2	10.5%	0	0	0	0	0	0
14	2	5.9%	1	1	0	0	0	0
15	153	35.3%	25	14	9	10	1	0
16	40	93.0%	4	13	1	5	0	0
20	12	6.5%	1	0	1	2	0	0
25	9	0.4%	1	0	3	0	0	0
30	1134	22.3%	68	28	748	3	2	0
	7970	12.1%						

1 and N where N is the number of hooks-per-float. If the same HPF configuration is used along the entire longline, then there will be an equal number of hooks deployed at each hook position (equal to H/N where H is the number of hooks deployed).

A summary of the total number of fish caught on the 1690 selected longline sets in the ETBF, stratified by HPF configuration, is shown in Table 5.1. Investigation of the observer data, however, indicated some instances where the hook-number was not recorded or greater than the number of HPF. These latter data were deemed to be erroneous and classified as invalid. A summary of the number of catch records with either a missing or invalid hook-number is given in Table 5.1b. In total there were 57,766 catch records (87.9% of the all catch records) with a valid hook-number and 7,970 records (12.1.8%) with a missing or invalid hook-number. In order to incorporate all catch data into the analysis (important to provide the best estimate of

CPUE) in the following an approach was adopted which enabled both of these sets of data to be included.

5.4 Basic Equations

Here we fully describe the method to estimate the capture-depth profile for a given species which was briefly outlined in section 5.1. The main equations will be used for the remaining analyses described in this chapter.

Let $\widehat{N}_{pgs}$ be the number of fish recorded caught on hook-number p within a gear configuration of g hooks-per-float on longline set s and let $\widehat{N}_{ogs}$ be the corresponding number of fish recorded caught on an unspecified (or invalid) hook-number. If it is assumed that all fish with an unrecorded hook-number were actually caught in the same proportion as the fish with a recorded hook-number, then an estimate of the total number of fish caught on hook-number p within a gear configuration of g hooks-per-float on longline set s is given by:

$$N_{pgs} = \widehat{N}_{pgs} + \widehat{N}_{ogs}.p_{ps}$$

where p_{ps} is the proportion of all fish recorded with a hook-number p in set s and is given by:

$$p_{ps} = \frac{f_{ps}}{\sum_{p=1}^{n} f_{ps}}$$

where f_{ps} is the number of fish in set s recorded caught on hook-number p.

Let H_{gs} be the number of hooks deployed on set s having g hooks-per-float. Then the number of hooks deployed at each hook-number on set s is given by H_{gs}/g and the associated nominal catch rate (fish per 1000 hooks), C_{pgs}, on hook-number p is:

$$C_{pgs} = \frac{1000.g.N_{pgs}}{H_{pgs}}$$

The catch rate at hook-number p aggregated over all sets, N_g, with a configuration of g hooks-per-float is then:

$$C_{pg} = \frac{1000.g.\sum_{s=1}^{N_g} N_{pgs}}{\sum_{s=1}^{N_g} H_{pgs}} \qquad (1)$$

To model the data on hook depth, the depths recorded by the TDRs were stratified into strata of 20m intervals based on the following definition:

stratum = 20[1+floor(depth/20)]

Hence, stratum d corresponds to depths in the range 20(d-1) to (20d-1).

Let t_{rdpgs} be the time spent by TDR r at hook-number p within a gear configuration of g hooks-per-float on longline set s is within depth stratum d. Then the total time spent by all TDRs at hook-number p within a gear configuration of g hooks-per-float on longline set s within depth stratum d is given by:

$$T_{dpgs} = \sum_{r=1}^{n_{pgs}} t_{rdpgs}$$

where n_{pgs} is the number of TDRs at hook-number p within a gear configuration of g hooks-per-float on longline set s. The proportion of time spent by monitored hooks at hook-number p within a gear configuration of g hooks-per-float within set s within stratum d can then be found:

$$P_{dpgs} = \frac{T_{dpgs}}{\sum_{d=1}^{N_d} T_{dpgs}} \qquad (2a)$$

where N_d is the number of individual depth stratum fished by all hooks.

From (2a) it follows that the proportion of time spent within depth stratum d by all monitored hooks at hook-number p within a gear configuration of g hooks-per-float across all sets is given by:

$$P_{dpg} = \frac{\sum_{s=1}^{N_g} T_{dpgs}}{\sum_{s=1}^{N_g}\sum_{d=1}^{N_d} T_{dpgs}} \qquad (2b)$$

Taking the average across all hook-numbers provides an estimate of the mean proportion of time all hooks within a gear configuration of g hooks-per-float spend within depth stratum d:

$$P_{dg} = \frac{1}{g}\sum_{p=1}^{g} P_{dpg} \qquad (2c)$$

Combining (1) and (2b) gives an estimate of the catch rate within each depth stratum for a hook at hook-number p within a gear configuration of g hooks-per-float:

$$C_{dpg} = C_{pg}P_{dpg} = \frac{1000.g.\sum_{s=1}^{N_g} N_{pgs}}{\sum_{s=1}^{N_g} H_{pgs}}.\frac{\sum_{s=1}^{N_g} T_{dpgs}}{\sum_{s=1}^{N_g}\sum_{d=1}^{N_d} T_{dpgs}}. \qquad (3a)$$

Aggregating across all hook-numbers, the expected catch rate within each depth stratum for a gear configuration of g hooks-per-float is given by:

$$C_{dg} = \frac{1}{g}\sum_{p=1}^{N_p} C_{pg}P_{dpg} = \sum_{p=1}^{N_p}\left[\frac{1000.\sum_{s=1}^{N_g} N_{pgs}}{\sum_{s=1}^{N_g} H_{pgs}}.\frac{\sum_{s=1}^{N_g} T_{dpgs}}{\sum_{s=1}^{N_g}\sum_{d=1}^{N_d} T_{dpgs}}\right]. \qquad (3b)$$

Finally, dividing the catch rate within each depth stratum by the proportion of time all hooks for a given gear configuration spend within that depth stratum (given by 2c), then dividing by the sum across all strata, provides an estimate of the proportion of all fish available to all hooks for the given gear configuration within each depth stratum:

$$A_{dg} = \frac{C_{dg}}{P_{dg}} \Bigg/ \sum_{d=1}^{N_d} \frac{C_{dg}}{P_{dg}} \qquad (4)$$

5.5 Distribution of Observed Catch by Hook-Number

The total number of fish observed caught on selected observed trips for which either a valid or estimated hook-number was used in the subsequent analyses is given in Table 5.2. The majority of observations were made on sets with gear configurations of 4-10 HPF, 25 HPF or 30HPF with these sets accounting for 98.4% of the total catch. The distributions of the catch by hook-number across all sets for a range of different gear configuration, N_{pg}, after distributing the catch on missing or invalid hook-numbers using equation (1):

$$N_{pg} = \sum_{s=1}^{N_g} N_{pgs} = \sum_{s=1}^{N_g} \left(\widehat{N}_{pgs} + \widehat{N}_{ogs} . p_{ps} \right)$$

are shown in Figure 5.1. (It should be noted that these distributions are the same for the catch with valid hook-numbers only as the catch with missing or invalid hook-numbers are distributed in the same proportions.)

Table 5.2 Total number of observed fish caught on selected observed trips.

HPF	All Fish	YFT	BET	ALB	SWO	STM	SBT
4	2468	1724	38	498	16	13	0
5	9356	4268	272	1998	156	90	429
6	15388	4963	536	2899	1129	151	385
7	2513	434	145	561	161	18	17
8	20433	4422	1304	3650	2833	229	180
9	1940	409	159	133	277	16	0
10	5341	1816	639	545	280	34	0
11	166	9	5	14	40	0	0
12	241	44	19	53	13	1	0
13	19	3	5	1	3	0	0
14	33	4	5	1	7	0	0
15	435	113	19	16	16	2	0
20	184	15	37	27	8	0	0
25	2094	229	10	1047	3	3	0
30	5074	325	179	2812	13	3	0
	65685	18778	3372	14255	4955	560	1011

For configurations using 4 HPF the distribution of the catch across the different hook-numbers is seen to be relatively uniform for all species (noting the small sample sizes for swordfish and striped marlin). This impression is supported by a chi-square test where the observations support adoption of the uniform distribution hypothesis at the 1-percent level (Table 5.3). However, the other results shown in Figure 5.1 do not appear to generally support a uniform distribution of the catch across all hooks. Again, this is supported by the results of applying a chi-square test in each instance (c.f. Table 5.3).

If hook-number is related to the depth at which a hook fishes, and if fish have a non-uniform distribution with depth, then one would expect a non-uniform distribution of the catch with hook-number. However, if the shape of the longline between the floats is generally symmetric then one would, nevertheless, expect to see symmetry in this distribution as the hook-number increased from 1 to HPF. However, examination of the distributions shown in Figure 5.1 indicates that the main reason for rejecting the uniform distribution hypothesis is the asymmetry of the observed distributions. For example, for those sets deploying 8 HPF there is a large difference in the percentage

Figure 5.1 Distribution of the catch by hook-number across all selected observed sets for a range of HPF configurations.

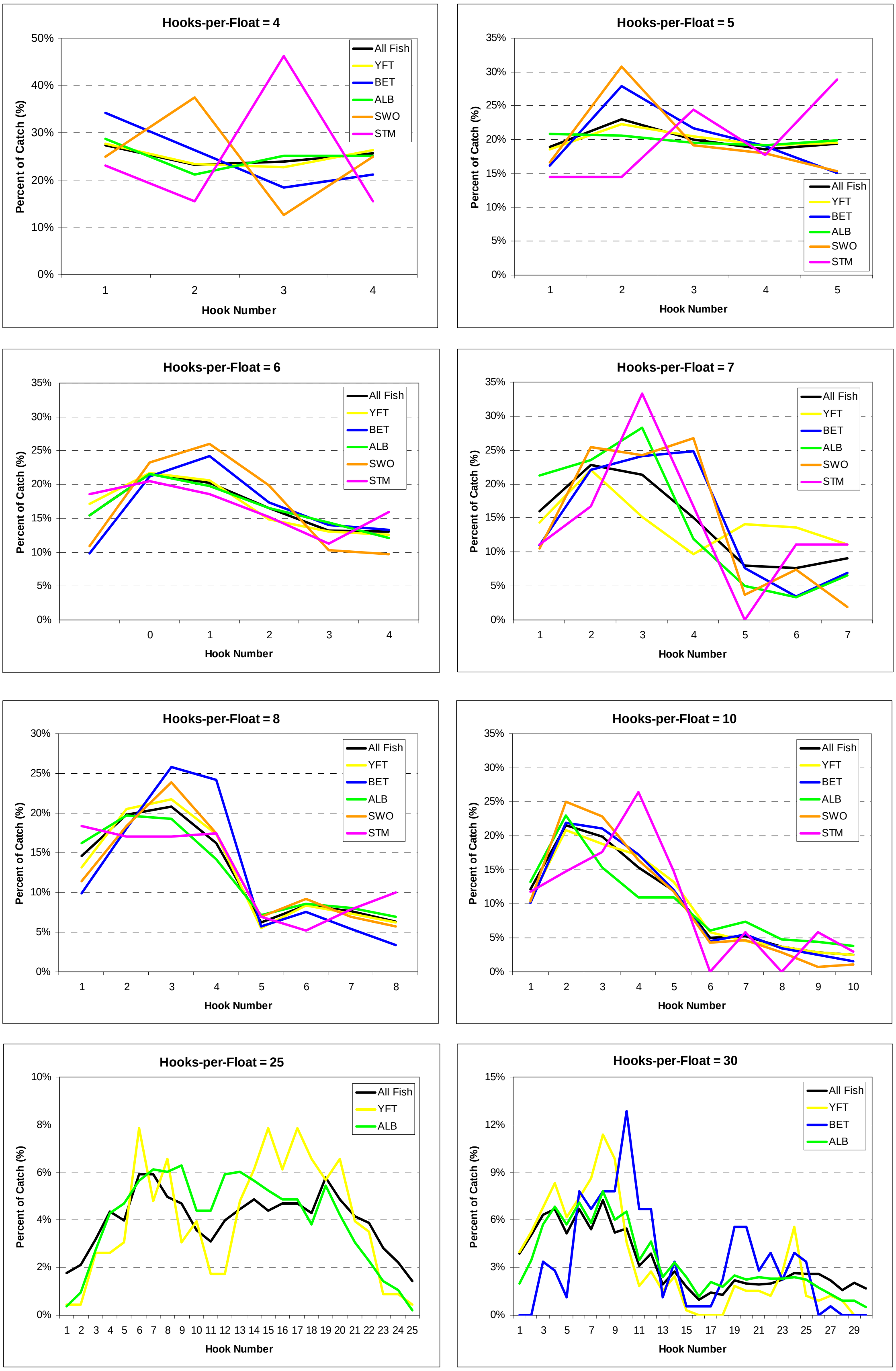


Table 5.3 Chi-squared test values for testing the hypothesis that the distribution of fish on hooks between floats is uniform. Bold indicates those cases where the hypothesis is rejected at the 0.01 level. Blank cases indicate those cases where the number of fish in the sample was deemed to be insufficient (less than 4xHPF).

HPF	All Fish	YFT	BET	ALB	SWO	STM
4	10.7	11.3	2.2	5.8		3.3
5	**59.6**	**18.8**	**14.4**	2.1	11.9	7.4
6	**584.8**	**221.6**	**46.3**	**106.3**	**178.9**	4.9
7	**418.2**	**28.7**	**50.4**	**235.9**	**79.4**	
8	**4223.2**	**1076.3**	**577.7**	**610.5**	**696.5**	**38.6**
9	**539.4**	**133.9**	19.1	18.8	**77.6**	
10	**2476.6**	**818.4**	**346.7**	**178.8**	**199.7**	
12	**191.6**		**43.5**			
15	**70.3**					
20	**228.8**					
25	**190.8**		25.0			
30	**1555.3**	**303.9**	**164.4**			

of the total catch (for all species) observed caught on hook-numbers 1-4 (>70%) compared to hook-numbers 5-8 (<30%). The reasons for this asymmetry remain unclear, however it may be due to the fact that (some) observers (sometime) count the hook-number from the nearest float instead of sequentially from the previous float. If this is the case, and there is symmetry in the shape of the longline between floats so that hooks in similar positions fish similar depths, then this re-defining of the hook-number should not cause a problem in the subsequent calculation of catch by depth. However, if there is an asymmetry in the shape of the longline then the resulting calculations of catch by depth will be biased to some extent.

5.6 Depth Profiles by Hook-Number

For the remainder of this section, the calculations and results are limited to those observed sets where usable TDR data were collected. A listing of the number of sets deploying these TDRs and number of such TDRs attached to each hook-number within each gear configuration is shown in Table 2.5. A total of 1719 usable TDR deployments made across 219 sets utilizing 15 different gear settings were available with the associated hook-number information. For many gear configurations the number of observed sets is not large (sometimes only 1) with usable TDR data from more than 10 sets only available for four different gear configurations (6, 8, 25 and 30 HPF), with these accounting for 185 (84.5%) of the 219 TDR-related sets.

To model the data on hook depth, the depths recorded by each TDR were stratified into strata of 20m intervals (in order to provide 20 strata over the 400m depth range observed) based on the following definition:

$$\text{stratum} = 20*\text{floor}(\text{depth}/20)+10$$

Hence, stratum d corresponds to depths in the range 20(d-1) to (20d-1). Calculating the total time t_{rdpgs} spent by each TDR r within depth stratum d at hook-number p on longline set s having a gear configuration of g hooks-pe*/r-float, then the total time spent by all TDRs at hook-position p within set s having a gear configuration of g hooks-per-float within depth stratum d is given by:

$$T_{dpgs} = \sum_{r=1}^{N_{pgs}} t_{rdpgs}$$

where N_{pgs} is the number of TDRs at hook-number p within a gear configuration of g hooks-per-float on longline set s . It then follows that the proportion of time spent within stratum d by all TDRs at hook-number p within set s having a gear configuration of g hooks-per-float will be given by:

$$P_{dpgs} = \frac{T_{dpgs}}{\sum_{d=1}^{N_d} T_{dpgs}} \tag{2a}$$

where N_d is the number of individual depth stratum fished by all hooks. If one assumes that the hook-depths monitored with TDRs are indicative of all hook-depths at similar hook-numbers with the same set then the proportion of time spent within stratum d (P_{dpgs}) will apply to all hooks at hook-number p within set s.

Finally, if one assumes that the set-types and corresponding hook-depths monitored with TDRs are indicative of all sets across the ETBF then it follows that the proportion of time spent within depth stratum d by all hooks at hook-number p within a gear configuration of g hooks-per-float across all sets is given by:

$$P_{dpg} = \frac{\sum_{s=1}^{N_s} T_{dpgs}}{\sum_{s=1}^{N_s} \sum_{d=1}^{N_d} T_{dpgs}} \tag{2b}$$

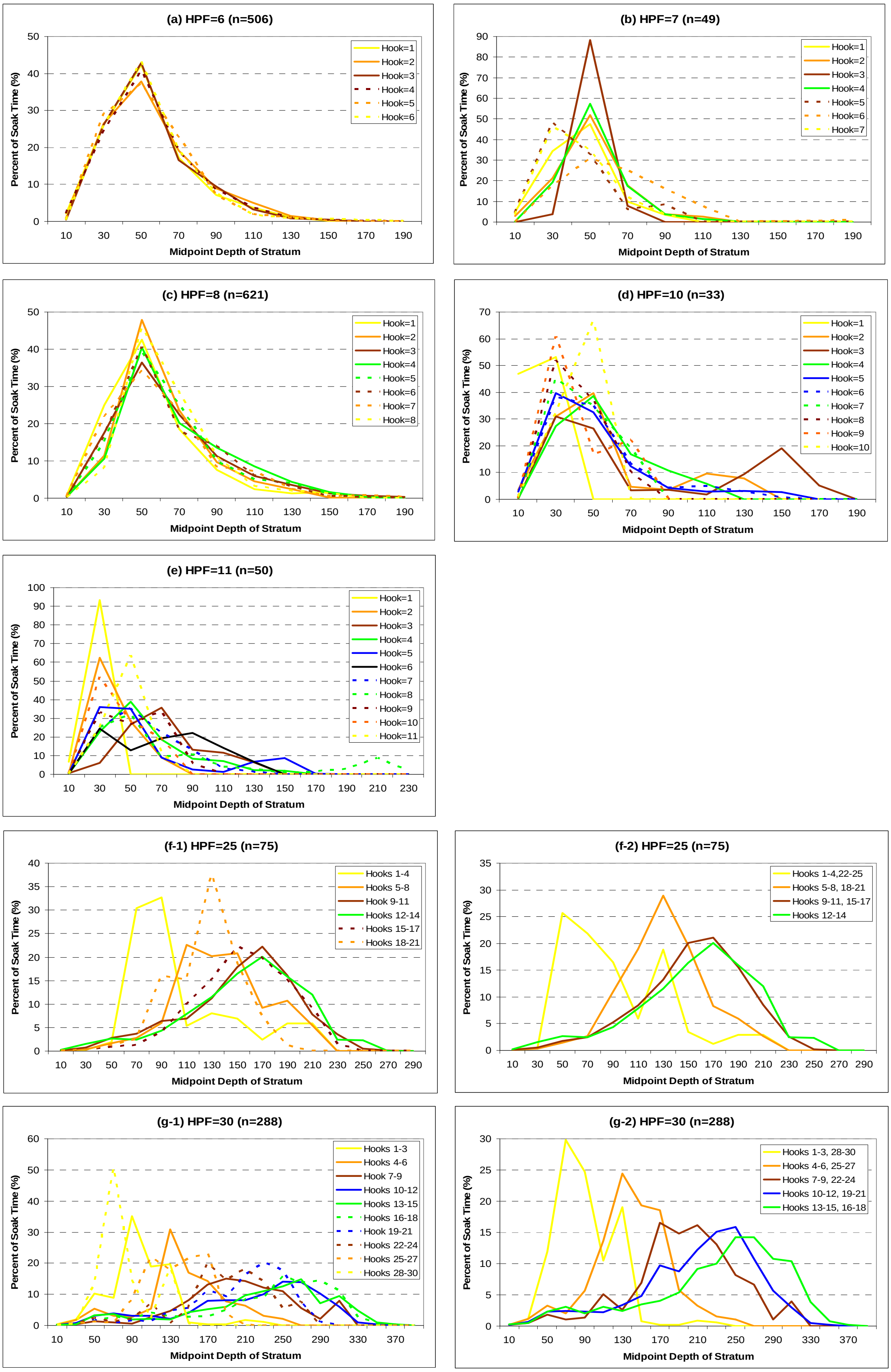
where N_s is the number of sets with g hooks-per-float. Taking the average across all hook-numbers provides an estimate of the mean proportion of time all hooks within a gear configuration of g hooks-per-float spend within depth stratum d:

$$P_{dg} = \frac{1}{g} \sum_{p=1}^{g} P_{dpg} \tag{2c}$$

As explained in section 5.3, the depth-profile P_{dpgs} (the proportion of time spent by each TDR-monitored hook within depth stratum d) fished by each hook-number p within a gear configuration of g hooks-per-float on set s was determined from the data collected. This profile took into account the periods that the hook was sinking and being hauled and was based on the aggregate profile taken across all monitored hooks with hook-number p within set s.

The depth-versus-hook profiles, P_{dpg}, are shown in Figures 5.2 for those gear configurations where more than 30 TDR recordings were obtained. The observed profiles for gear configurations with 6 HPF are seen to be almost identical and correspond to the previous result given in Section 3.4 describing the mean depths fished by TDRs attached at each hook-number. The profiles for gears with 8 HPF are also seen to be very similar. For gear configurations with 9 or more HPF there is a pattern of hooks closer to the floats generally spending a higher proportion of their time in shallower waters than hooks closer to the middle of the basket. Again, this is expected for lines hanging under the influence of gravity. This is clearly seen in the profiles for gears with 25 and 30 HPF where corresponding groups of hook-numbers a similar distance from either end float have been grouped together (right-hand plots). The mean depths for these five profiles are as follows:

Figure 5.2 Mean depth-profile P_{dpg} (percent of total soak time spent within depth strata d) fished by hook-number p within a gear configuration of g hook-per-floats. The number of TDR recordings associated with each HPF, n, is also shown.



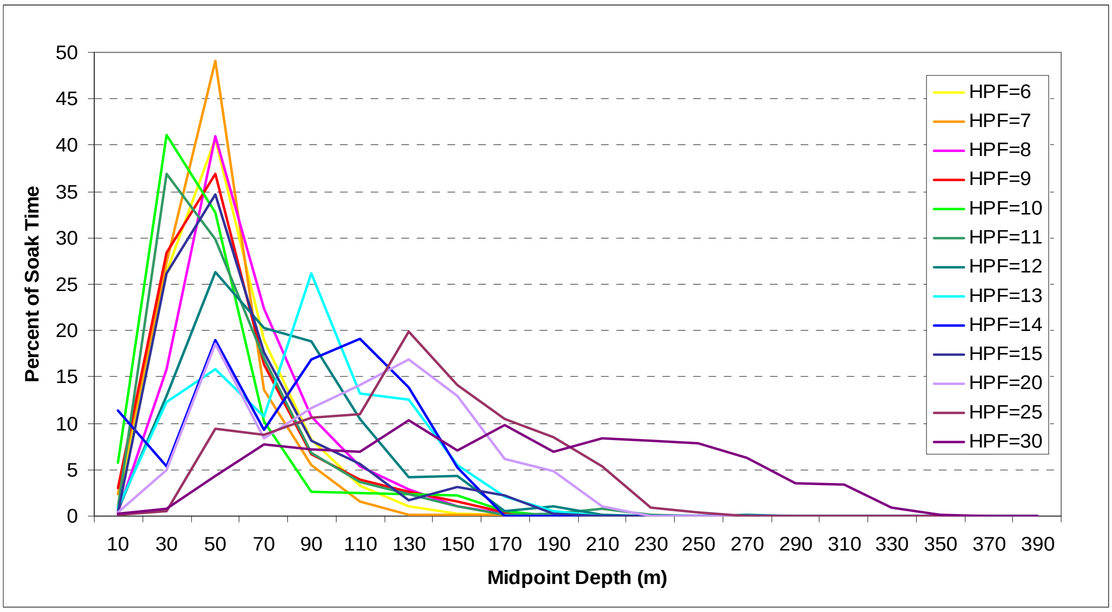
- Hooks 1-3, 28-30) Mean depth = 91 m
- Hooks 4-6, 25-27) Mean depth = 140 m
- Hooks 7-9, 22-24) Mean depth = 196 m
- Hooks 10-12, 19-21) Mean depth = 209 m
- Hooks 13-15, 16-18) Mean depth = 229 m

Combining the profiles across all hook-numbers provides an estimate of the mean proportion of time all hooks within a gear configuration of *g* hooks-per-float spend within depth stratum *d*. These estimates are provided in Table 5. 4 and are displayed in Figure 5.3. Consistent with previous results, all gear configurations with less than 10 HPF are seen to have a similar depth profiles and it is only for gears with 10 or more HPF that the profiles have a successively deeper and greater depth range.

Table 5.4 Estimated percent of total soak time spent within depth strata *d* by all hooks within a gear configuration of *g* hook-per-floats.

Depth	HPF=6	HPF=7	HPF=8	HPF=9	HPF=10	HPF=11	HPF=12	HPF=13	HPF=14	HPF=15	HPF=20	HPF=25	HPF=30
0-19	1.06	2.37	0.42	3.07	5.71	0.95	0.71	0.95	11.39	0.45	0.42	0.18	0.24
20-39	26.30	27.29	15.86	28.46	41.06	36.87	13.01	12.32	5.39	26.16	4.97	0.56	0.78
40-59	40.73	49.10	40.96	36.86	32.77	29.80	26.31	15.85	18.94	34.67	18.55	9.44	4.32
60-79	19.00	13.67	22.40	16.32	10.23	17.01	20.26	10.68	9.31	17.64	8.33	8.73	7.66
80-99	8.19	5.54	10.69	6.66	2.64	6.86	18.81	26.16	16.92	8.13	11.66	10.58	7.20
100-119	3.23	1.62	5.38	3.94	2.49	3.72	10.44	13.20	19.05	5.68	14.18	10.93	6.91
120-139	1.02	0.07	2.88	2.61	2.35	2.38	4.25	12.54	13.82	1.71	16.94	19.84	10.36
140-159	0.32	0.08	1.00	1.61	2.23	1.02	4.31	5.50	5.20	3.10	12.92	14.18	7.08
160-179	0.09	0.10	0.27	0.40	0.52	0.17	0.54	2.14	0.00	2.22	6.12	10.49	9.81
180-199	0.03	0.14	0.11	0.06	0.00	0.27	1.00	0.56	0.00	0.26	4.89	8.51	6.98
200-219	0.03	0.00	0.02	0.01	0.00	0.80	0.12	0.06	0.00	0.00	1.02	5.30	8.33
220-239	0.00	0.00	0.01	0.00	0.00	0.16	0.01	0.05	0.00	0.00	0.00	0.92	8.07
240-259	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.33	7.88
260-279	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.01	6.33
280-299	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	3.50
300-319	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.46
320-339	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86
340-359	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19
360-379	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
380-399	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Figure 5.3 Plots of the estimated depth-profiles P_{dg} (percent of total soak time spent within depth strata *d* by all hooks within a gear configuration of *g* hook-per-floats).



5.7 CPUE Profiles by Depth

For any set where TDRs have been used to monitor the depth profiles of the hooks, if one assumes that these depth profiles are indicative of the profiles for all hooks at a given hook-number along the entire longline, then one can match these profiles with the aggregate catch-profile for each hook-number in the set to obtain a catch-by-depth profile for that set. One can then aggregate the catch-at-depth profiles across all sets to obtain an overall catch profile for the fishery.

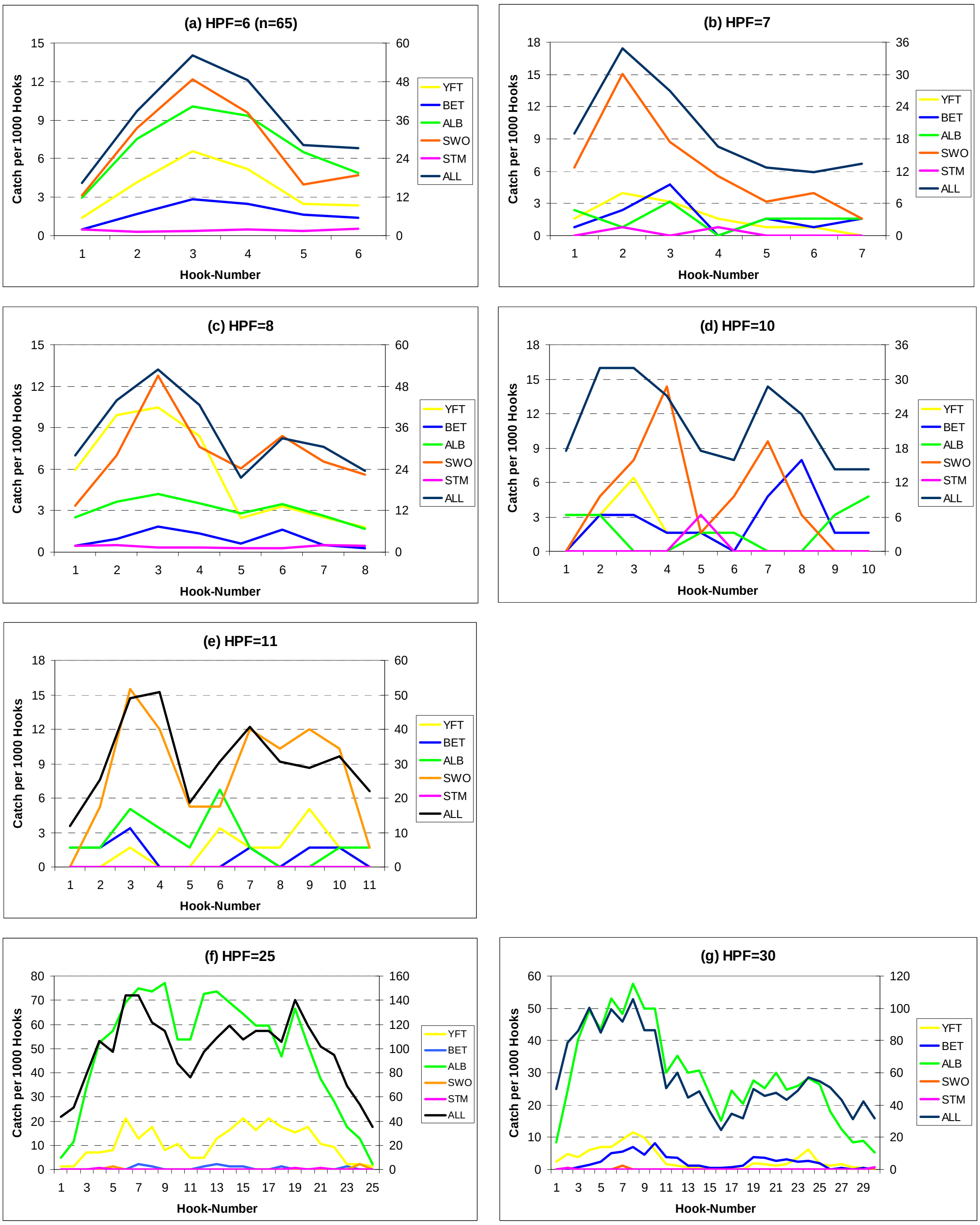
However, two problems were encountered in applying this approach to the data available. First, for most TDR-monitored sets not all hook-numbers were monitored and so it was not possible to always match the catch-profile for a specific hook-number with the corresponding depth-profile. Indeed, of the 2674 specific catch locations (i.e. unique set/hook-number with a catch) across the TDR-monitored sets, only 1061 (40%) had corresponding TDR depth profile. Whilst in some situations one could take an average of two adjacent profiles, in most situations (especially those with a large number of HPF) this was considered not possible as there were too many missing profiles for this approach to be applied. Second, the size of the catch for any set is likely to be dependent on the number of hooks deployed. As a different number of hooks were deployed on each set this would mean that the catch-by depth profiles for each set would not be readily comparable unless scaled.

In order to overcome these problems, the following approach was adopted. First, the estimated depth-profiles P_{dpg} for each hook-number p within a gear configuration of g HPF, as described in the previous section, were used. Second, the corresponding nominal catch-rate profiles, C_{pg}, for hook-number p within a gear configuration of g HPF was calculated based on the corresponding aggregate catch and effort across all TDR-sets (c.f. equation 1). Combining these two profiles then gives an estimate of the catch rate within each depth stratum for a gear configuration of g HPF (c.f. equation 3a). Whilst some of the set-specific catch-at-depth detail will be lost by taking an average across all sets, the resulting depth-profiles should still provide an indicative measure of the depths at which specific species are caught across all sets.

Table 5.5 Number of sets and hooks deployed together with the number of observed fish caught for each HPF gear configuration where usable TDR data was collected.

HPF	Number of Sets	Number of Hooks	Distinct Hook-Num	All Fish	YFT	BET	ALB	SWO	STM
6	65	80,368	6	2883	296	141	553	561	33
7	8	8,858	7	171	15	15	14	56	2
8	87	95,008	8	3275	530	89	290	682	36
9	1	1,050	4	15	1	2	1	4	0
10	7	6,273	10	140	8	16	11	29	2
11	7	6,521	11	201	9	7	15	52	0
12	3	3,422	6	67	18	11	10	6	0
13	1	1,295	6	19	3	5	1	3	0
14	1	1,200	4	10	0	0	0	3	0
15	2	2,318	7	84	0	0	0	0	0
20	3	8,311	10	131	5	46	11	6	0
25	13	21,441	25	2094	229	10	1047	3	3
30	46	77,292	30	4498	240	176	2257	4	3
32	1	2,085	3	5	0	2	0	0	0
35	1	1,700	5	46	3	0	27	0	0
Total	246	317,142		13639	1357	520	4237	1409	79

Figure 5.4 Catch rates on observed TDR sets, by hook-number, for specified hook-per-float configurations.



For sets with attached TDRs and an associated observer catch data, a summary of the number of sets and hooks, the number of distinct hook-numbers on which fish were observed caught, together with the total number of fish observed caught is provided in Table 5.5. The corresponding species-specific CPUE-by-hook-number profiles are shown in Figures 5.4. For each gear configuration each species is seen to be caught across all hook-numbers, though in some instances there is an asymmetry in the catch rates associated with hooks having the same hook-position (c.f. swordfish for 7 HPF and albacore for 30 HPF). As noted in Section 5.5, this may be due to the fact that some observers recorded catch by hook-position instead of catch by hook-number.

The rate at which species are caught also varies considerably across the different gear configurations, with albacore CPUE for 7 HPF being less than 3 fish per 1000 hooks and between 20-50 fish per 1000 hooks for 30 HPF.

After matching the CPUE-by-hook-number profiles with the depth-by-hook number profiles found in the previous section, then summing the CPUE-by-depth profiles for each hook-number, the combined CPUE-by-depth profile can be obtained for each gear configuration (c.f. equation 3b). These profiles are shown in Figure 5.5. To provide a better comparison of these profiles across each species the CPUE profiles for each species expressed as a percentage of the total CPUE are also shown (c.f. Figure 5.5b). Note, in Figure 5.5b the profiles for swordfish and striped marlin are not shown for gear configurations with 25 and 30 HPF due to the small catch sample (<5 fish in all situations).

The CPUE-by depth profiles for each species for the 6 and 8 HPF gear configuration (c.f. Figure 5.5b) are seen to be almost identical, despite slight differences in the distributions of catch across the hook-numbers (c.f. Figure 5.4a,c). This is because the depth-profiles for each hook-number are very similar (c.f. Figure 5.2) and so the catch-by-depth profile is relatively independent of the hook-number that the catch is taken on. The profiles for the different species for the other gear configurations are also seen to be very similar, suggesting that there is little difference in the relative availability-by-depth of these species despite absolute differences in availability (as noted by the absolute differences in the profiles shown in Figures 5.5a). This result also holds for the deeper longline configurations using 25 and 30 HPF where, unlike the shallower set gears, there are distinct differences in the depth-profiles fished by the different hook-positions. (Note, this result does not take into account the fish that may have been caught whilst the line is sinking or being hauled. However, as shown previously the time for the hook to sink, and presumably the time for the hook to be hauled, is a small proportion of the total soak time, it is unlikely that the above results are influenced to a large extent by such catches.)

On first impressions this result is somewhat surprising for it is generally believed that some species have quite distinct depth preferences (e.g. yellowfin shallow, bigeye deeper and albacore deep) and as such one would expect these species to have distinct catch and CPUE-by-depth profiles. Instead, the similarity in the observed CPUE-by-depth profiles for the species shown in Figure 5.5 indicates that the relative distributions of these species over the depths (and times) fished by each gear type are similar. However, given the observations of the large vertical movements that many of these species undergo (obtained from the deployment of electronic data loggers, CSIRO unpublished data), often on a daily basis, it is perhaps not surprising that these species have quite extensive depth distributions which makes them available to both shallow and deep set gears.

Finally, the CPUE-by-depth profiles for each species across each of the different gear configurations are shown in Figure 5.6a. Again, in order to better compare these profiles across each gear configuration the CPUE profiles expressed as a percentage of the total CPUE are also shown in Figure 5.6b.

For yellowfin tuna the distribution of CPUE by depth is very similar for sets deploying 10 or less HPF, with the highest catch rates being achieved within the depth interval

Figure 5.5. (a) CPUE by depth and (b) CPUE profile by depth for specified hook-per-float configurations. Note, in (a) the right-hand axis give the CPUE for the ALL fish.

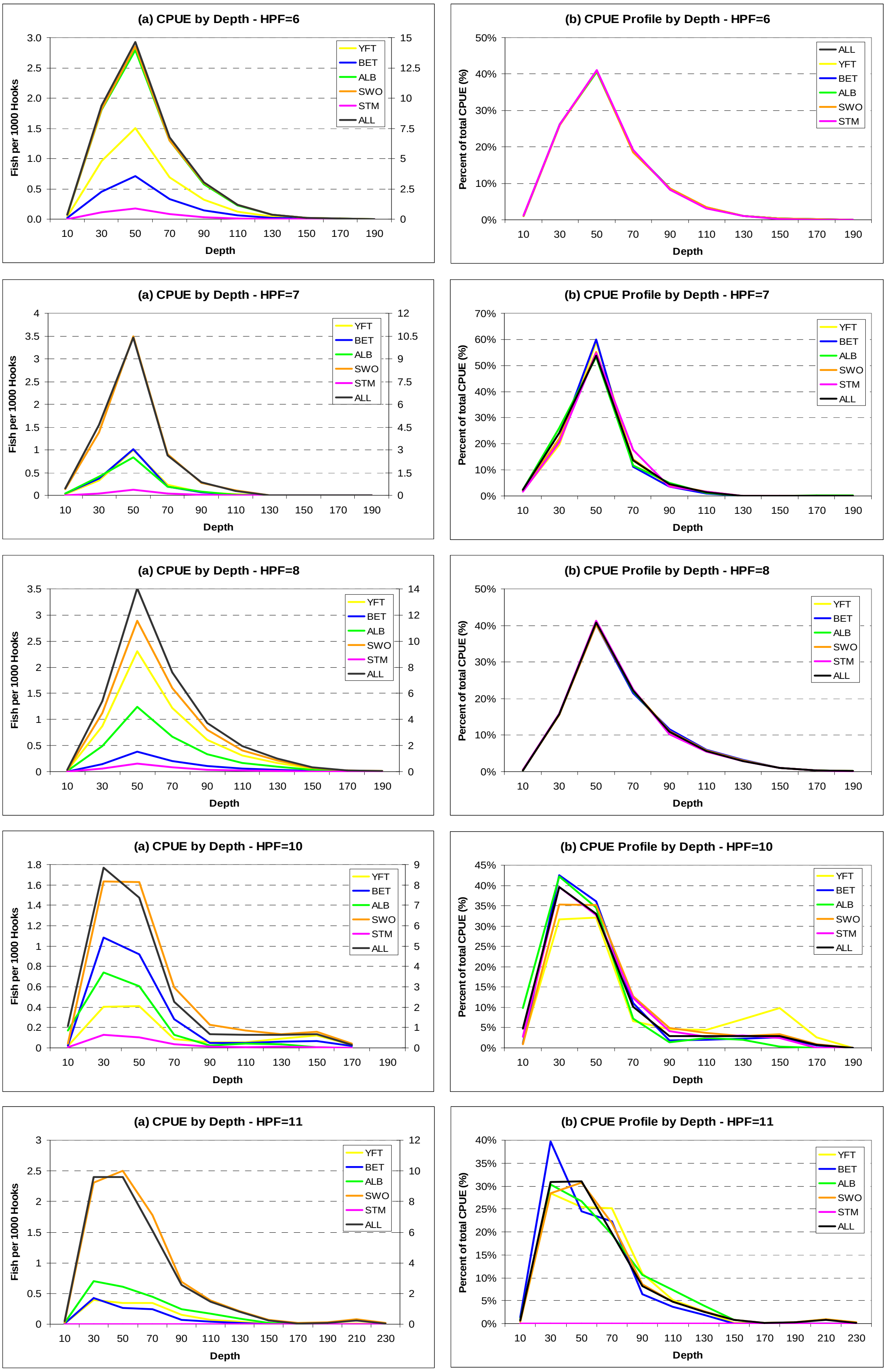
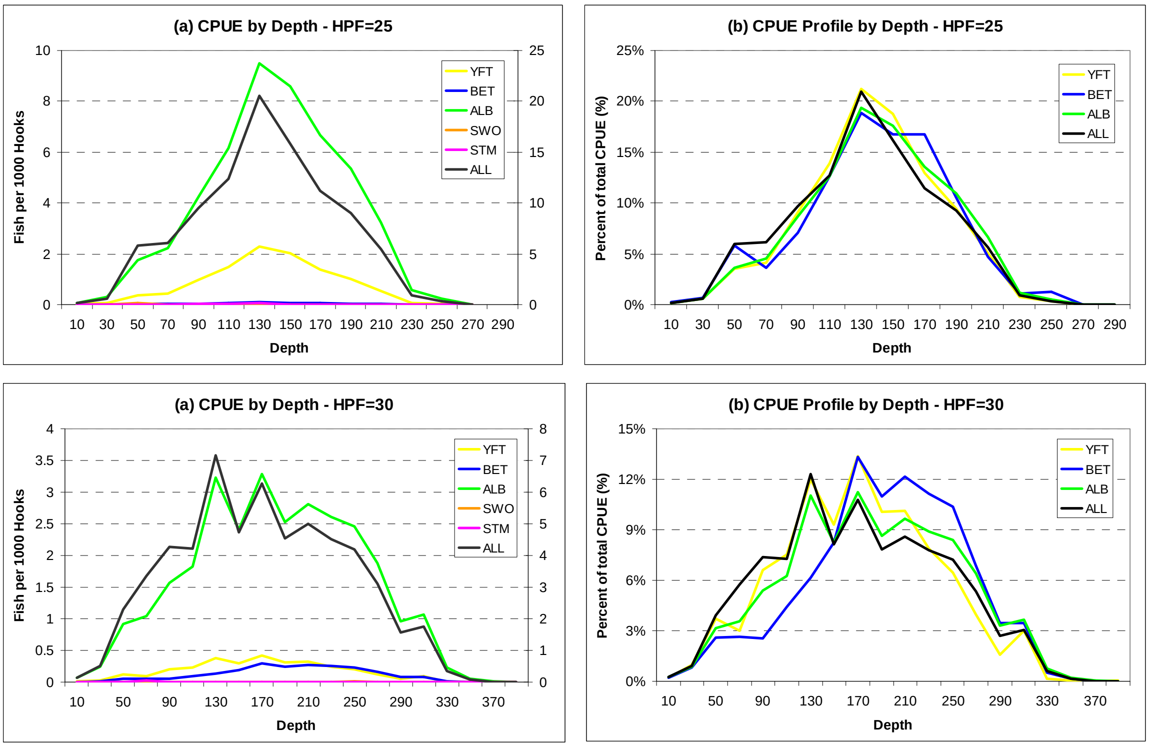


Figure 5.5 (cont'd). (a) CPUE by depth and (b) CPUE profile by depth for specified hook-per-float configurations. Note, in (a) the right-hand axis give the CPUE for the ALL fish.



40-59m. However, the distributions for those gears deploying 25 and 30 HPF are significantly different. For example, at depths between 40-59m the 65 monitored sets with 8 HPF had a mean CPUE of 2.31 fish per 1000 hooks while the 13 monitored sets with 25 HPF had a mean CPUE of only 0.38. On the other hand, these latter gears had a mean CPUE of 2.27 fish per 1000 hooks at depths between 120-149m which is very similar to the CPUE achieved by the 8 HPF configured gear at the shallower depths. The sets deploying 25 HPF were, in general, more than 5-degree further north than sets deploying 8 HPF (c.f. Figure 2.4), and while noting the different sample sizes for these two gears, this result suggests some degree of spatial in-homogeneity in the catch rates of yellowfin by depth across the ETBF. Thus while catches and catch rates of yellowfin tuna are generally considerably higher in the inshore regions of the ETBF, the availability of yellowfin by depth may change as one shifts to other regions of the fishery. However, it is also likely that other factors, such as day versus night setting, different seasons of the year, and differences in the availability of yellowfin by size, explain some of the observed differences in the catch rates of yellowfin tuna with depth.

In order to investigate further some of these other factors, the size of yellowfin tuna caught on different gear configurations was compared between sets deployed in the following two areas of the ETBF: between -15°S and -20°S (the North area where most of the sets with 25-30 HPF were deployed) and between -30°S and -25°S (the South area where most of the sets with 8 HPF were deployed). The size of fish caught was obtained from the data collected as part of the ETBF size monitoring program (summarised in Campbell et al, 2009). The size of yellowfin tuna was categorised into three size classes – Small, Prime and Large – whilst the HPF configurations were

Figure 5.6. (a) CPUE by depth and (b) catch profiles by depth by species across all hooks for specified hook-per-float configurations.

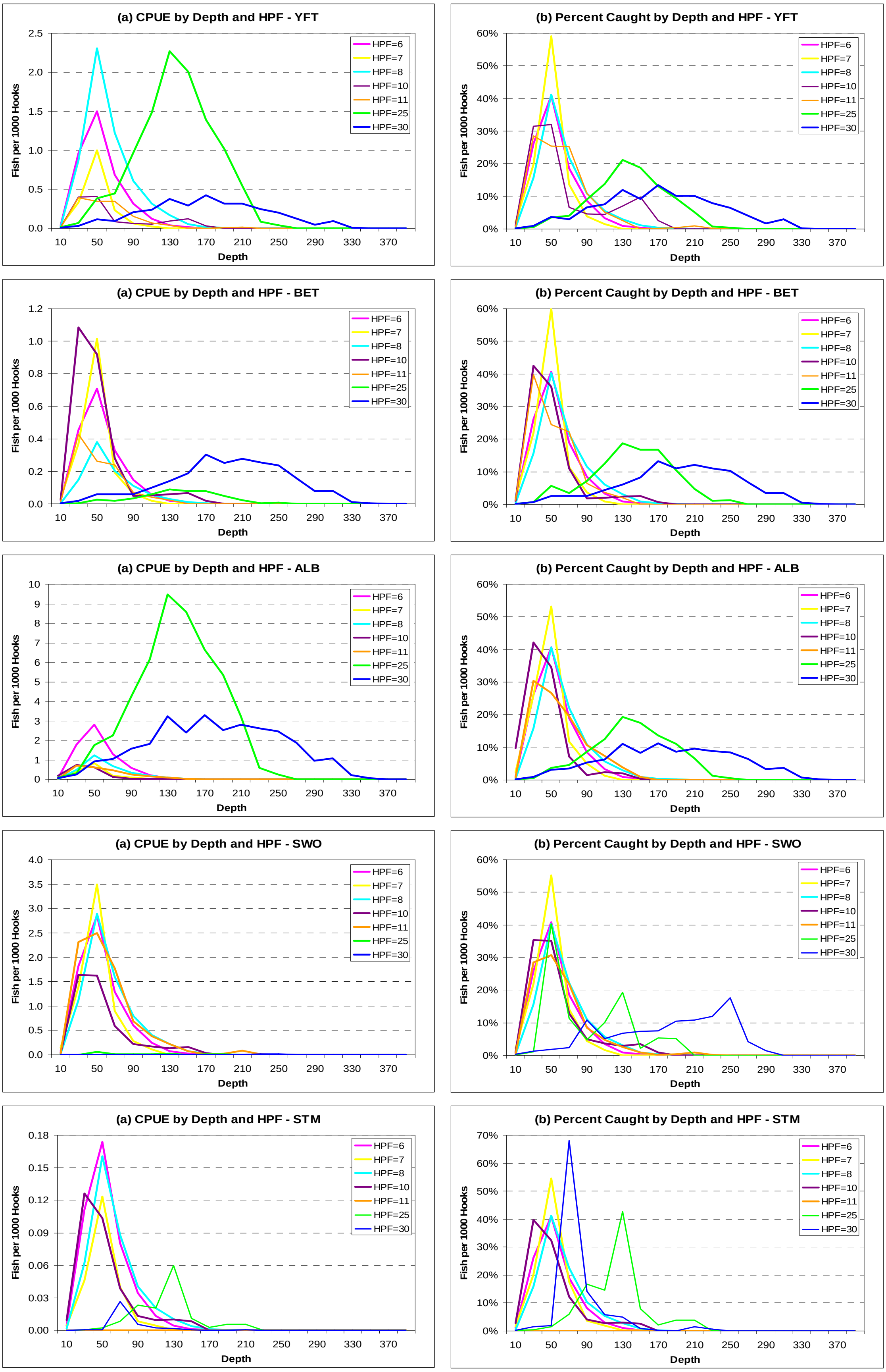
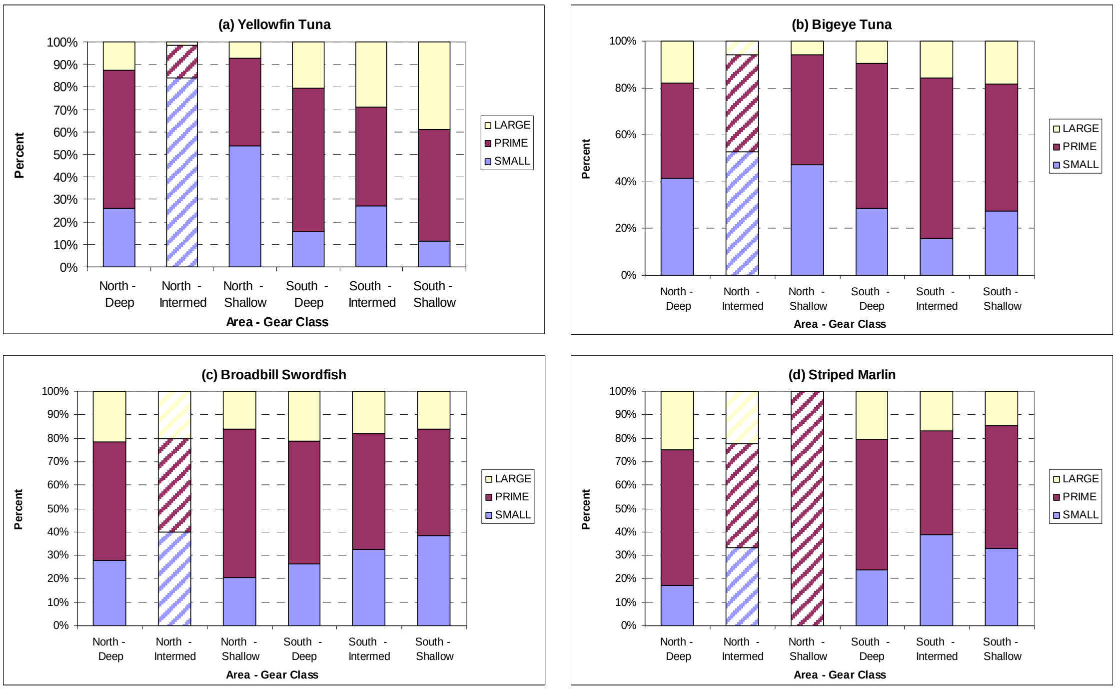


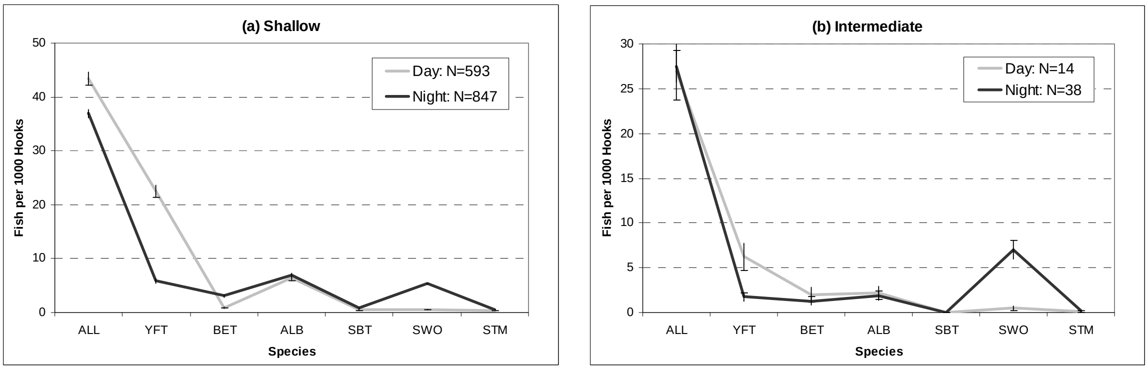
Figure 5.7 Comparison of the percentage of fish caught within each size-class between sets classified by different area and gear configuration. Cross-hatched bars indicate those results based on less than 15 sets.



categorised into the following three gear classes (c.f. section 3.4) – less than 12 HPF (Shallow setting), between 12 and 20 HPF (Intermediate depth setting) and more than 20 HPF (Deep setting). The percentage of yellowfin tuna caught within each size-class on sets within each Area-Gear category is shown in Figure 5.7. It is apparent that there is a much higher proportion of small yellowfin tuna caught in the sets deployed on the northern area and a corresponding higher proportion of large yellowfin tuna caught in the sets deployed in the southern area. (Note: bigeye tuna also shows a higher proportion of small fish in the north and a higher proportion of prime sized fish in the south). These differences may be associated with differences in water temperatures between the two regions, with the availability of large yellowfin tuna being higher in the generally lower water temperatures found in the southern area Within each region there are also some differences in the proportion caught by size-class between gear-type but these differences are not large and not consistent between regions.

Differences in the catch rates between day and night sets (see section 2.4) and for the different gear configurations are shown in Figure 5.8. (Note, as there were no night sets for the deep gear configuration no comparison is shown for this configuration). For yellowfin tuna, there are significant differences between the day and night catch rates for the shallow and intermediate gear configurations, with catch rates of yellowfin tuna around 3.9 times higher for day sets using shallow gears and around 3.5 times higher for day sets using intermediate gears. For bigeye higher catch rates are observed on shallow sets at night and deeper sets during the day, and this result is consistent with our knowledge the diurnal vertical migrations that bigeye make (c.f. Figure 7.4). Unlike the other tunas, albacore catch rates are seen to be similar between day and night sets. On the other hand, the most striking difference is seen for swordfish where catch rates for night sets on both gear types are observed to be around 10 times those achieved on day sets. Catch rates of striped marlin are also greater on

Figure 5.8 Comparison of catch rates of the principal target species stratified by gear configuration (HPF) and time of set (day versus night). (Note: The error bars indicate the standard errors associated with the mean catch rates, while N indicated the number of sets observed for each temporal period and gear configuration).



sets though the difference is smaller than for swordfish.

These results indicate that the observed catches of most species are influenced by a range of factors other than just the depths fished by the longline gears. Many large pelagic species undergo both diurnal and seasonal movements in response to changes in their habitat and whilst undertaking feeding and spawning migrations. The influence of these factors on catch rates is more fully explored in Section 7, where the habitat-based method is applied to standardising the catch rates of bigeye tuna.

5.8 Species Availability by Depth

As seen in Figure 5.3, the profile of depths fished by the hooks of any longline gear is far from uniform with the consequence that the fishing power of the longline gear (i.e. the probability of catching a fish in a given time) also varies considerably by depth. If the distribution-by-depth of the target species is given by S_d, then the catch (or catch rate, C_{dg}) of that species by the longline gear within depth strata d will be proportional to $S_d P_{dg}$ where, as before, P_{dg} is the proportion of the time spent within depth strata d by all hooks within a gear configuration of g HPF, i.e.

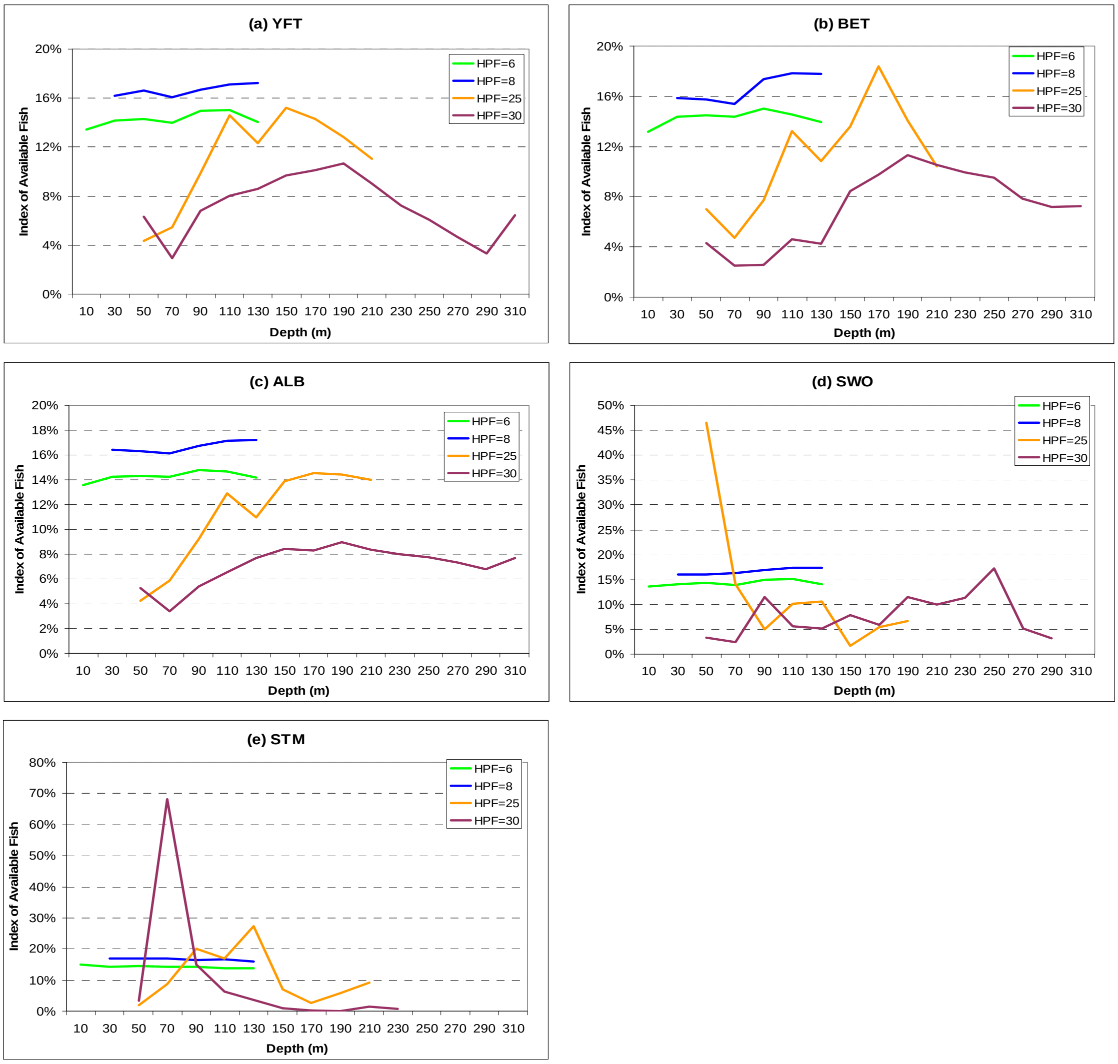
$$C_{dg} = q.S_d P_{dg}$$

where q is some measure of the catchability of the gear. An index of the availability ($q.S_d$) of a species to the longline gear within a given depth stratum d can therefore be obtained by knowledge of P_{dg} and C_{dg}. Furthermore, by dividing this index by the sum of the index over all depth strata fished by the hooks, a measure A_{dg} which is equivalent to the proportion of all fish of that species available to the gear which occur within depth strata d, is obtained:

$$A_{dg} = \frac{C_{dg}}{P_{dg}} \Bigg/ \sum_{d=1}^{N_d} \frac{C_{dg}}{P_{dg}} \tag{4}$$

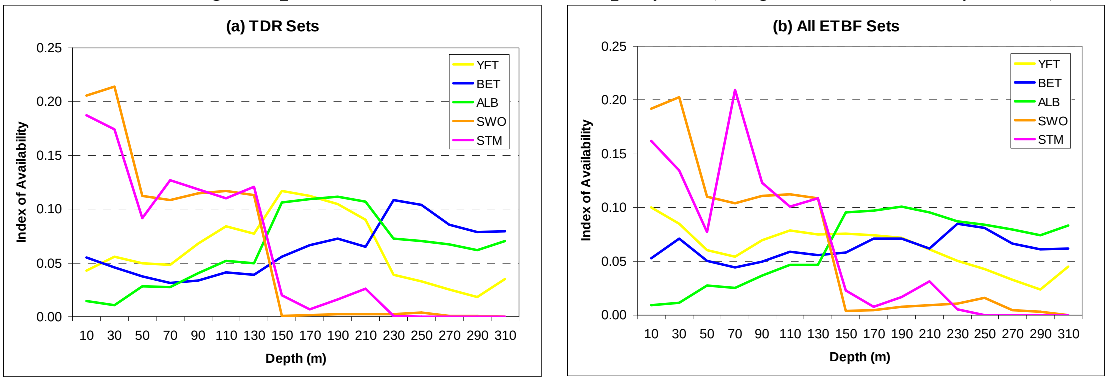
Using the values of P_{dg} and C_{dg} summarised in the previous two sections, indices of resource availability to each of the main gear-types used in the ETBF for several of the principal target species were calculated and are shown in Figure 5.9. Note, in order to minimise spurious results, for each gear configuration the calculation of A_{dg} was limited to those depth strata where P_{dg} >1%. Gear types were also limited to those where more than 10 sets were sampled.

Figure 5.9 Indices of resource availability by depth of the principal target species for specified hook-per-float configurations.



For all species shown in Figure 5.9 and for longline gears with 6 and 8 HPF the estimated availability-by-depth is seen to be relatively uniform down to depths of around 140m. On the other hand, the distributions of tuna availability-by-depth for the two gear configurations with 25 and 30 HPF show significant variations with depth, initially increasing to depths around 180m then decreasing. The decline with depth of yellowfin tuna is greater than that for bigeye with little overall decline seen in the availability of albacore with increasing depth. The results for the two billfish species for the 25 and 30 HPF configurations are more variable and this result is influenced by the small number of billfish caught on these sets (c.f. Table 5.5). Some of the differences between the profiles for the 6 and 8 HPF configurations and those for 25 and 30 HPF configurations are likely to be due to the time of the day that the sets were deployed. As noted in section 2.3, all but one set deploying either 25 or 30 HPF were classified as day sets, whilst only 6% of sets deploying 6 or 8 HPF were classified as day sets, with 62% classified as night sets. As some tuna and billfish species have different vertical distributions in the water between the day and night, the availability-at-depth profiles estimated here will be influenced by the timing of the observed sets.

Figure 5.10. Indices of resource availability by depth for the principal target species in the ETBF based on (a) catch rates for the observed TDR sets and (b) catch rates for all ETBF sets during the period that TDRs were deployed (August 2004 to may 2007).



Finally, the indices of availability calculated for all four HPF configurations were combined to provide a single index, A_d, of availability for each species. This was achieved by scaling each index by the associated total nominal catch rate for each gear configuration, C_g, and for each depth strata dividing by the mean index, i.e.

$$A_d = \frac{1}{N_d} \sum_{g=1}^{N_d} \frac{C_g A_{dg}}{\overline{A_g}}$$

where $\overline{A_g}$ is the mean of the index A_{dg} over all depth strata for which it is defined and N_d is the number of gear-specific indices defined for depth-strata d. Two sets of indices were calculated. First, the catch rates C_g were set equal to the mean nominal catch rates observed on the associated TDR sets. Second, in order to overcome the limited sample sizes of the TDR sets, the catch rates C_g were set equal to the mean nominal catch rates observed on all related sets deployed in the ETBF during the period that the TDRs were deployed. This assumes that the indices A_{dg} calculated for the TDR sets are appropriate for all sets deployed in the ETBF. The two sets of catch rates are given in Table 5.6 while the calculated indices are shown in Figure 5.10 where each index has been scaled so that $\sum A_d = 1$. Scaled in this way, the value of

Table 5.6 Number of sets, hooks deployed and associated catch rates for (a) those sets deployed with TDRs and (b) all sets deployed in the ETBF during the period that the TDRs were deployed (August 2004 to May 2007).

(a) TDR Sets

HPF	NSETS	NHOOKS	YFT	BET	ALB	SWO	STM
6	65	80,368	3.68	1.74	6.87	6.98	0.42
8	87	95,008	5.59	0.95	3.05	7.17	0.39
25	13	21,441	10.72	0.47	48.95	0.14	0.14
30	46	77,292	3.15	2.28	29.17	0.05	0.04

(b) All ETBF Sets

HPF	NSETS	NHOOKS	YFT	BET	ALB	SWO	STM
6	3013	3,113,781	9.51	1.56	4.74	3.85	0.75
8	8171	8,327,567	5.94	2.42	5.99	4.05	0.54
25	228	380,605	5.40	0.98	38.33	0.15	0.30
30	2285	3,835,478	4.49	1.65	37.21	0.14	0.37

the index equals the proportion of the total population available (down to a depth of 320m) to the gear within each depth stratum.

The two sets of indices display a number of differences. This is related with the fact that there are large differences in the catch rates associated with each gear configuration between the TDR-related sets and all ETBF sets. For example, the highest catch rates of yellowfin tuna for the TDR-related sets were obtained on gears with 25 HPF while for all ETBF sets catch rates of yellowfin tuna decrease across the four gear configurations shown in Table 5.6. This difference explains the initial increase in yellowfin availability with depth down to around 150m for the TDR-related sets compared to the general decrease in yellowfin availability with depth for the all ETBF sets. Nevertheless, both sets of indices for yellowfin tuna indicate that availability remains relatively high (above 5% per depth stratum) down to around 220m.

The results for bigeye tuna also display differences associated with the relative differences in the catch rates between the TDR-related sets and all ETBF sets. Catch rates for the former were highest on the deepest sets (those with 30 HPF) and consequently the availability of bigeye at depths around 230m is more than twice that for depths less than 100m. While availability for the ETBF sets is also highest at depths around 230m, the relative change from shallower depths is not as great. Indeed, the index indicates that availability remains relatively high for all depths down to 320m. The indices for albacore tuna are similar for the two groups of sets and display considerable variation with depth. Availability increases from around 1% in the 0-20m depth stratum to around 10% at depths between 150-200m before declining to some extent. The extent of this decline is smaller for the ETBF sets and as for bigeye tuna availability remains high down to the deepest depth stratum shown.

Apart from some variation in the ETBF striped marlin index within the top 100m (most likely associated with the large variations in the individual gear related indices shown in Figure 5.7 due to the small number of striped marlin observed) the indices for the two billfish species are seen to be similar for both groups of sets. They indicate that the availability of these species is highest in the top 40m of the water column where around 40% of the total available resource is to be found. Availability then declines to half these levels at depths between 50-130m before dropping to near zero at greater depths.

Section 6: Time-of-Capture of Principal Target Species

6.1 Species caught

Hook-timers were deployed during 36 of the 52 trips listed in Table 1. Hook timers (HTs) consist of a simple release mechanism that starts a timer when a baited hook is jerked by a fish attacking the bait. If the fish is caught on the hook at this time, then upon retrieval of the HT the time elapsed since the fish was caught can be ascertained. If there is no fish on the hook when a triggered HT is retrieved, then it is likely that the fish either attacked the bait without getting hooked, or was hooked then managed to escape. At least one HT was activated on 186 sets and of the total of 682 HTs that had been triggered when retrieved, a fish was on the attached hook for 385 (56.5%) whilst no fish was retrieved on 276 (43.5%). A listing of all species caught and the associated life-status profile upon retrieval for each species is given in Table 6.1.

Table 6.1. Listing of all species caught and the associated life-status profile upon retrieval for each species caught on lines with an attached hook-timer. Note: The unknown category generally relates to hook-timers which were observed to have been triggered upon retrieval but for which no fish was attached to the hook, though this number may include a few observations for which the species name of the attached fish was not recorded.

			Life-Status					
			0	1	2	3	4	5
Species Code	Species Name	Number	Not Recorded	Dead in rigor	Dead Flexible	Alive Just	Alive Sluggish	Alive Vigorous
ALB	Albacore Tuna	138	4%	54%	17%	11%	9%	6%
YFT	Yellowfin Tuna	68	9%	22%	7%	10%	13%	38%
SWO	Swordfish	51	6%	10%	37%	16%	16%	16%
LEC	Dolphin Fish	25	8%	0%	8%	12%	32%	40%
DOL	Black Oilfish	24	0%	0%	0%	0%	8%	92%
BET	Bigeye Tuna	20	15%	10%	10%	0%	25%	40%
SKJ	Striped Marlin	14	0%	100%	0%	0%	0%	0%
MLS	Blue Shark	9	11%	0%	0%	0%	11%	78%
BSH	Skipjack Tuna	8	0%	0%	0%	0%	13%	88%
MOP	Sunfish	5	20%	0%	0%	0%	40%	40%
ALX	Longnosed Lancetfish	4	25%	0%	25%	25%	25%	0%
KAW	Eastern Little Tuna	2	0%	100%	0%	0%	0%	0%
DUS	Dusky Shark	2	0%	0%	0%	0%	0%	100%
WAH	Wahoo	2	0%	0%	100%	0%	0%	0%
CEO	Rudderfish	2	50%	0%	0%	0%	0%	50%
PTH	Pelagic Thresher	2	50%	0%	0%	0%	0%	50%
BRO	Bronzed Whaler Shark	1	0%	0%	0%	100%	0%	0%
ALV	Thresher Shark	1	0%	100%	0%	0%	0%	0%
BLM	Black Marlin	1	0%	100%	0%	0%	0%	0%
BLZ	Blue Marlin	1	0%	0%	100%	0%	0%	0%
OCS	Oceanic Whiteip Shark	1	0%	0%	0%	0%	0%	100%
TIG	Tiger Shark	1	100%	0%	0%	0%	0%	0%
MOO	Moonfish	1	0%	0%	100%	0%	0%	0%
LAG	Opah	1	0%	0%	0%	0%	100%	0%
LAG	Opah	1	0%	0%	0%	0%	100%	0%
UNK	Unknown / No Fish	297						
Total		682	25	115	56	35	51	103

6.2 Profile of Capture Times

The profile of the number of fish caught versus elapsed time (number of hours between HT being triggered and retrieval) for those fish caught on a line with a hook-timer is shown in Figure 6.1a. Subtracting the elapsed time from the time-of-day that the HT is retrieved gives the time-of-day that the HT was triggered (which is assumed to have occurred when the fish took the bait and was hooked). Based on this calculation, the profile of the number of fish caught versus time-of the day for those fish caught on a line with a HT is shown in Figure 6.1b. This indicates that while fish are caught during all hours there is an indication of increased likelihood for fish to be caught during the evening hours (with 55% of all fish caught between 6pm and 6am).

The number of fish observed caught during any given hour will be influenced by the profile of the hours of the day that the longline gears are deployed. For example, if there is a preference to soak the gears during the night then it is not surprising that there is a greater tendency for more fish to be observed caught during this period. If an unbiased profile of capture times is to be obtained, one needs to adjust the observed profile of capture times for the proportion of all hooks in the water during each hour. Note, that it is also likely that the bait loses it effectiveness over time and so the rate at which fish are caught will not be uniform whilst the hooks are in the water, However, as the duration of bait effectiveness remains unknown this factor could not be taken into account in calculating the profile of capture times.

Using the times that the first and last hooks are deployed and the times that the first and last hooks are retrieved, as recorded by the observer, the average number of hooks N_{ij} in the water during each one-hour period j was calculated for each set i with

Figure 6.1 (a) Profile of the number of fish caught versus elapsed time (number of hours) for those fish caught on a line with a hook-timer, (b) Profile of the number of fish caught versus time-of the day for those fish caught on a line with a hook-timer (all species), (c) Proportion of the total soak time of all sets deploying hook-timers within each hour-of-the day, and (d) Observed and adjusted profiles of the number of fish caught versus time of capture (for all species).

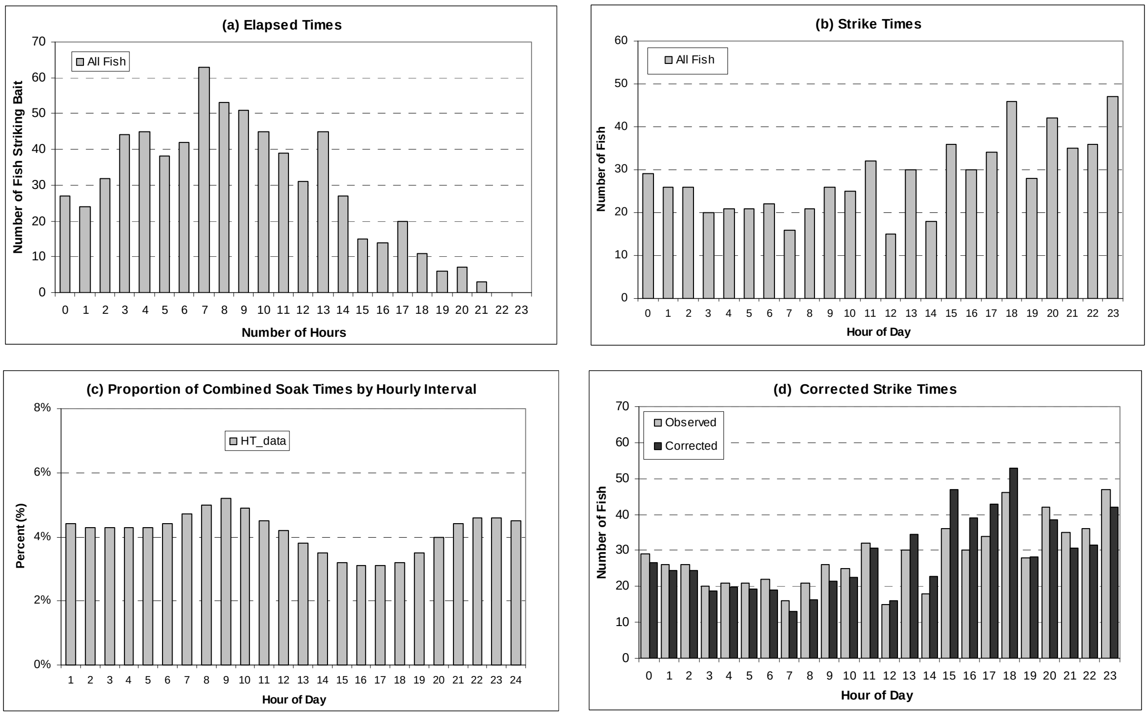
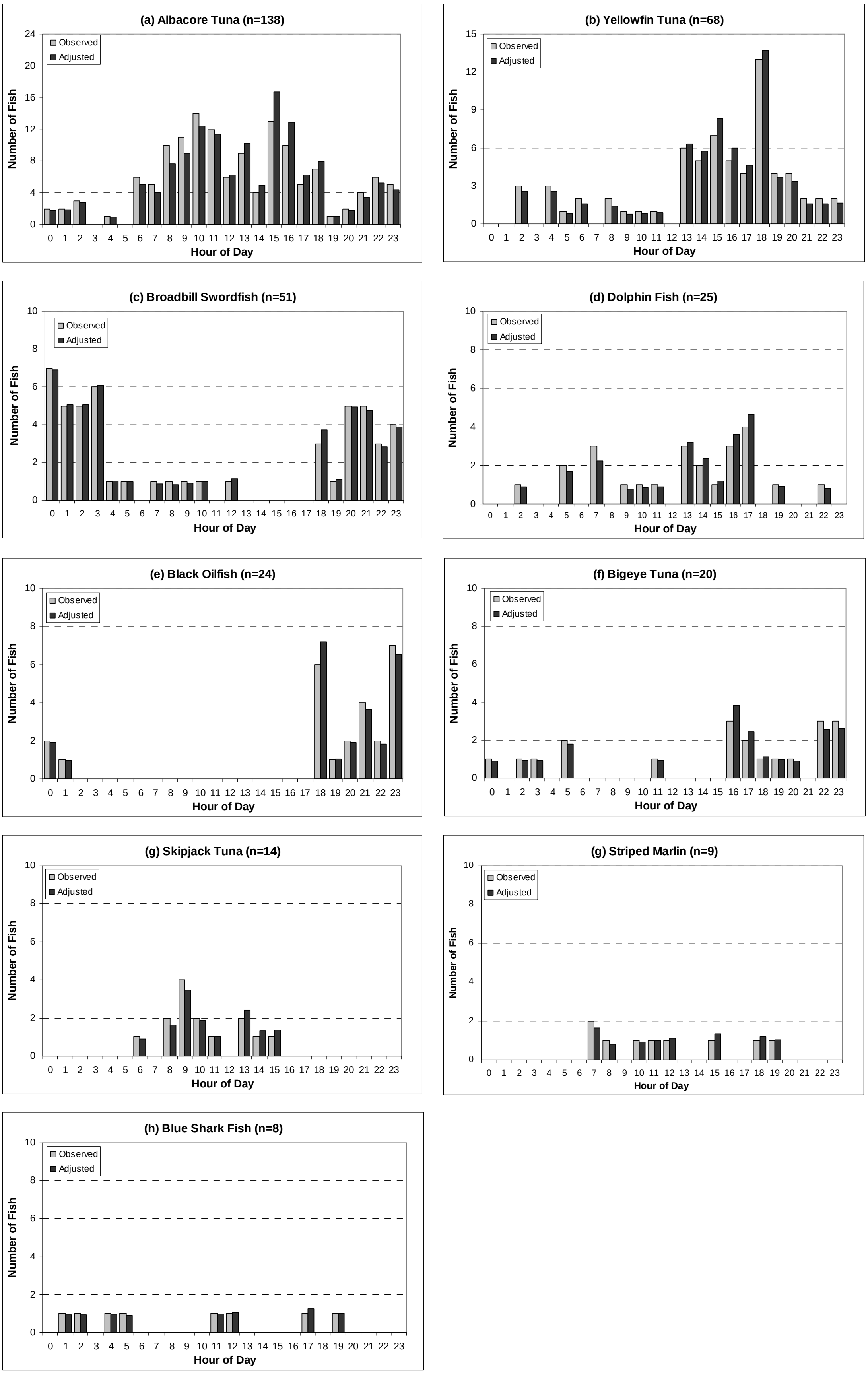


Figure 6.2. Observed and adjusted profiles of the number of fish caught versus time of capture for eight individual species.



associated HT data. The total number of hooks in each one-hour interval across all sets was then calculated and then divided by the total across all hours to provide a profile, p_j, of the proportion of all hooks in the water during each one hour interval j.

$$p_j = \frac{\sum_{i=1}^{186} N_{ij}}{\sum_{j=1}^{24}\sum_{i=1}^{186} N_{ij}}$$

The resulting profile is shown in Figure 6.1c and indicates that the proportion of all deployed hooks in the water during any given hour for these 186 sets is relatively constant, though the proportion was highest in the mid-morning period (8-9am) and lowest in the mid-afternoon (4-5pm). The adjusted profile of the number of fish, C_j^{adj} captured within each one-hour interval j can then be obtained as follows:

$$C_j^{adj} = \frac{\overline{p}}{p_j} C_j^{obs}$$

where $\overline{p}$ is the mean proportion across all 24 hours. Adjusting the profile of the bite-times of fish caught to account for these differences in the proportion of each hour that the gears are deployed, should provide a more accurate profile of the time-of-capture of fish. This adjusted profile (together with the observed profile) is shown in Figure 6.1d and indicates an increased likelihood of fish being caught during the mid-to-late afternoon period (3-6pm).

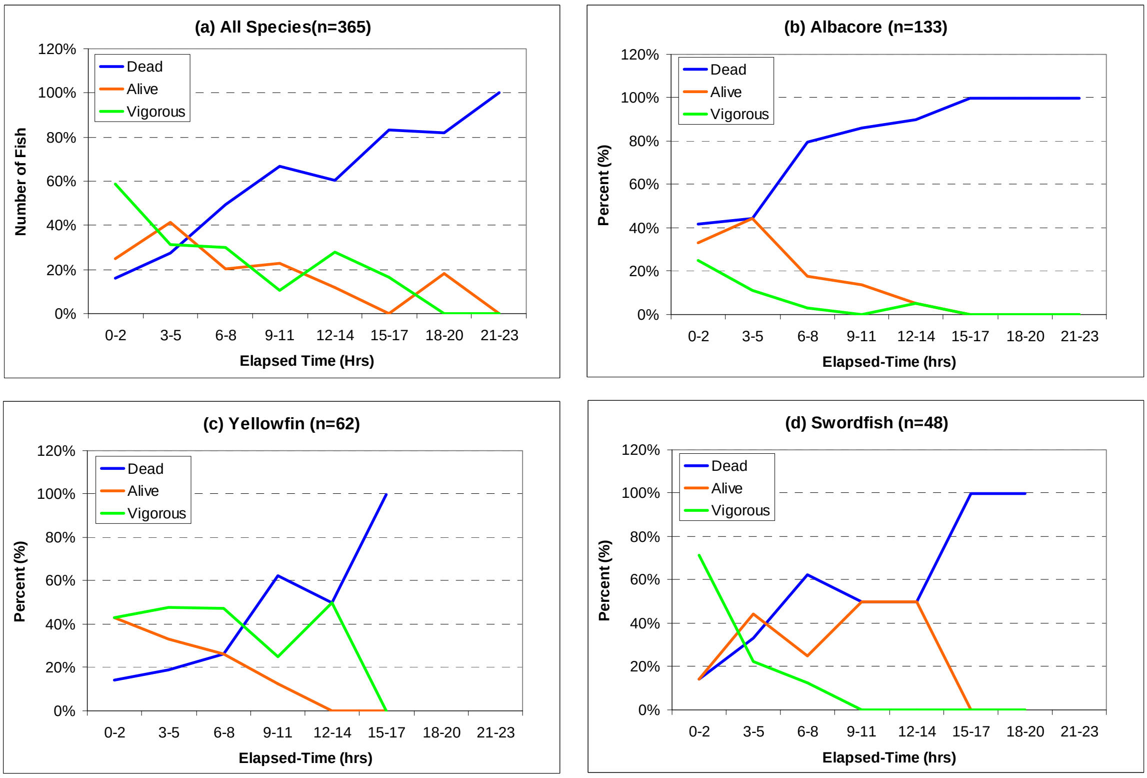
Similar results were also obtained using the data for individual species. The results for the nine most commonly caught species are shown in Figure 6.2 and indicate a number of different behaviours. For example, both yellowfin tuna and dolphin fish have a propensity to the caught during the afternoon, while both swordfish and bigeye are most likely caught during the night. These results are in general agreement with hook-timer observations made on longline vessels operating in the Coral Sea during the mid-1990s (Campbell, et al 1997) and the behavioural data from the electronic tagging work on a number of tuna and billfish species (see, for example, Gunn et al 2005). While, these results still need to take into account differences in the depth profiles of the species and the fishing gears, they do nevertheless provide a preliminary indication of possible different feeding behaviours of the different species.

6.3 Life-Status versus Elapsed Time

Table 6.1 indicates a number of differences in the life-status of different species upon retrieval. For example, the majority (54%) of the 138 albacore caught with a HT were observed to be dead and in rigor on retrieval whilst the most common observed life-status of the 51 yellowfin tuna was alive and vigorous (38%).

Life-status upon retrieval will depend on a number of factors, including the time elapsed since capture, the temperature of the water, the depth from which they are retrieved and the resilience of the fish to remain alive whilst hooked. Information on the latter issue can be ascertained by investigating the relationship between elapsed time between capture and retrieval and the life-status upon retrieval. A plot of the percent of fish in each life-status category versus elapsed time since capture is shown in Figure 6.3. Note, due to the generally small sample sizes the life-status categories

Figure 6.3 Percent of fish in each life-status category versus the elapsed time since capture for (a) all species, (b) albacore, (c) yellowfin tuna and (d) swordfish. The total number of fish, n, in each sample is indicated.



have been aggregated into three categories – alive and vigorous, alive (sluggish and just) and dead. The aggregate result for all species indicates that around 60% of fish are alive and vigorous if retrieved within 2 hours of capture, but this percentage generally declines as the elapsed time increases. With an elapsed time of greater than 20 hours all fish are recorded as being dead. These results also show some difference across different species. For example, around 50% of yellowfin and swordfish remain alive up to 14 hours after capture but after 5 hours more than 80% of albacore are dead. This difference may be influenced by the generally greater depths that alabacore are caught. Yellowfin also appear to have a greater propensity to staying alive and vigorous, with around 50% remaining in this condition. up to 14 hours after capture whilst only 20% of swordfish remain alive and vigorous between 3-5 hours after capture and none after 8 hours.

Section 7: Habitat-based Method of Standardising CPUE

7. 1 Outline of Approach

Catch rates are known to be influenced by several factors other than general abundance and knowledge of those factors which influence CPUE underlies the statistical analysis known as effort standardisation. Most analyses make use of General Linear Models (GLMs) or General Additive Models (GAMs) which are well known statistical methods for estimating the relationship between a dependent variable (CPUE) and a number of independent variables. For standardising longline CPUE a number of variables are known to influence CPUE and, where the information is available, the following variables are usually included:

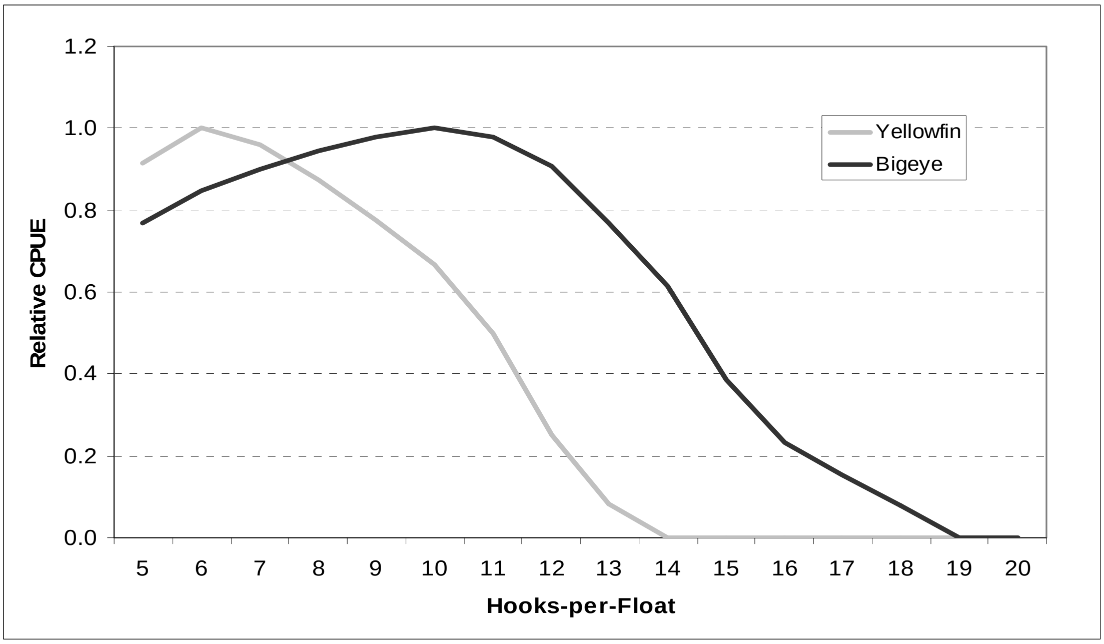
- Time stratum (e.g. Year-quarter)
- Spatial stratum (e.g Area effect)
- Hooks-per-Float
- Bait-type
- Time of day
- Use of fish attracting devices (e.g. lightsticks)

In fitting these variables within a GLM (or GAM) framework, the data is used to estimate the nature of the relationship between each variable and the dependent variable. This is a generally a purely statistical exercise as no process model is invoked to connect the two variables. However, one may use the results of such analyses to infer the nature of the underlying processes that results in the observed relationship.

For example, consider the illustrative GLM result shown in Figure 7.1, which shows the relative influence of the number of hook-per-float on CPUE. From this result it is seen that the CPUE of yellowfin tuna is highest when 6 HPF are deployed and that CPUE decreases when a higher HPF is deployed. On the other hand, the CPUE of bigeye tuna is highest when 10 HPF are deployed. In order to understand this statistical result, we need to combine this result with the knowledge that (all other features constant) the number of hooks-per-float (HPF) is an indicator of the depths fished by the longline gear with these depths generally increasing with the number of HPF (Suzuki et al 1977). Hence, the GLM result can be used to infer that the number of yellowfin tuna available to the longline gear is highest at the depths fished by those gears set with 6 HPF, whilst the greatest number of bigeye tuna are found at the relatively greater depths fished with 10 HPF. The conclusion that gear fishing deeper in the water column is more effective in targeting bigeye tuna has been confirmed by a number of studies (Hanamoto 1987, Boggs 1992) and is thought to be due to a preference by bigeye tuna for cooler 10-15^{o}C water (Holland et al. 1990; Boggs 1992; Brill 1994). In this manner, one can combine the knowledge about the depth distributions of both the hooks deployed by a longline and the target species to interpret and understand the purely statistical results of the GLM.

An alternative to the above statistical approach to standardising CPUE is to instead use our knowledge of the distribution of the target species and the fishing gears more

Figure 7.1 Hypothetical result of a GLM illustrating the relationship between the number of hook-per-float and relative CPUE of both yellowfin and bigeye tuna.



directly. Indeed, this was the approach developed by Hinton and Nakano (1996) who presented a method of standardsing CPUE which combined information on the spatial and depth distributions of the target species (using information on habitat preference and mapping of this habitat provided by oceanographic models) with information on the depths fished by longline hooks. This method was first applied to Pacific blue marlin before being applied to bigeye tuna in the WCPO by Hampton, Bigelow and Labelle (1998). The method has subsequently been further developed and in recent years has been routinely applied to both bigeye tuna and yellowfin tuna within the context of the stock assessments undertaken for these species within the WCPO (see Langley et al 2005). The approach is generally known as the habitat-based-standardisation (HBS) method.

7.2 Basic Equations

A form of the basic equation for applying the habitat model was presented by Hampton, Bigelow and Labelle (1998). However, as the actual derivation of this equation was poorly described in this paper here we present a more complete description of the rationale behind the development of the required equations.

Consider the volume of water fished by the longline gear during a single set. From the catch equation the number of fish in the catch, *C*, is related to the total fishing effort, *E*, and the average fish population density in this volume of water, *D* as follows:

$$C=qED \tag{1}$$

where *q* is a fixed constant of proportionality known as the catchability coefficient and is related to the efficiency of the fishing gear. From this equation

$$CPUE = \frac{C}{E} = qD = \frac{qN}{V} \tag{2}$$

where N is the number of fish and V is the volume of water fished. Without loss of generality, we assume this volume is divisible into N_d depth stratum each of depth d and cross-sectional area A. Let N_k be the number of fish within the depth stratum k so that the average density of fish within this stratum is $D_k=N_k/V$. If E_k is the effort (number of hooks) within stratum k, and q_k is the corresponding catchability, then from (1) the catch, C_k, within stratum k is:

$$C_k = qE_k D_k = q_k E_k \frac{N_k}{V}$$

If q_k is considered to be a constant across all stratum then the total catch over all stratum is:

$$C = \sum_{k=1}^{N_d} C_k = \frac{q}{V} \sum_{k=1}^{N_d} E_k N_k$$

Finally, if $E_k=h_kE$ where E is the total effort (number of hooks) deployed and h_k is the proportion of these hooks within stratum k, and $N_k=p_kN$ where N is the total number of fish in all depth stratum and p_k is the proportion of these fish in stratum k, then (3) can be expressed as follows:

$$C = \sum_{k=1}^{N_d} C_k = \frac{qEN}{V} \sum_{k=1}^{N_d} h_k p_k$$

from which

$$CPUE = \frac{C}{E} = \frac{qN}{V} \sum_{k=1}^{N_d} h_k p_k$$

Solving for N provides an estimate of the number of fish in the volume of water based on an observed CPUE:

$$N = \frac{V.CPUE}{q\sum_{k=1}^{N_d} h_k p_k} = \frac{V.C}{qE\sum_{k=1}^{N_d} h_k p_k}$$

Where there are a number of longline sets, S, each having a constant catchability q, this equation can be expressed as follows.

$$N = \frac{V}{q} \frac{\sum_{i=1}^{S} C_i}{\sum_{i=1}^{S} E_i \sum_{k=1}^{N_d} h_{ik} p_k}$$

where h_{ik} is the proportion of hooks in set i which fish within depth stratum k.

If there are T volumes of water each with N_d equally divided depth stratum each of cross-sectional area A and depth d, but each containing a different number of fish N_j and a different number of longline sets, S_j, then the total number of fish across the entire region can be expressed as follows:

$$N = \sum_{j=1}^{T} N_j = \frac{V}{q} \sum_{j=1}^{T} \left(\frac{\sum_{i=1}^{Sj} C_{ij}}{\sum_{i=1}^{S_j} E_{ij} \sum_{k=1}^{N_d} h_{ijk} p_{jk}} \right) \qquad (3a)$$

where: E_{ij} is the number of hooks in the set i in water volume j,
C_{ij} is the number of fish caught in set i in water volume j,
h_{ijk} is the proportion of hooks in set i in water volume j in depth stratum k,
p_{jk} is the proportion of the fish in water volume j in depth stratum k,

Where aggregate data is being used this can be expressed as

$$N = \sum_{j=1}^{T} N_j = \frac{V}{q} \sum_{j=1}^{T} \left(\frac{C_j}{E_j \sum_{k=1}^{N_d} h_{jk} p_{jk}} \right) \tag{3b}$$

where: E_j is the total number of hooks in water volume j,
C_j is the total number of fish caught in water volume j,
h_{jk} is the proportion of all hooks in water volume j in depth stratum k,
p_{jk} is the proportion of the fish in water volume j in depth stratum k,
(Note, the equation presented by Hampton, Bigelow and Labelle (1998) was expressed as an index, I, and is related to the above equations by $I=qN$.)

In order to use the above equations, as well as information on the catch and effort by depth information on the profiles h_{jk} and p_{jk} is also required. In the application of the HBS method in the WCPO the information on each of these has been ascertained as follows:

a) Hook profiles, h_{jk}. The depth attained by longline gear has been shown to be influenced by the set configuration, primarily the length of the float line, the length of the branch line (snood), the length of the main line between the floats (a basket) and the sagging rate (Suzuki et al 1977). While the depth of longline hooks for a given gear configuration can be easily calculated from the known catenary geometry, fishing depth will also be influenced by a variety of *in situ* environmental and oceanographic factors, particularly the wind and currents. Whilst the influence of these factors on longline shape and depth remains uncertain and is the subject of ongoing research, data on these other factors is usually not available. As a consequence, direct observations of hook depths using time-depth recorders (TDRs) were used to estimate the proportion of time spent within pre-specified depth stratum by all hooks within various HPF configurations.
b) Fish density profiles, p_{kj}. It has been assumed that the depth distribution of a particular species is a simple function of its temperature preference and minimum dissolved-oxygen (DO) requirements. Temperature preferences have generally been inferred from data collected using archival tags (e.g. Holland et al. 1990) while DO preferences have been inferred from physiological observations and catch information (Bushnell et al. 1990, Boggs 1992). These temperature and DO preferences are then mapped into each depth layer, 5x5-degree square and quarter using global ocean-circulation models. A p_{jk} value is then calculated for each area-depth stratum based on the product of the temperature and DO preference indices, then normalised such that $\sum_k p_{jk} = 1$ so that the p_{jk} values describe the relative depth distribution in each area stratum j (Hampton, Bigelow and Labelle 1998).

7.3 Initial Application to ETBF

In this section we apply the HBS method to the catch of bigeye tuna in the ETBF. This species is chosen over the other principal target species in the ETBF as unlike these other species there is a large amount of data available from the archival tagging of bigeye tuna within the ETBF that provide information on the habitat preference of this species within this region (Gunn et 2005, Evans et al 2006). Furthermore, in order to keep this initial analysis simple so that the consequences of changing aspects of the model can be clearly identified and explained, the following assumptions were made:

1) The ETBF was treated as a single oceanographic entity so that only a single area (or water volume) was required in the analysis. From equation (3b) above, an annual index of bigeye abundance in year y, I_y, can be calculated as follows:

$$I_y = \frac{q.N_y}{V} = \frac{C_y}{E_y \sum_{k=1}^{N_d} h_{ky} p_{ky}} \tag{4a}$$

where: E_y is the total number of hooks in deployed in year y,
C_y is the total number of bigeye tuna caught in year y,
h_{ky} is the proportion of all hooks in depth stratum k in year y,
p_{ky} is the proportion of bigeye tuna in depth stratum k in year y.

2) The depth-profile of hooks is controlled solely by HPF configuration, i. Hence, total annual effort E_y can be equated to the sum of the number of hooks deployed within each HPF configuration, E_{iy}, with each HPF category having a distinctive depth-profile, h_{ik}, which is independent of year. Equation (4) then gives:

$$I_y = \frac{C_y}{\sum_{i=1}^{N_c} \left(E_{iy} \sum_{k=1}^{N_d} h_{ik} p_{ky} \right)} \tag{4b}$$

where N_c is the number of HPF categories deployed in the fishery.

3) The habitat preference of bigeye tuna, measured by the term h_{ky}, is the same across all years. As such, the y index can be dropped from this term.

Based on the above assumptions, the annual index of bigeye tuna abundance can be written as:

$$I_y = \frac{C_y}{\sum_{i=1}^{N_c} \left(E_{iy} \sum_{k=1}^{N_d} h_{ik} p_k \right)} \tag{5}$$

This equation requires the following information:

- Total effort within each HPF category each year, $E_{iy.}$
- Total catch for each year, $C_{y.}$
- The proportion of hooks in each HPF category within each depth-stratum, $h_{ik.}$
- The proportion of bigeye tuna within each depth-stratum, p_k.

A description of the data used in each instance is provided below. In order to be able to compare the results with previous standardisations using GLMs (Campbell 2008) the method was applied for the period July 1997 to June 2007 (i.e. the financial years (FY) 1997/08 to 2006/07).

i) Effort data, E_{iy}

We use the logbook data supplied by AFMA. A listing of the number of sets deployed during the period FY 1997-2006 for each hook-per-float gear configuration is shown in Table 7.1. As there is no data on the depth profile of the hooks for all of the HPF configurations, in most instances the profile of the most similar HPF configuration was used as a proxy. On the other hand, the data for those configurations using less then 5 or more than 40 HPF were not used. The corresponding HPF configurations used in the HBS model are indicated. In total 99.6 of all sets were used.

A listing of the number of hooks deployed each year in the ETBF within each of the HPF categories used in the HBS model is shown in Table 7.2 while the percent of hooks each year within each HPF category is shown in Figure 7.2. For most years, the most common HPF categories used are 8, 10 and 12, with more than a third of all hooks deployed using an 8 HPF configuration during six of the ten years shown. However, there have been significant shifts in the HPF profile over time. Between 1997 and 2004 the percent of hooks deployed on configurations with less than 10 HPF increased from 56% to 78% while the percentage with 10-20 HPF configurations decreased from 43% to 22%. Less than one-percent of hooks during these years were deployed on configurations with more than 20 HPF. During the last two years the percentage of hooks deployed on configurations with more than 20 HPF has increased to 45%, with 21% deployed on 10-20 HPF and 33% on configurations with less than 10 HPF.

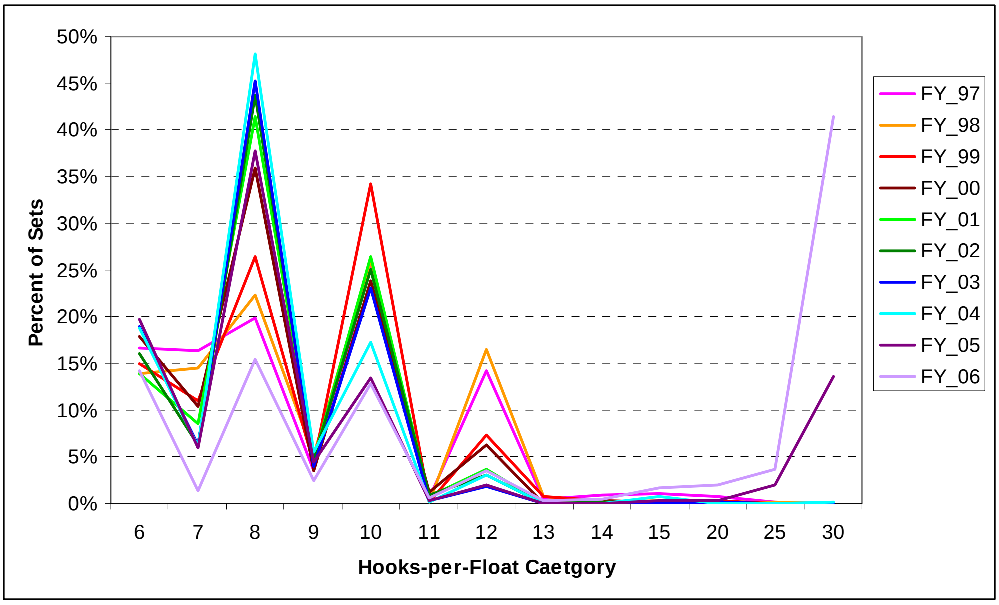
Table 7.1 Total number of sets deployed during the financial years 1997-2006 by gear setting (hooks-per float). The corresponding HPF setting used in the HBS model is also shown.

HPB	HPB-mod	NSETS
1	not used	3
2	not used	10
3	not used	48
4	not used	305
5	6	4186
6	6	13146
7	7	8577
8	8	35260
9	9	4765
10	10	28640
11	11	624
12	12	5924
13	13	237
14	14	262
15	15	389
16	15	82
17	15	11
18	20	78
19	20	2
20	20	216
21	20	1
22	20	8
23	25	1
24	25	38
25	25	257
26	25	4
27	25	35
28	30	16
29	30	16
30	30	2421
31	30	39
32	30	193
33	30	3
34	30	9
35	30	94
36	30	3
38	30	1
40	30	23
>40	not used	28
Total Sets		105955
HPB-mod>0		105561

Table 7.2 Number of hooks deployed each financial year in the ETBF within each of the hook-per-float categories used in the HBS model described in the text

HPF	FY_97	FY_98	FY_99	FY_00	FY_01	FY_02	FY_03	FY_04	FY_05	FY_06
6	1,213,163	1,350,736	1,464,358	1,788,300	1,632,519	2,022,845	2,095,808	1,764,336	1,670,597	1,256,474
7	1,185,902	1,408,672	1,074,767	1,045,417	1,007,355	791,244	686,961	571,811	508,275	124,323
8	1,450,542	2,171,877	2,581,374	3,591,689	4,860,642	5,528,144	5,019,216	4,504,226	3,205,779	1,376,208
9	254,059	503,470	419,738	355,487	556,105	596,964	448,976	508,236	372,951	221,811
10	1,850,289	2,530,209	3,351,308	2,383,228	3,097,630	3,162,858	2,560,337	1,620,646	1,140,279	1,134,561
11	40,029	19,650	12,084	124,115	95,620	109,436	28,630	17,201	21,880	58,800
12	1,033,449	1,613,494	712,591	629,645	426,828	380,796	211,268	286,882	168,575	307,497
13	28,725	75,020	79,400	6,080	7,290	1,000	1,160	620	3,000	33,603
14	69,785	12,730	25,730	28,550	11,240	9,920	6,100	600	3,180	47,332
15	76,375	30,660	18,430	12,480	23,406	17,470	7,950	73,210	23,800	145,979
20	60,460	10,100	33,293	19,715	1,100	3,670	9,980	3,340	23,257	169,706
25	12,806	12,300	0	0	1,200	0	0	900	173,885	318,730
30	3,400	1,400	0	0	0	0	4,500	9,230	1,157,726	3,674,990
Total	7,278,984	9,740,318	9,773,073	9,984,706	11,720,935	12,624,347	11,080,886	9,361,238	8,473,184	8,870,014

Figure 7.2 Percentage of hooks deployed each financial year within each of the hook-per-float categories used in the HBS model described in the text.



ii) Catch data, C_y

We use the catch information (number of bigeye caught and discarded) recorded in the AFMA logbook data for each longline set. The catch is summed across all sets to provide an estimate of the total catch in each year.

iii) Hook-depth profiles, $h_{ik.}$.

The profiles described in section 5.6 are used.

iv) Fish-depth profiles, p_k.

We used the time-series of depth and temperature data collected by 15 archival tags retrieved from a total of 161 tags deployed on bigeye tuna in the Coral Sea between October 1999 and October 2001. Time at liberty for these tags varied between 16 and 1441 days. A full description of the tagging operations and the data collected is provided in Gunn et al (2005) and Evans et al (2008). Percent time-at-liberty versus depth profiles and percent time-at-liberty versus temperature profiles collected from these 15 tags are shown in Figure 7.3a and Figure 7.3b respectively. Each profile displays the generally bi-modal distribution associated with the vertical diurnal movement of this species through the water column and observed for bigeye from other tagging experiments (Schaefer and Fuller 2002, Musyl et al. 2003). Unlike other applications of the HBS method, where the temperature preference profile for the species of interest are combined with the spatial distribution of temperature-at-depth provided by Global Circulation Models to provide a species-depth profile within each spatial-temporal stratum in the model, here we use the mean time-at-liberty versus depth profile over all tags to provide a time and space invariant estimate of the fish-depth profile, p_k, over the entire ETBF.

Figure 7.3a Percent time-at- depth profiles collected from 15 archival tags attached to bigeye tuna tagged in the Coral Sea. The mean profile across all tags is also shown.

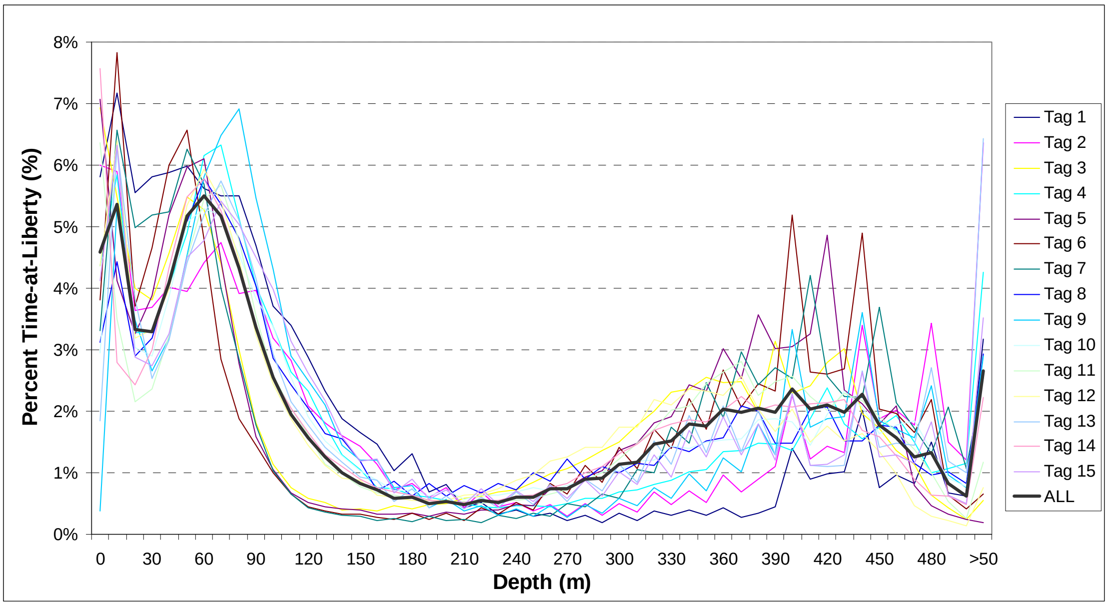
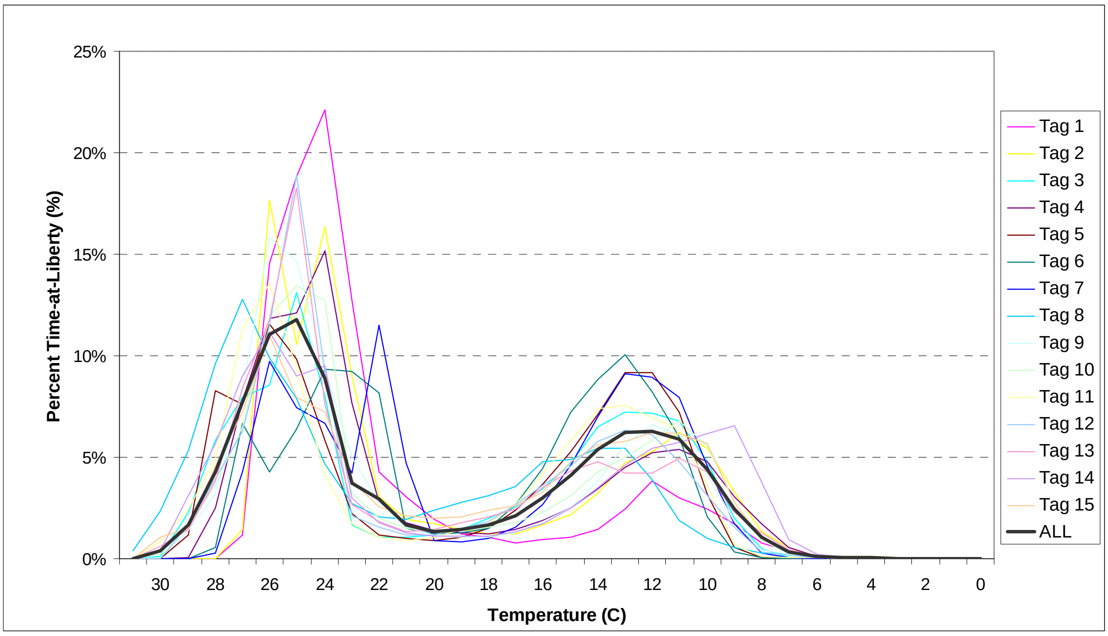


Figure 7.3b Percent time-at-temperature profiles collected from 15 archival tags attached to bigeye tuna tagged in the Coral Sea. The mean profile across all tags is also shown.



Two other variants were also fitted to the above model.

2) We assume a seasonal (i.e. quarter of the year) variation in the proportion of bigeye tuna with depth. Again, the tag data was used to determine the mean percent time-at-depth profile for each season (1=Jan-Mar, 2=Apr-Jun, 3=Jul-Sep, 4=Oct-Dec). These profiles are shown if Figure 7.4a. The effective effort was calculated for each quarter of the year, then summed across all four quarters to give the total effective effort for the year. In this instance, equation (5) becomes:

$$I_y = \frac{C_y}{\sum_{q=1}^{4}\sum_{i=1}^{N_c}\left(E_{iqy}\sum_{k=1}^{N_d}h_{ik}p_{qk}\right)} \qquad (6)$$

where: E_{iqy} is the total number of hooks deployed with HPF configuration i in quarter q in year y,
p_{qk} is the proportion of bigeye tuna in quarter q in depth stratum k (and were assumed to constant across all years).

As before we assume h_{ik}, the proportion of all hooks with HPF configuration i in depth stratum k, is constant across all quarters and years.

3) We assume a diurnal variation in the proportion of bigeye tuna with depth. As previously described in section 2.3e, each longline set was classified into one of the following three set types - day, night or combined. However, as it was not possible to calculate for each set the proportion of the total soak that occurred during day-light hours, this classification was based on the hour of the day that the set commenced. Using the observer data collected from 2003 sets, the proportion of each 24 hour period that the total soak of each observed set occurred during daylight hours, defined as between 6am and 6pm, is shown in Figure 7.5. Using the mean proportion for each hour, P, and again defining a day-set as that where $P>0.66$ and a night set where $P<0.33$, then each set-type was defined as follows:

Day-set:	Set commences between 1am and 10am
Night –set	Set commences between 1pm and 8pm
Combined-set:	Set commences between 10am-1pm or 8pm-1am

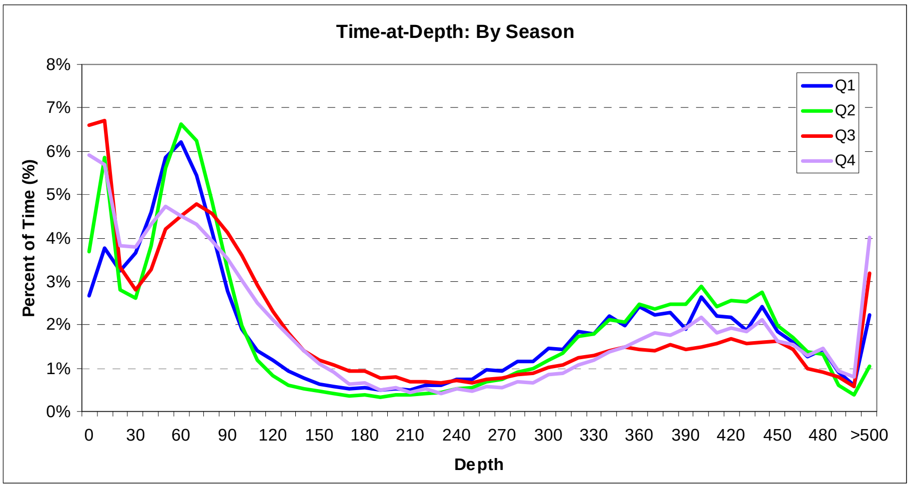
The mean percent time-at-depth profile within each day/night/combined period was again determined from the tag data. The profiles for each period are shown in Figure 7.4b. The effective effort was calculated for each diurnal period, then summed across these periods to give the total effective effort for the year. In this instance, equation (5) becomes:

$$I_y = \frac{C_y}{\sum_{t=1}^{2}\sum_{i=1}^{N_c}\left(E_{ity}\sum_{k=1}^{N_d}h_{ik}p_{tk}\right)} \qquad (7)$$

where: E_{ity} is the total number of hooks deployed with HPF configuration i in diurnal period t in year y,
p_{tk} is the proportion of bigeye tuna during diurnal period t in depth stratum k (and were assumed to constant across all years).

As before we assume h_{ik}, the proportion of all hooks with HPF configuration i in depth stratum k, is constant across all periods and years.

Figure 7.4 The mean percent time-at-depth profiles from 15 archival tags attached to bigeye tuna tagged in the Coral Sea stratified by (a) season (quarter of the year) and (b) day and night.



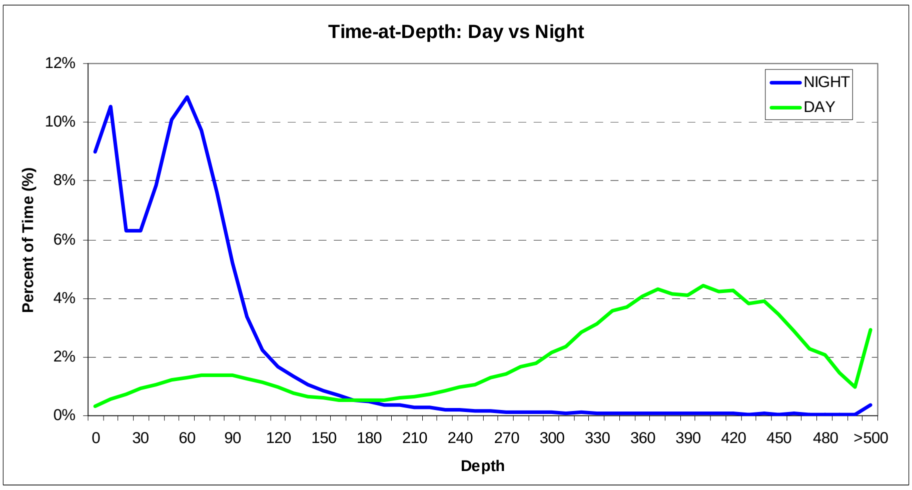
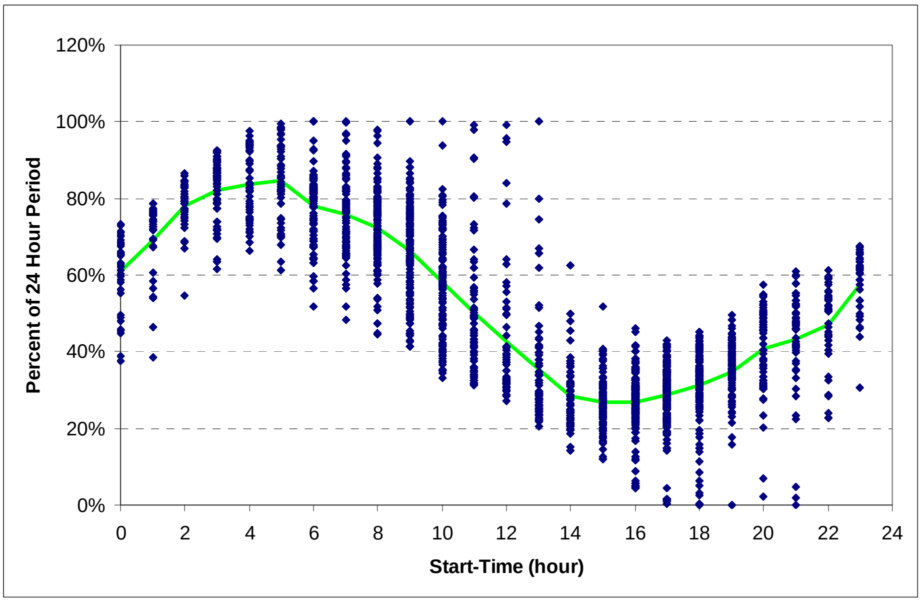


Figure 7.5. Proportion of each 24 hour period that the total soak of each observed set occurs during daylight hours, defined as between 6am and 6pm.



7.3.2 Results

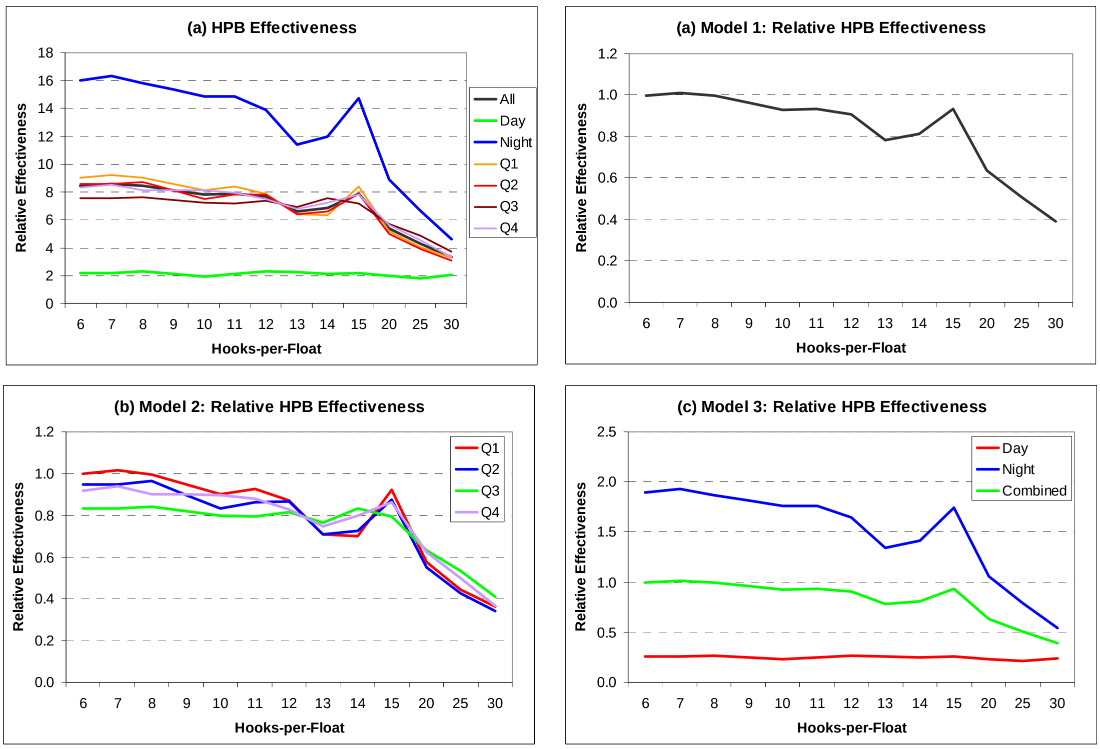
From equation (5) the effective effort can be written in the form:

$$EE_y = \sum_{i=1}^{N_c}\left(E_{iy}\sum_{k=1}^{N_d} h_{ik}\, p_k\right) = \sum_{i=1}^{N_c}\left(E_{iy} R_i\right) \tag{8}$$

where $R_i = \sum_{k=1}^{N_d} h_{ik}\, p_k$ (the cross product of the depth-profile of the hooks within each HPF configuration with the depth-profile of the fish) provides a measure of the effectiveness of the hooks in each HPF configuration in fishing for the target species. The values of R_i for each HPF configuration included in the models and for each of the three models fitted to the data are shown in Figures 7.6. In Figure 7.6a the raw values of R_i are displayed whilst in Figures 7.6b-d relative values are displayed for each of the three models. For model 1 the values of R_i have been made relative to the 6 HPF configuration, for Model 2 relative to the 6 HPF configuration deployed during quarter 1 (Jan-Mar), and in Model 3 relative to the 6 HPF configuration deployed during the combined period. (Note, in calculating the indices given by equations (5)-(7) it was found useful to adopt similar relative measures when calculating each R_i value as this helps to preserve the effort scale.)

These results indicate that there is a relative decrease in the effectiveness of hooks in targeting bigeye tuna as hooks are deployed in configurations with increasing HPF. For Model 1, hooks in a 13 HPF configuration are found to be only 80% as effective as hooks deployed in a 6 HPF configuration, while hooks in a 30 HPF configuration

Figure 7.6 Relative effectiveness of each HPF configuration with (a) no temporal stratification and relative to a 6 HPF configuration, (b) a seasonal stratification and relative to a 6 HPF configuration deployed during season 1 (Jan-Mar) and (c) a day-night stratification and relative to a 6 HPF configuration deployed during the day.



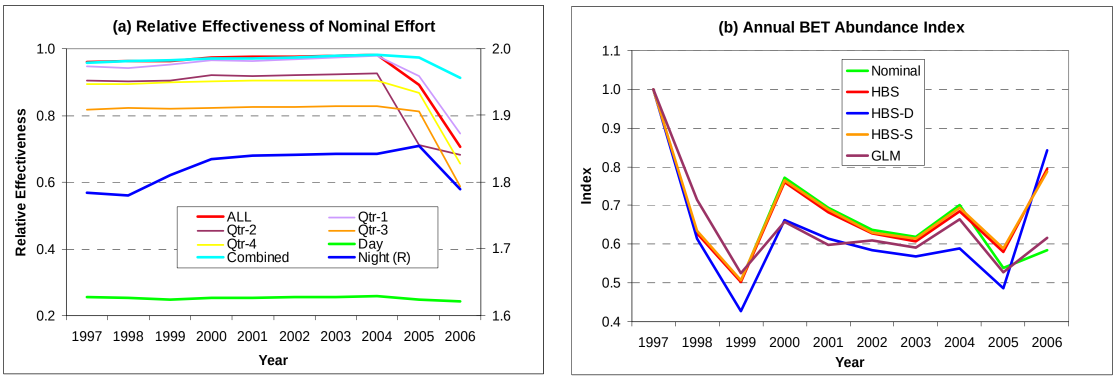
are found to be only 40% as effective. A similar pattern is also found for each of the four seasonal results. The most striking results are seen in those for Model 3, where the model took into account diurnal variation in the depths of the targeted fish. Hooks deployed in a 6 HPF configuration during the night are found to be more than 7 times as effective as hooks deployed in a similar configuration during the day. This result is explained by reference to Figures 5.3 and 7.4b where it is seen that there is great overlap in the depths of the hooks and bigeye during the night but relatively little overlap during the day. Consequently, hooks deployed in a 6 HPF configuration have a much greater effectiveness at targeting bigeye at night than during the day. The difference in relative effectiveness between deploying hooks during the night versus the day decreases as the number of HPF increases due to the fact that overlap of these hooks with the depth distribution of bigeye during the day decreases.

The effective effort calculated in equation (8) can be expressed in the following form:

$$EE_y = e_y E_y$$

where e_y is the relative effectiveness of the nominal effort E_y for the entire year. The values of e_y for each temporal stratification used in of the three models are shown in Figure 7.7a. As noted previously, effectiveness is relative to hooks deployed in a 6 HPF configuration and during one of the temporal strata used in the model (season 1 and combined set-types for models 2 and 3 respectively). All results, except that for the Night stratification, display a fairly constant effectiveness between 1997 and 2004, after which the effectiveness decreases significantly. This decrease coincides with the large increase in deploying 25 and 30 HPFs. The results for the four seasons indicate that effect is most effective during the first quarter (around 90% until 2004 then decreasing to around 75%) and least effective during the third quarter (arousnd 83% until 2004 then decreasing to around 60%). The Night result again indicates that the effectiveness of hooks deployed during the night is around 7 times that of hooks deployed during the day.

Figure 7.7 (a) Relative effectiveness of nominal effort at targeting bigeye tuna (NB, values for Night effectiveness corresponds to right-hand axis), and (b) annual indices of bigeye abundance based on various CPUE models.



Finally, the annual index calculated for each of the three models is shown in Figure 7.7b. These indices are compared with both the nominal CPUE for each year and an index based on a GLM where the effort has been standardised for a range of gear (HPF, bait, start-time of set, light-sticks used) and environmental (moon-phase, sea-surface temperature and southern-oscillation index) effects (Campbell 2008). Despite some differences in the size of the annual change, all indices display a similar pattern over the ten year time-series. However, there are some significant differences in the size of the change between years, with the model accounting for diurnal differences in effort effectiveness displaying the greatest changes between years and the greatest differences with the other indices. Of particular note is the large increase in the diurnal-model index in 2006. As noted, previously there was a large increase in the use of longline configurations with 30 HPF (up from 3.6% in 2005 to 40.4% in 2006, c.f. Figure 7.2) which may have resulted in a large decrease in the overall effectiveness of the hooks in targeting bigeye (c.f. Figure 7.7a).

7.4. An Alternative Temperature-based Model

The above modelling approach is premised on the belief that the distribution of the target fish in the water column is determined by depth alone, and that if one knows this depth distribution then one can match this with the depth distribution of the hooks to determine the effectiveness of these hooks. An alternative approach is to assume that the distribution of the target fish in the water column is determined by water temperature. Then if one knows the distribution of the preferred temperature range of the species then this can be correlated with the distribution of temperatures fished by the hooks to estimate the relative effectiveness of these hooks.

Using this alternative approach, the model equations are obtained by simply replacing the depth stratification of the water column by stratification based on temperature. Hence, equation (5) becomes:

$$I_y = \frac{C_y}{\sum_{i=1}^{N_c} \left(E_{iy} \sum_{k=1}^{N_T} h_{ik} p_k \right)} \qquad (10)$$

where: C_y is the total number of bigeye tuna caught in year y,
E_{iy} is the number of hooks deployed within HPF category i in year y,
h_{ik} is the proportion of hooks within HPF category i in temperature stratum k,
p_k is the proportion of bigeye tuna in temperature stratum k,
N_T is the number of temperature stratum in the model,
N_C is the number of HPF categories used in the model.

Compared to the previous depth-based model the only new information required to apply this model is the information on h_{ik}, the proportion of hooks within HPF category i in temperature stratum k, and p_k, the proportion of bigeye tuna in temperature stratum k. The former were calculated from the TDR data (in a similar manner to the depth profiles shown in Figure 5.4) whilst the latter information was again based on the data collected from the 15 archival tags retrieved from the bigeye tuna tagged in the Coral Sea. The mean percent time-at-liberty versus temperature profile collected these tags, together with the mean profiles stratified by season (quarter of the year) and day-versus night are shown in Figure 7.8.

The results from applying the above model are shown in Figure 7.9 and 7.10. The raw and relative values of the HPF effectiveness term, $R_i = \sum_{k=1}^{N_T} h_{ik} p_k$ (shown in Figure 7.9) indicate a pattern of relative HPF effectiveness quite different to that seen for the depth-based model. Unlike the declines in effectiveness with increasing HPF evident

Figure 7.8 The mean percent time-at-temperature profiles collected from archival tags attached to 15 bigeye tuna in the Coral Sea. The mean profiles stratified by (a) season (quarter of the year) and (b) day and night are also shown.

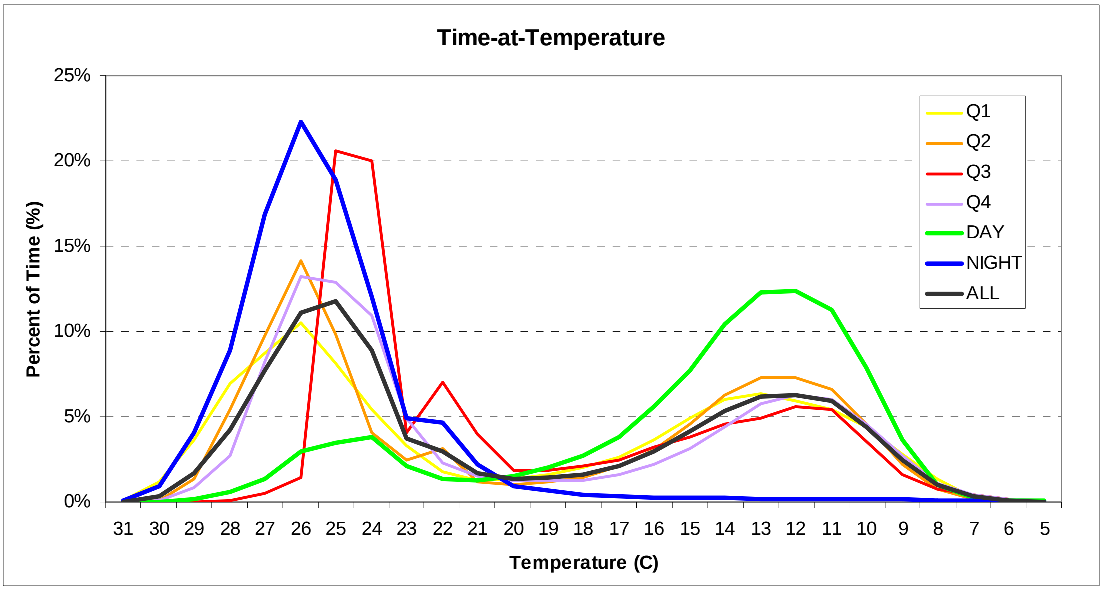


Figure 7.9 Relative effectiveness of each HPF configuration based on the temperature-based model with (a) no temporal stratification and relative to a 6 HPF configuration, (b) a seasonal stratification and relative to a 6 HPF configuration deployed during season 1 (Jan-Mar) and (c) a diurnal stratification and relative to a 6 HPF configuration deployed during the combined period.

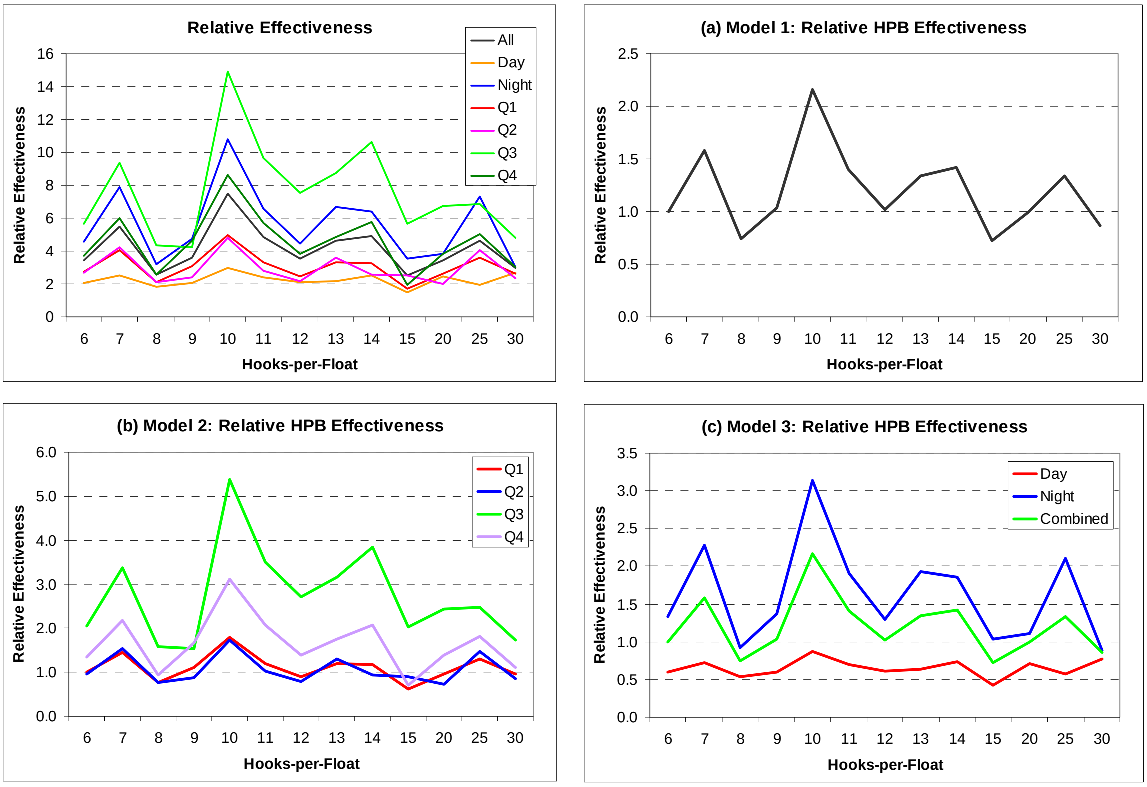
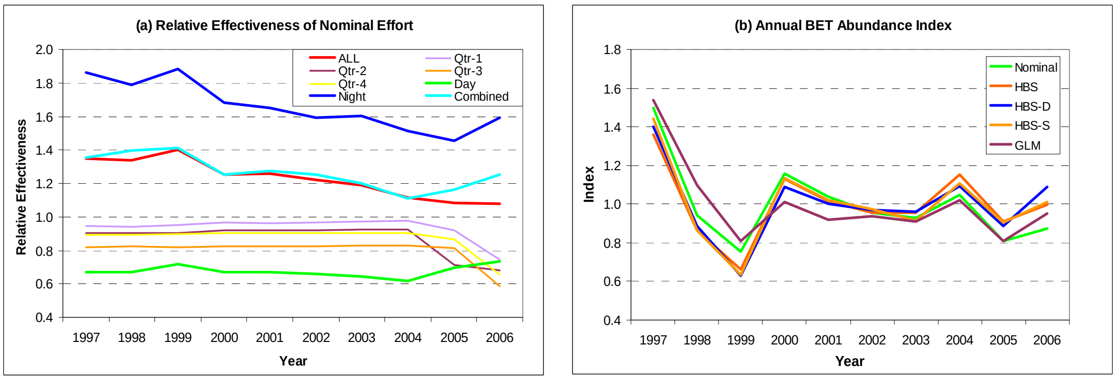


Figure 7.10 Results for the temperature-based model: (a) Relative effectiveness of nominal effort at targeting bigeye tuna, and (b) annual indices of bigeye abundance based on various CPUE models.

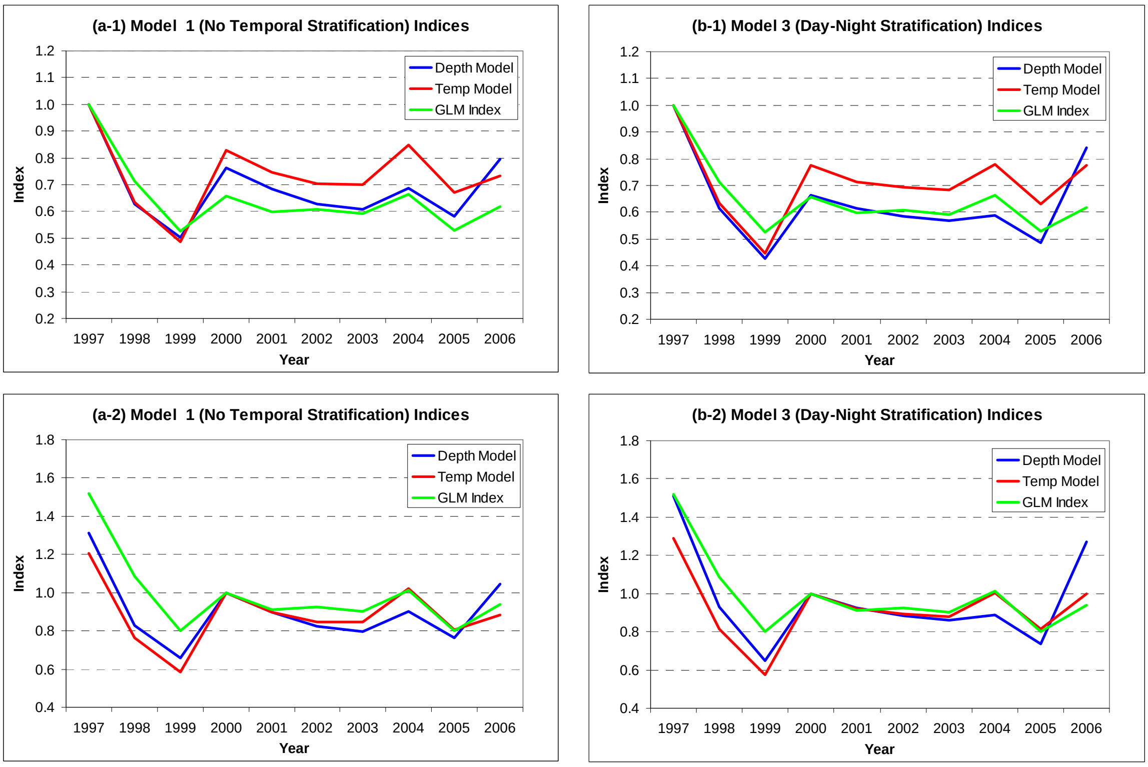


for the depth-based model, this model indicates that while there can be large differences in effectiveness between HPF categories there is no overall trend as HPF increases. Nevertheless, as with the depth-based models the temperature-based models also show significant differences in the effectiveness between temporal strata. For example, most HPF categories are 2-3 times more effect during the third quarter (Jul-Sep) than during the first and second quarters, while the average difference in effectiveness between the fourth quarter and the first quarter is around 50 percent. The deployment of hooks at night is also, on average, 2.5 times as effective as day deployments.

The overall effectiveness of all hooks deployed each year, relative to the nominal effort, is shown in Figure 7.10a. Like the previous depth-based models, the effectiveness for each season is relatively constant across years before decreasing significantly in the last two years (again due to the increase in 25 and 30 HPF configurations). On the other hand, there is a decrease in effectiveness over time for hooks deployed during the night resulting in a similar, but smaller decrease, in the effectiveness of all hooks.

Finally, the annual indices of bigeye tuna abundance, shown in Figure 7.10b, display less variability compared to those based on the depth-based models with the overall trend since 2000 closer to the GLM-based index. A closer comparison of the indices for the depth-based HBS model, the temperature-based HBS model and the GLM-based models are shown in Figure 7.11. For the models with no-temporal stratification, all three models indicate a similar decline in abundance between 1997 and 1999, though the HBS-T model indicates the greatest change between 1999 and 2000 with the GLM-based model indicating the least change. Since 2000 the HBS-T model and the GLM model display the most similar trend, with the HBS-D model generally remaining lower before displaying a large increase in 2006. For the models which include the day-night stratification, the two HBS-based models indicate a greater decline between 1997 and 1999 and greater increase between 1999 and 2000 than the GLM-based model. Since 2000 the HBS-T model and the GLM model again display the most similar trend, with the HBS-D model remaining lower before displaying a large increase in 2006. However, despite these differences for each model the relative change since 1997 is very similar whether the day-night stratification is included or not.

Figure 7.11 Comparison of the indices for the depth-based HBS model, the temperature-based HBS model and the GLM-based models for (a) those HBS models with no temporal stratification, and (b) those HBS models with a day-night temporal stratification. (Note: For (a-1) and (b-1) all indices are relative to the corresponding value in 1997, while for (a-2) and (b-2) all indices are relative to the corresponding value in 2000.)



7.5 Statistical HBS

As noted previously, the applications of the HBS method to the ETBF data presented above made a number of simplifying assumptions. In particular, the habitat preference profile was assumed to be a function of depth or temperature alone and the same profile was assumed to apply across all areas of the fishery. In the original HBS method, the habitat-at-depth profile was assumed to be a function of temperature and dissolved-oxygen preferences, and the distribution of these two physical properties across each spatial area, mapped using an Ocean Global Circulation Model (OGCM) was used to determine the habitat-profile within each area. In the application above we have circumvented this process by simply using the mean time-at-depth profile obtained from the archival tags data. One could overcome the second simplifying assumption by simply stratifying the archival data by area and then determining a unique time-at-depth profile within each area.

The habitat-based standardisation methods outlined above are often called "deterministic." This is because it assumed that all the components of the model, including the habitat preference, are known and once all the data elements have been obtained, the data is simply fitted to the model equations in a deterministic and non-statistical manner. More recently this approach has been modified to allow for recognition of the uncertainty in the habitat preference estimates (and the functional form of the underlying models). In particular, it is assumed that the temperature preference profile is uncertain and this profile is estimated using the temperature preference data from the tag observations as a prior distribution in a Bayesian modelling framework (Maunder et al 2005). This approach has since become known as the statHBS method and has been applied to both bigeye and yellowfin tuna within the WCPO (Langley et al, 2005).

In order to gain a better understanding of the potential utility of this statistical approach, the statHBS method was applied to the bigeye data for the ETBF and the results compared with the results from detHBS method and the two alternative tag-only-based approaches applied in the previous section (i.e. the HBS-D and HBS-T models). The application of the statHBS and detHBS methods was undertaken by Keith Bigelow at the NOAA Pacific Island Fisheries Science Centre in Honolulu, Hawaii who made use of previously designed software for linking the catch and effort data to the temperature at depth data from an OGCM. However, some missing data in the OGCM (mainly in the northern part of the ETBF) resulted in around 6 percent of the data records not been used. A full description of the methods and OGCM data used is provided in Bigelow (2006). Each method was applied separately to the three diurnal periods identified previously - Day, Night and a Combined day/night period. A comparison of the resulting standardised annual CPUE index for bigeye is shown in Figure 7.12a whilst a comparison of the estimated temperature-preference profile from the statHBS method with the tag-data based prior is shown in Figure 7.12b.

For each diurnal period, the four time-series of standardised CPUE-based indices are seen to be similar for each standardisation method, but for the Day and Combined periods the detHBS indices appear to be the most dissimilar while the HBS-D index appears to be the most dissimilar for the Night period. In order to provide a better quantitative measure of similarity between different indices, the absolute percentage difference between any two indices *i* and *j* in year *k* was calculated and then the mean calculated across all years, *N*, i.e.

$$S_{ij} = \frac{100}{N}\sum_{k=1}^{N}\frac{abs\left(I_{ik} - I_{jk}\right)}{I_{jk}}$$

The values of S_{ij} for each diurnal period and each standardisation method are listed in Table 7.7.

For both the Day and Combined periods the HBS-D and HBS-T indices are seen to be the most similar while for the Night period the statHBS and HBS-T are most similar. On the other hand, for all periods the indices based on the detHBS method are generally the most dissimilar from the three other indices (though this difference is small for the Night period). This result is perhaps somewhat surprising, as the detHBS and the two tag-based indices both make "deterministic" use of the tag data while the statHBS method allows more freedom for the temperature profile to be determined by the catch and effort data. In this regard, this result raises the issue of what elements of the data are perhaps to most important and accurately measured from a habitat perspective. While the depth and temperature data retrieved from the archival tags are deemed to be relatively accurate and have a fine-scale resolution, the distributions of temperature and dissolved-oxygen profiles taken from any OGCM are likely to be poorly resolved at the scales required to model the daily habitat ranges of the species

Figure 7.12 (a) Comparison of annual bigeye abundance indices based on the statHBS, detHBS and the two tagged-only based HBS methods applied to the data for each of the three identified diurnal periods (note, all indices are scaled such that the mean across the time-series is one) and (b) comparison of the prior (tag-data) temperature preference profile with that estimated from the statHBS model.

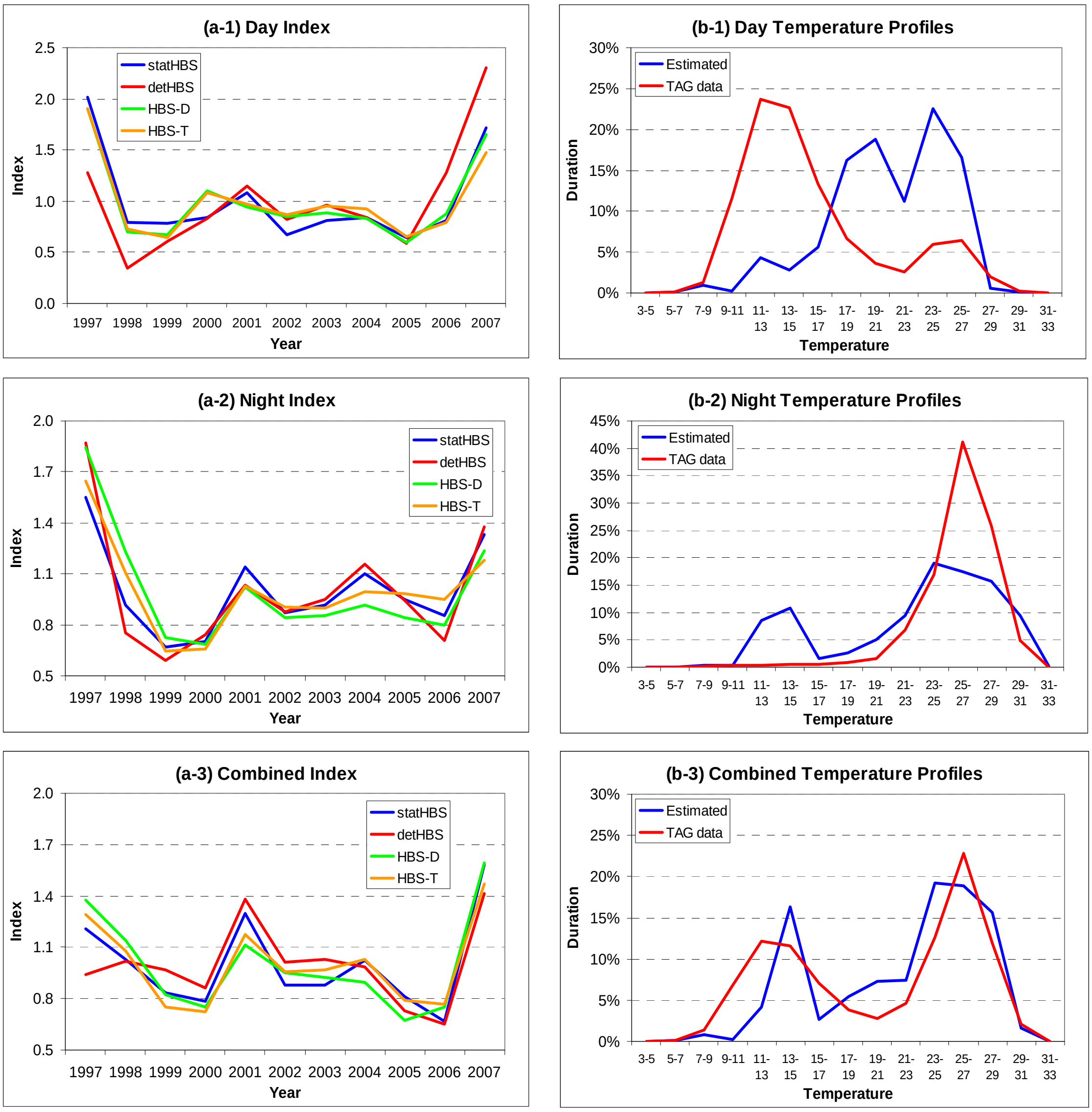


Table 7.7 Measure of similarity between the annual standardised CPUE-based indices for each period and standardisation method.

Period	DAY				NIGHT				COMBINED			
Method	statHBS	detHBS	HBS-D	HBS-T	statHBS	detHBS	HBS-D	HBS-T	statHBS	detHBS	HBS-D	HBS-T
statHBS		24%	12%	13%		9%	11%	8%		10%	9%	8%
detHBS	30%		26%	28%	9%		15%	14%	10%		15%	13%
HBS-D	11%	22%		6%	11%	13%		9%	9%	14%		7%
HBS-T	12%	25%	6%		8%	13%	8%		8%	13%	7%	
Mean	18%	24%	14%	16%	9%	11%	12%	10%	9%	13%	10%	9%

of interest. In particular, the primary issue is whether the temporal and spatial resolution of the OGCM temperature and DO profiles relative to 1) the effort distributions, 2) the diurnal vertical migrations of the fish, and 3) the seasonal horizontal migrations of the fish. If they do not have adequate resolution at these scales then there is potential for considerable bias. At worst they could be inaccurate and unreliable. How adequate and how reliable these data are at these required resolutions remains uncertain. The model for which the accuracy of the OGCM data is most important is the detHBS model and it is therefore of interest that the results of this model are the most different in comparison to those from the other two models.

Finally, the estimated temperature profiles from the statHBS model show several major differences when compared to the profiles from the tag data (c.f. Figure 7.12b). This is most clearly seen in the profiles for the Day period. The tag-based profiles indicate that during this period bigeye spend the majority of their time in temperatures between 10-15C (i.e. deep water) with a smaller mode between 24-27C (i.e. surface waters). However, the statHBS model estimates that bigeye spend nearly all their time during the day at temperatures above 17C. Differences are also seen in the Night-period profiles, thought the two profiles for the Combined period are the relatively similar. Again, the issue of whether the resolution of the data from the OGCMs is adequate for these CPUE standardisation models is important in the estimation of these temperature profiles, and biases in these data would propagate through to the estimated profiles. Whether or not this is the reason behind the differences noted remains uncertain.

Section 8: Discussion and Conclusions

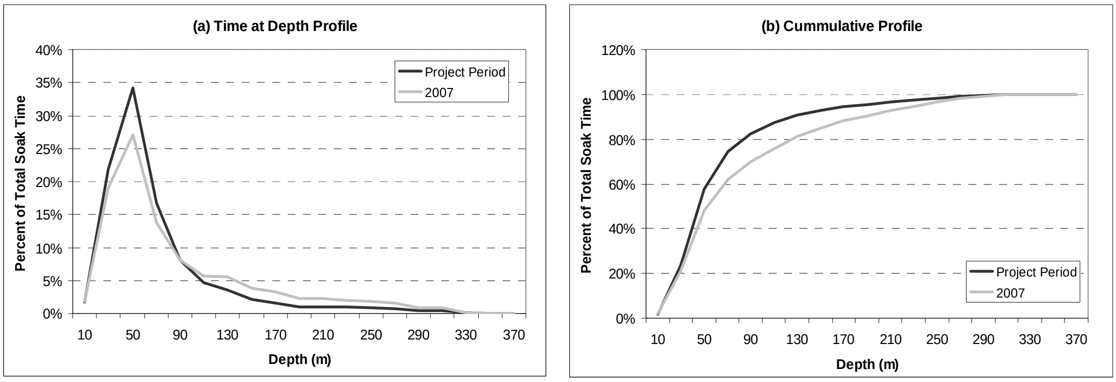
The primary objective of this study was to gain greater knowledge of the operational characteristics of longlines deployed in the Eastern Tuna and Billfish Fishery (ETBF) so as to better understand how these characteristics influence the effectiveness of longline effort targeted at the principal catch species in this fishery and resulting catch rates. The second objective was to test the utility of the habitat based method of standardising catch rates. These are important research issues as the dynamic nature of a fishery in general, and the ETBF in particular, means that operation characteristics remain constant over time. Furthermore, as catch rates (CPUE) are a central input into stock assessments and the harvest strategy for the ETBF, effective monitoring and sustainable management of the ETBF is dependent on having a good understanding of the how such changes in operational characteristics may affect CPUE and to be able to account for them in standardising abundance indices for the fishery.

In addressing the above objective this project has achieved a number of firsts. Using Temperature-Depth Recorders (TDRs) it has undertaken the first systematic examination of the depths and temperatures fished by longlines deployed across the ETBF by a range of vessels using a range of different fishing practices and gear configurations. A total of 2050 individual TDR recordings were obtained between August 2004 and May 2007. It has also allowed an investigation of the factors influencing the depths fished by these hooks. Furthermore, by combining these depth data with the catch and associated hook position data collected by AFMA observers, this project has achieved the first comprehensive understanding of the range of depths at which individual species are caught by longline hooks within the ETBF. Finally, by combining the understanding of the depth profiles fished by hooks with the observations from archival tags on the depth-profiles fished by bigeye tuna, for the first time it has been possible to apply the habitat-based method to standardising catch rates in the ETBF.

8.1 Depths Fished by Longline Hooks

The TDR data has shown that hooks deployed in the ETBF longline fishery fish a range of depths down to around 400m, with the deepest recorded depth being 395 m. (Note: it remains possible that a few hooks attained a greater depth but the depth sensor on the TDRs maxed out at about 400m). The depth profiles fished by sets deploying less than 10 HPF were found to be very similar, though the depth-profiles associated with those sets deploying more than 15 HPF were considerably deeper. As most sets identified by observers as targeting yellowfin, bigeye or swordfish generally deploy less than 10 HPF, the depths fished by hooks targeting each of these species were found to be similar. This result indicates that this variable has little discriminating power in distinguishing different fishing practices and targeted depths associated with these three species. On the other hand, for gear configurations deploying more than 10 HPF a near linear relationship was found in the mean depth fished by all hooks within a HPF configuration and the number of HPF. This latter result supports the assumptions often used in the CPUE standardisation models for longline fishing that the number of HPF is a proxy for fishing depth, but the former result shows that this assumption is not true for across all HPF configurations (at least within the ETBF).

Figure 8.1 Estimated soak-time versus depth profile for all sets in the ETBF during the period of the project (August 2004-May 2007) and for all sets during 2007.

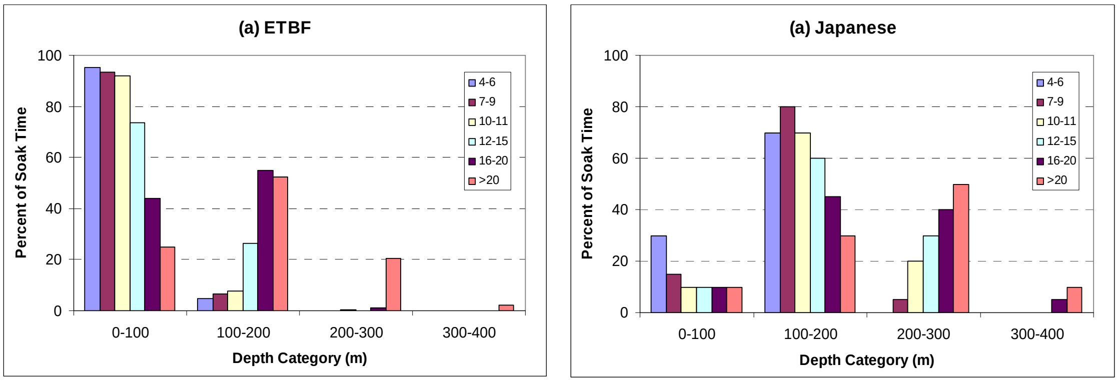


Combining the observed depth-profiles associated with each HPF configuration (c.f. Figure 5.3) with the profile of sets deploying each HPF configuration provides a profile of depths for all hooks deployed in the ETBF. This profile is shown in Figure 8.1 for all sets deployed in the ETBF during the period that TDRs were deployed (August 2004 to May 2007) and for all sets deployed during 2007. These profiles indicate that the most common depths fished by hooks are relatively shallow, with hooks monitored during the project spending around 34 percent of the soak time between 40-60 meters and around 75 percent of the time at depths less than 80 meters. Only 10 percent of the time was spent fishing depths greater than 140 meters. The greater use of sets deploying 20 or more HPF during 2007 increased the percentage of time hooks fished below 140 meters to 20 percent and below 200 meters to 10 percent.

The depths to which hooks were observed to sink where found to be highly variable for a given HPF configuration and hook number. Furthermore, for configurations with 6 and 8 HPF the mean depths attained where found to be very similar for each hook-number, and the lack of a catenary shape indicates that these lines are generally deployed in a taut manner. On the other hand, for sets deployed with more than 10 HPF the mean depths to which hooks sank to varied with hook number, and the relation between mean depth and hook-position approximated the expected catenary shape. Furthermore, for sets where the observer data was considered of a high quality, the mean depths attained by hooks were found to be accurately predicted by the longline catenary equation of Yoshihara (1951). However, despite this finding, considerable variation was observed in the depths attained by hooks, with current-speed, HPF configuration and the use of a line shooter found to be the main factors influencing this variation from the predicted depth. While currents can act on the gears directly to shoal the line, current may also influence the sag ratio of the line (and depths of the hooks) significantly during the fishing operation due to currents influencing the separation between floats (Mizuno et al 1999). Based on the observations made during this study, the depths fished by hooks were found to decrease during the soak, with the mean depth fished being, on average, 87 percent of the depth to which the hook originally sank.

The collection by the observers of data on setting practices also allowed the estimation of the sag angle of the long line for a range of gear configurations. This angle is difficult to measure and in many studies a value of 72^o has been assumed (Ward and

Figure 8.2 Estimated depth profiles for respective HPF categories for (a) ETBF longliners and (b) Japanese longliners.



Myers 2006, Bigelow and Maunder 2007, .Ward and Myers 2007). This angle also proved difficult to estimate within the present study, with many estimated values of the associated Sag-ratio being greater than 1, which is technically impossible. For the subset of data which was considered to be the most reliable the estimated sag angle was found to vary between 24 and 87 degrees, with a mean of 57 degrees. This angle is considerably less than that usually assumed, and will result in the line fishing shallower depths. For example, for a line with 7 HPF and 45 meters between branchlines, the depth attained by the deepest (middle) hook with a sag angle of 57^{o} will be around 30m less than with a sag angle of 72^{o}.

Finally, it is informative to compare the estimated depth profiles of hooks observed in the ETBF with those estimated for Japanese longliners. The latter were estimated by Hampton, Bigelow and Labelle (1998) based on a number of studies undertaken by Japanese scientists and are shown in Figure 8.2 for a range of HPF categories. The corresponding depth-profiles observed in the ETBF (based on combining the depth profiles shown in Figure 5.3) are also shown in the same figure. The two sets of profiles are seen to be very different with Japanese hooks fishing considerably deeper than hooks deployed in the ETF. For example, hooks deployed within the ETBF using configurations of less than 15 HPF generally spend more than 70 percent of their time at depths less than 100m, while corresponding hooks deployed by Japanese longliners are estimated to spend more than 60 percent of their time at depths between 100-200 meters. The same pattern is also seen for sets deploying a higher number of HPF. The reasons for these significant differences in depths remain uncertain, but are most likely due to shorter branchlines and floatlines used in the ETBF and the smaller sag angle. This result also indicates that the deployment of the longline can vary significantly between fishing fleets as can the depths fished by the deployed hooks. Hence, assuming the depth-profiles of different fleets are similar may not be valid and, in turn, will limit the application of the habitat-based method of standardising catch rates to those fleets for which the depth-profiles of the hooks has been ascertained.

8.2 Capture Depths of Species

The distribution of the catch by hook-number, obtained from the observer data, indicated that the catch was generally not uniformly distributed by hook-number for most HPF configurations. While this result would be expected if the availability of fish varied with depth and depth-profiles fished by the hooks also varied with hook number, the latter assumption was found not to be valid for sets deploying 8 or less HPF. Also, despite hooks at similar positions having similar depth profiles, there was an asymmetry in the catch distribution by hook-position. The reasons for this asymmetry remain unclear, but the fact that the observer recorded catch by hook-position and not hook-number cannot be ruled out.

The hook-depth profiles discussed above were combined with the observer-recorded information on the catch-by-hook-number for each set to provide estimates of the depth-profiles of catch rates for each of the principal target species. Due to the fact that a depth-profile could not be obtained for all hook-numbers for a given set, these profiles were based on combining the mean depth-profile over all monitored hooks for a given hook-number within each HPF configuration with the associated mean CPUE observed for that hook-number/HPF configuration. The results indicated that although there were significant differences in the catch rates of the different target species between gears deploying different HPF configurations, the associated depth-profiles were usually very similar. Indeed, the profiles for each of these five species for HPF configurations with less than 10 hooks were extremely similar indicating that for these gear configurations the relative availability of each species with depth was also very similar over the range of depths fished by these gears. The species-specific catch rate profiles for gears deploying between 10 and 25 HPF were also very similar indicting a similar result.

The above results are somewhat surprising, as although it is known that these species undergo large vertical movements in the water column (usually on a daily basis) it is usually assumed that each species has a different profile of availability with depth with respect to the longline gears (i.e. catch rates obtained from different parts of the longline gear will vary dependent on how closely the depth-profile of the hooks overlaps this availability profile). For example, it is often believed that shallower hooks achieve higher catch rates of yellowfin tuna and deeper hooks achieve higher catch rates of bigeye tuna. Indeed, this was the rationale used by the Japanese longline fleets when they introduced the deeper longline technique in the mid-1970s to target the deeper swimming bigeye (Suzuki et al, 1977). However, in the present study no strong evidence was observed for such systematic differences in the catch rates of different species across those parts of the longline gears fishing different depths. Only for sets with 30 HPF was it observed that the catch of bigeye tuna generally occurred on deeper hooks than yellowfin tuna. While this result is a composite result in the sense that it does not take into account differences in catch rates between day and night sets, or possible differences in the size of fish caught, it may also be possible that hooks associated with shallow longlines (i.e. using less than 12 HPF and which were the most frequently observed during this study) only fish a small proportion of the extended depth range that a given species inhabits, and that the availability of fish within this limited range of depths is relatively uniform. Only for longlines that fish a large enough proportion of this extended depth range (e.g. those with 30 HPF) do we notice differences in species specific profiles.

Despite these similarities within HPF configurations, there were nevertheless large and significant differences observed in the mean catch rates between sets deploying different HPF configurations. As a consequence, it was possible to discern major differences in the average availability-by-depth across the five main target species. For yellowfin tuna availability was estimated to be highest in the top 40 meters (as generally expected) and to then decline with depth, though availability was estimated to remain quite high down to around 200 meters. This increased understanding of the availability of yellowfin down to these deeper depths has been one of the unforeseen benefits of the move to deeper longlining within the ETBF that accompanied the increased targeting of albacore tuna a few years ago. On the other hand, availability for albacore was estimated to be relatively low in the upper parts of the water column and to be highest between 150-200 meters, though remaining high at deeper depths down to 310m. Bigeye tuna availability was found to be more evenly distributed with depth, though with a tenancy for higher availability at deeper depths. Availability for both swordfish and striped marlin was found to be low at depths below 150m and again highest in the top 40 m. It will be interesting to compare these results with the time-at-depth data being collected for species such as swordfish and yellowfin tuna from the recent deployment of archival tags within the ETBF.

These results, combined with the depth profiles observed for each gear configuration should be of particular interest to fishers as this knowledge will assist them better understand the factors that control the depths fished by hooks and how effective each gear configuration is at targeting a given species.

8.3 Habitat-Based Standardisation (HBS) Models

The HBS method of standardising CPUE provides an alternative to the usual approaches based on the application of a GLM or GAM. In particular, it provides an opportunity to use our increasing knowledge of the distribution of the target species and the fishing gears more directly. Information on the depth distributions of the target species is being obtained from the increasing use of electronic data storage tags whilst information on the depth-distributions of the fishing gears can be obtained from the deployment of depth monitors such as the TDRs utilised in this project. However, while the general rationale behind the HBS method appears to remain valid in principle the utility of the method remains somewhat constrained in practice by the applicability and accuracy of the data required.

In past applications of the HBS method to yellowfin and bigeye tuna in the WCPO three sets of data have been used. The first consists of the estimated depth-distributions of Japanese longline hooks. However, as there has been no systematic survey of the depths attained by hooks deployed by Japanese longliners, the accuracy of these latter estimates remains unknown. Furthermore, as highlighted in the previous section, one cannot assume similar depth distributions for hooks deployed by different fleets.

The second set of data used in the HBS models consists of the temperature and depth preferences of target species obtained from the deployment of archival tags in several regions of the WCPO. However, as the regions of the WCPO included in the assessment models are large, it has been assumed that the habitat preferences for each species are uniform across these regions. Without further information from the wider deployment of archival tags the accuracy of this assumption remains unknown, but given that there are gradients in water temperatures (as well as changes in the depth of the thermocline) across the Pacific it is possible that these preferences may vary between regions, and possibility even within a single region. Indeed, differences observed in the time-at-temperature histograms for bigeye tuna tagged within the

Coral Sea and in the waters off PNG indicates the possibility of such differences between two relatively close regions (Bigelow et al 2004). While the number of tags deployed in each region of the WCPO varies, with very few being deployed in some regions, ongoing deployment of such tags should improve both the general utility of the observations and the coverage within regions.

Together with the assumption concerning the extrapolation of the archival data over wide spatial regions, is the related issue of the lack of any temporal stratification of the habitat preferences in the application of the HBS model in the WCPO. For example, the application of the method has been limited due to the fact that the time of deployment of the Japanese sets has not been included in the available catch and effort data and as such it has not been possible to stratify the HBS model by time-of-day as undertaken for the ETBF analyses. It is well know that the habitat preferences (i.e. depths and associated water temperatures) for bigeye tuna vary significantly on a day-night basis and, as the results for the ETBF indicate, accounting for differences in set times can have a significant impact on the calculated annual abundance index . (Note, it may be semantics, but it can be argued that the habitat of the bigeye tuna does not change on a diurnal basis, only that the position of the bigeye within their extended habitat changes in response to other factors, in this case due to them following the meso-pelagic forage species up and down the water column).

Finally, the third set of data used in the HBS models consists of the temperature-at-depth data generated by an Ocean General Circulation Model (OGCM). Theses data are used together with the time-at-temperature data obtained from the archival tags to estimate the depth distribution of the species of interest across the WCPO. However, while the depth and temperature data retrieved from the archival tags are deemed to be relatively accurate and have a fine-scale resolution, the distributions of temperature and dissolved-oxygen profiles taken from any OGCM are likely to be poorly resolved at the scales required to model the daily habitat ranges of the species of interest, and the reliability of using the outputs from them for this purpose is yet to be tested. As such it remains an open question as to how accurately these depth distributions are being estimated. Furthermore, given that the temperature preferences for some species such as bigeye tuna vary significantly on a diurnal basis, it remains unclear as to how suitable is the use of a single temperature profile based on the combination of day and night preferences. This also raises the question of how relevant temperature is to defining the habitat of these species (and consequently the functional assumptions underlying the habitat model). If it is purely depth and time of the day or night that is important (which would be a reasonable conclusion given the results of this study), and the association with the mixed layer depth and where the meso-pelagic forage species occur, then the use of temperature in the model may be inappropriate. Of course, temperature may be correlated with depth, but it is not a casual factor for determining the habitat.

The analyses undertaken for the ETBF attempted to overcome a number of these problems. First, there was a systematic survey undertaken of the depths fished by the hooks deployed in the ETBF so that the mean depth-profile for each HPF configuration could be estimated. Second, the archival tag data used to determine the temperature and depth-profile of bigeye tuna in the ETBF was based on data collected from tags deployed within the ETBF. This overcomes the problem of having to extrapolate this data over too great a region. Third, a seasonal and diurnal component was added to the HBS model to allow for difference in the habitat preferences over these temporal periods. Addition of the diurnal component was made possible by use of set-by-set data with known set times and is the first time that such an analysis has been undertaken with an HBS model. Finally, in order to test, and possibly circumvent, the issue of using the possibly poorly resolved OGCM data to estimate the spatial distribution of the habitat, a number of different approaches were adopted and the results compared. In the initial two approaches, it was assumed that there was a single depth or temperature profile for all bigeye in the ETBF similar to those obtained from the tag-based observations. This negates having to use an OGCM. Alternatively, the traditional deterministic and statistical approaches making use of the data from an OGCM were utilised.

The results based on the models utilizing the above improvements in data and model indicated that addition of the diurnal component to the model made a significant improvement to the result. This is not unexpected, as it is well known that the depth and temperature preferences for bigeye tuna are significantly different between the day and night and there have been shifts over time in the proportion of sets in the ETBF deployed during the day and night. Obviously where such shifts like this occur, it is important to include these in any standardisation model.

Comparison of the relative abundance indices calculated using the four different approaches used to estimate the spatial distribution of the habitat found that the index based on the deterministic HBS model (which relies to the greatest extent on the use of the OGCM data) was the most dissimilar, with the indices from the two models making no use of the OCGM data (instead using the tag-based depth and temperature distributions directly for the entire fishery) and the statistical based HBS model were quite similar. In the detHBS model the OGCM and tag data are combined deterministically to obtain the depth-distributions of the fish across the fishery. On the other hand, in the statHBS model the tag-based temperature-at-depth distribution is only used as a prior and this temperature profile is allowed to be modified in order to obtain a better fit. However, this model still relies on the use of the OGCM data in a deterministic manner. It is interesting then to note that the results of the statHBS model are most similar to the results which only rely on the deterministic use of the tag-data. One can infer from this result that the statHBS model needs to modify the tag-based temperature-preference profile of the fish in order to overcome the biases inherent in the use of poorly resolved OGCM data to obtain a similar result where the tag-based depth-preference profiles have been assumed to be correct and the OGCM data has not been used. The amount of tag-based observations on habitat preferences continues to increase and while the spatial coverage of this data can be improved, within a single fishery such as the ETBF this result indicates that it is perhaps preferable to assume that the tag data more accurately reflects the habitat preferences of the fish across the fishery than some other model with relies on the use of the possibly poorly resolved and inaccurate distributions based on the OGCM data.

Furthermore, the statHBS and detHBS models both assume the depth profiles of the fish are determined to a large degree by the temperature profiles of the water column. However, such models do not allow for significant shifts in depth-preferences of fish which are not related to temperature preferences. For example, it is well established that species such as bigeye tuna undergo large vertical shifts in depth preferences between the day and night despite the water temperature profiles remaining relatively constant. In these situations it is obvious that the fish are responding to other changes in the habitat apart from water temperature, such as diurnal shifts in the feeding layer. If this is the case, then a habitat model based on temperature profiles alone will not be able to accurately model these diurnal shifts. In this situation, the direct use of observations which provides information on changes in the depth-profiles of the fish, such as those obtained from tag-data, may be preferable to use of modelled data (such as OGCM) where the required information is missing.

To the extent that the spatial coverage of the tag-based observations currently remains limited, and if one believes that there are differences in the habitat profiles and habitat preferences across larger spatial regions on the WCPO, then if one is to continue using the HBS models there remains a need to obtain information on the spatial distribution of the habitat across these larger regions, such as is currently obtained from the OGCMs. However, unless the spatial resolution of the data from the OGCM can be improved to some extent, the uncertainties expressed above about the use of this data will remain. If this remains the situation then it would perhaps be more prudent to commence a coordinated program of deploying archival tags across the WCPO so that a systematic mapping of the habitat preferences of each primary target species can be obtained. This will be an important consideration for the managers of this fishery.

Finally, the HBS method was developed to provide an alternative means of standardising CPUE which made direct use of the information on the habitat preferences of fish that has been obtained from the deployment of archival tags over the past decade. However, whilst the HBS method provides a more direct method of matching habitat usage with the depth profiles of longline hooks, it is limited in that it does not incorporate other factors which are known to also influence the catchability of a longline hook such as bait type, use of lightsticks, etc. As such there remains a role for the use of the more traditional statistical GLM in standardising catch rates. Comparisons of the results of both GLM and HBS based approaches for the ETBF display some differences which may be overcome by the development of a third approach that is able to combine the use of the currently disparate data sources used by the HBS and GLM methods. This would be seen as an important advance and should remain the focus of ongoing research, especially given the central role played by standardised catch rates as indices of resource abundance in the harvest strategy adopted for the ETBF.

8.4 Data Collected from the Fishery

The results of this project provide an opportunity to comment on the data presently being collected from the fishery and how the collection of this data can be improved. However, as this is a large and important topic and will be more fully covered in the ongoing AFMA funded project "*Integrated analysis and assessment supporting implementation of the management and harvest strategy framework within the ETBF*", the following comments are limited to the data required to improve the calculation of abundance indices in the ETBF. In particular, it will focus on the data collected from logbooks and recorded by AFMA observers.

8.4.1 Logbook data

The catch and effort logbook data, recorded on a set-by-set basis by the skipper on each ETBF longline vessel, remains the most important source of data for input to estimating relative abundance indices in the ETBF. Together with the primary information on catch and effort (catch by species and number of fish, and number of hooks deployed) the following additional information recorded in logbooks since 1997 when the AL04 logbook was introduced into the fishery has been used in the GLM analyses undertaken to standardise catch rates:

- Primary gear configuration (i.e. number of hooks-per-float)
- Start-time of set
- Use of light-sticks (i.e. number deployed)
- Bait-type

The continued collection of this information will remain critical for standardising catch rates and should be augmented when other factors which influence the performance of the fishing gear become known. For example, the results in this study found that the use of a line-shooter is important in the depths attained by the fishing gears and as such the use or otherwise of a line-shooter on a set-by-set basis should be recorded in the logbook.

More recently, there has been a greater use of circle hooks in the fishery and it is important that the catch and effort logbooks be updated each time such a change occurs in the fishing practices used in the fishery so that the data can be incorporated into the models used to standardise catch rates. The latest update to the logbooks used in the ETBF occurred in 2007 when the AL06 series of logbook was issued and this allowed for the recording of hook type. However, this latter information is presently only recorded in the Boat and Gear Details form which is, unfortunately, only completed on an irregular basis and it is unlikely that the gear detailed recorded in this form correspond to the exact gears used on specific sets. As noted above, it is important that this information be collected on a set-by-set basis so that together with the other information already collected it can be used in the standardisation models.

With the need to incorporate aspects of the HBS method into the overall procedure of standardising catch rates, there will also be a need to collect an alternative range of information. In particular, this information will pertain to the need to estimate the depth profiles fished the hooks. This information is best collected from the continued use of TDRs (which provide a direct measure of the depths fished). An alternative will be to collect information on the configuration of the gears deployed so that an estimate of fishing depths can be obtained from the use of the catenary equation. Whilst this approach will at best only be able to approximate the depths for any individual set, the results of this project indicate that this equation can provide a reasonably accurate measure of the mean depths fished across the fishery. As such, use of the catenary equation will involve the need to collect the following information:

- Float line length
- Branchline length
- Length of mainline between floats (which can be estimated from knowledge of the total length of the mainline and the number of hooks-per-float and hooks deployed)
- The sag angle.

Information on the first three lengths is already recorded by the skipper on the Gear Form for each trip, but at this stage it remains uncertain as to how accurate this information is and how the gears deployed across the individual sets for a trip may vary in relation to the information recorded on this form. In this regard, it may be better to have this information recorded on a set-by-set basis. A comparison with the observer data may be able to provide some clarity on these issues.

The critical piece of information currently missing is that on the sag-angle (or related sag ratio) which, as this report has demonstrated, can be quite difficult to measure accurately. A range of indirect methods exist of estimating the sag angle, and require knowledge of the following line-setting details:

- Accurate recording of start and end set times and positions
- Vessel-setting speed
- Description of line deployment pattern (i.e. straight line, curved, etc)
- Distance between branchlines
- Line shooter speed
- Timer increments (i.e. time between attachment of branchlines)

Again, it would be prudent if this additional information could be recorded in the logbooks on a set-by-set basis.

Whilst there is often reluctance by some skippers to requests to record additional data, it may be hoped that with the downsizing of the ETBF fleet to a group of 40-45 dedicated vessels that this reluctance may be minimised, especially if the utility of this data could made directly apparent to the crew in providing them with knowledge of the depths being fished by their gears. However, given the issues related to the collection of additional data mentioned above, the direct collection of depth information through the use of TDRs is preferred. Indeed, as the cost of these units is likely to continue to come down and given a cooperative industry, who will have a direct interest in the data collected for their own purposes, the collection of this data on a routine basis is likely to be more cost-effective than relying on the additional gear data being collected through the logbook program

8.4.2 Observer data

This project has provided one of the first opportunities to use in a comprehensive manner the observer data collected from the ETBF for purposes other than the estimation of by-catch. In so doing it has highlighted the range of uses and analyses that this data can assist with and the generally excellent supportive role that the observer program plays in undertaking research within the ETBF. Indeed, it is hard to identify any major set of information relating to the details of longline fishing in the ETBF that is not already being collected by this program.

However, the analysis of the observer data has also raised a number of issues associated with the accuracy of the data and the manner in which the data is presently being recorded. Use of the observer data has raised the following issues:

- There is a need to define more appropriate units of measurements for some of the data collected (e.g. meters is a more appropriate unit for recording the length of the floatlines and branchlines than centimetres, which appears to be causing some confusion).
- The problems found in this project with the estimation of the Sag-ratio using the observer data highlights a need to better understand how this data is been

recorded and how accurately it reflects these parameters during the entire setting process

- The use of a single date for the recording of all time-based information for an entire set creates large problems when analysing the data and linking datasets.

Many of these issues are simple to address and as usual such issues are not identified until the data has been used in a comprehensive manner as done during this project. Furthermore, none of these issues detract from the excellent job that the observers are doing and the vitally important role the information collected by observers plays in improving our understanding of a range of issues in the fishery.

8.4.3 Further Monitoring

As this project has demonstrated, a greater understanding of the operational characteristics of the ETBF can be achieved through the collection of auxiliary information relating to the both the depths and temperatures fished by the deployed hooks and the corresponding depth and temperature profiles favoured by the target species. The ability to match these two sets of data in the HBS models is one of the attractions of using this model but to date its use has generally been hampered by the lack of data on these two sets of profiles. Whilst this study has made major advances in helping to outcome this problem for the ETBF, there are still large gaps in the information required, especially across all regions of the fishery. As such, it would be prudent to continue the collection of both sets of data as the opportunity allows. In particular, as a large number of TDRs remain operational and as there is no additional cost for observers to continue to deploy these monitors on observer trips, it is recommended that observers continue to deploy these monitors on a regular basis.

In relation to the need to continue the collection of archival data on habitat preferences, there are two priorities. The first is to expand the range of species on which such tags are being deployed and while good progress is being made in relation to this issue with a number of tags being deployed by CSIRO on both yellowfin tuna and swordfish in recent years, it would be useful to eventually expand coverage to include albacore and striped marlin. The second priority is to expand the spatial coverage of the data on habitat profiles across the entire spatial extent of the fishery. Again, a good start is being made with plans to deploy a number of tags on swordfish across the south Pacific over the next two years (Evans and Wilcox 2008). As recommended above, this could be part of a broader program of deploying archival tags across the WCPO so that a systematic mapping of the habitat preferences of each primary target species can be obtained.

Section 9: Benefits and Adoption

In December 2005, the Australian Government launched a new fisheries policy "*Securing our Fishing Future*" which aims to cease over-fishing and rebuild over-fished fish stocks (Australian Government, 2005). Coincident with this policy launch was a directive to the Australian Fisheries Management Authority (AFMA) which included the requirement for AFMA to develop and implement formal harvest strategies for all Commonwealth fisheries and default decision rules for the harvest strategies to be used in the absence of justifiable alternatives (McDonald, 2005). In response to the directive to AFMA the managers of the ETBF adopted a harvest strategy based on the use of empirical indicators (sized based catch rates and catch proportions) and the use of a multi-layered decision-tree process which is analogous to an age-structured assessment model (Campbell et al, 2007).

Given the central role played by catch rate-based indicators in the harvest strategy adopted for the ETBF, a necessary requirement to achieve both the effective assessment and successful management of the ETBF will be an improved understanding of the relationship between fishing effort, catch rates and relative abundance of the target species. Achieving this understanding is more difficult in multispecies fisheries, such as the ETBF, where catch rates of any species are dependent on the operational and gear setting practices associated with the targeting of different species. In particular, without an understanding of the operational characteristics of different targeting practices and changes in gear configuration, it is difficult to account for changes in the effective effort directed at particular species. In turn, this limits our ability to assess the status of the resource, and in particular understand the relationship between fishing levels and resource status, and determine sustainable future catch or effort levels.

By undertaking the first systematic monitoring study of the operational characteristics of the longline gears deployed in the ETBF, the results of this project provide a number of direct benefits to the management of the fishery through improvements in i) our knowledge of fishing and targeting practices in the ETBF, ii) the calculation of the fishery indicators used in the harvest strategy, iii) and the resulting management advice. In turn this will improve the ongoing management of the ETBF. In particular these benefits include:

- a greater understanding of the depths and temperatures fished by the longline gears deployed in the fishery,
- a greater understanding of the capture depths, capture times and availability-by-depth of the principal target species in the fishery,
- a greater understanding of the changes in effective effort targeted at individual species due to changes in gear settings,
- an improved understanding of the data-requirements and utility of the habitat-based method of standardising catch rates, and
- a greater understanding and improved modelling of the relationship between gear setting practices, catch rates and resource availability of the principal target species off eastern Australia.

These improvements provide the ETBF Resource Assessment Group with a greater confidence in the stock assessment outcomes and in particular the ability to construct reliable indices of stock status/availability for the principal target species in the ETBF. As these indices are the main inputs to the harvest strategy which is to be used to determine the annual TAE (or TAC) in this fishery this is an important and ongoing benefit.

The results of this study, in particular the investigation of the availability-by-depth and the time-of-feeding of the principal target species in the ETBF, have also been a significant input into another FRDC funded project "*Determining ecological effects of longline fishing in the eastern tuna and billfish fisher*y." This latter study, the results of which have been published in Young et al (2010), examined the feeding ecology and niche segregation of the ten most abundant fish species caught by longline operations off eastern Australia.

The conclusions from the present study also reaffirm the critical need to collect a range of information from the fishery on those fishing practices which influence the performance of the fishing gears and the resulting catch rates. By undertaking the first extensive survey of the depths fished by the longline gears deployed in the ETBF this study has provided a baseline against which future changes in fishing practices and changes in fishing effectiveness can be compared. This will be an important to understand changes in the fishing effectiveness and prevent biases entering the calculated indices of stock status due to effort creep.

Finally, the results of this project have also contributed to the international pool of knowledge on the fishing characteristics of longline gears, the habitat preferences of the main target species caught, the further development of the habitat-based method of standardising catch rates in a longline fishery, and an improved understanding of the general utility and applicability of this model in determining indices of resource abundance. In particular, the results of this project have been presented to two meetings of the Scientific Committee for the Western and Central Pacific Fisheries Commission: an Information paper to the third meeting held in 2007 (Campbell 2007) and a working paper to the fourth meeting held in 2008 (Campbell et al 2008). The dissemination of the results of this study in this manner has helped improve our understanding of the construction of indices of stock status which are used within the regional stock assessments undertaken by other scientists throughout the WCPO.

Section 10: Further Development

We intend to publish a summary of the work undertaken during this project together with the associated results and conclusions in a peer-reviewed journal in order to communicate the results of this project to a wider fisheries audience.

The groundwork laid by this project, in particular the wide-use of TDRs and hook-timers by AFMA observers, will also form the basis for further studies of the fishing and targeting practices within the ETBF (and the WTBF), particularly in relation to the future adoption of new fishing techniques and gears in the fishery. This will be important to update our understanding and knowledge of current fishing practices, the determination of the effective effort targeted at specific species, and the minimisation of any bias associated with the construction of fishery indicators to be used in the ETBF harvest strategy.

As this project has demonstrated, a greater understanding of the operational characteristics of the ETBF can be achieved through the collection of auxiliary information relating to the both the depths and temperatures fished by the deployed hooks and the corresponding depth and temperature profiles favoured by the target species. The ability to match these two sets of data in the HBS models is one of the attractions of using this model but to date its use has generally been hampered by the lack of data on these two sets of profiles. Whilst this study has made major advances in helping to outcome this problem for the ETBF, there are still large gaps in the information required, especially across all regions of the fishery. As such, it would be prudent to continue the collection of both sets of data as the opportunity allows. In particular, as a large number of TDRs remain operational and as there is no additional cost for observers to continue to deploy these monitors on observer trips, it is recommended that observers continue to deploy these monitors on a regular basis.

In relation to the need to continue the collection of archival data on habitat preferences, there are two priorities. The first is to expand the range of species on which such tags are being deployed and while good progress is being made in relation to this issue with a number of tags being deployed by CSIRO on both yellowfin tuna and swordfish in recent years, it would be useful to eventually expand coverage to include albacore and striped marlin. The second priority is to expand the spatial coverage of the data on habitat profiles across the entire spatial extent of the fishery. Again, a good start is being made with plans to deploy a number of tags on swordfish across the south Pacific over the next two years (Evans and Wilcox 2008). As recommended above, this could be part of a broader program of deploying archival tags across the WCPO so that a systematic mapping of the habitat preferences of each primary target species can be obtained.

Finally, the further development of the habitat-based standardisation model is required in order to combine the use of the currently disparate data sources used by the HBS and GLM methods. Indeed, further developments to either the GLM-based methods or the HBS-based methods so as to incorporate all factors relating the fishing practices and habitat-preferences of the targeted species which influence the catchability of the fishing gears should be seen as an important advance and should remain the focus of ongoing research. This is especially the situation given the central role played by standardised catch rates as indices of resource abundance in stock assessments and for the harvest strategy adopted for the ETBF.

Section 11: Planned outcomes

In achieving its stated objectives this project has also achieved a number of planned outcomes including a number of firsts. Through the use of Temperature-Depth Recorders (TDRs) and hook-timers the project has undertaken the first systematic examination of the depths and temperatures fished by longlines deployed across the ETBF and the associated times-of-capture. A total of 2050 individual TDR recordings were obtained between August 2004 and May 2007. Furthermore, by combining these depth data with the catch-by-hook position data collected by AFMA observers, this project has achieved the first systematic understanding of the range of depths at which individual species are caught within the ETBF. Finally, by combining the observed depth-profiles of the longline hooks with observations of the depth-profiles of bigeye tuna obtained from archival tags, it has been possible for the first time to apply the habitat-based method to standardising catch rates to an Australian fishery.

A major outcome of this project has been the greater understanding gained of i) the targeting practices and the behaviour of longline fishing gears used in the ETBF, and ii) the relationship between catch rates and resource availability of the principal target species off eastern Australia. In particular, by identifying fishing practices which influence variations in catch rates, and by providing an understanding of the variations in availability of fish by depths and times-of-the day, this project has improved our understanding of species-specific effective longline effort in the ETBF. In turn, this knowledge has allowed the application and further development of an alternative habitat-based method for the standardization of catch per unit effort, which in turn has allowed the further development of indices of stock abundance used to assess the impact of the ETBF on the available fish resources. Improving indices of stock status is important for application of the Harvest Strategy within the ETBF. Furthermore, the outcomes of this project will assist the further development of the habitat-based standardisation model used in the stock assessments for the main tuna species within the WCPO.

An additional outcome of this project will be an improved understanding of the relation between depths attained by longline gears and the distribution of threatened and endangered species. For example, determining the overlap between hook depths and the vertical distributions of turtle species can inform action plans to minimise or eliminate potential interactions between the two.

There will also be a direct benefit to the domestic longline fishery by providing feedback to fishers on the effectiveness of their present gear setting practices and information on the most effective gear settings. However, as this information may lead to an increase in the effectiveness of fishing in the ETBF (i.e. significant effort creep) this will have important implications for the management of the fishery, particularly if the fishery were to be continued to be managed by a TAE. Allowing effort creep under a constant TAE regime is equivalent to allowing an increase in the TAC. However, if the fishery is managed under a TAC, which is due to be introduced into the ETBF in 2011, then this knowledge will allow fishers to improve the effectiveness of their gears and in so doing making the overall fishery more economically efficient.

This project will also have a flow on benefit to the Southern and Western Tuna and Billfish Fishery (SWTBF). As this fishery uses similar fishing gear and captures a similar suite of species as the ETBF, the monitoring protocols and analytical methods developed for the ETBF have the potential to be incorporated into the monitoring of resource status in the SWTBF and ongoing stock assessments in the broader Indian Ocean. This project has also examined the utility and adequacy of the AFMA logbook and observer data for these fisheries and provided guidance on where the collection of this data can be augmented and its accuracy improved.

Through the provision of improved indices of stock availability in the south-west Pacific, the results of this project will also help improve the precision of the regional stock assessments undertaken by SPC.

Finally, the results of this project will contribute to the international pool of knowledge required to improve our understanding of the fishing characteristics of longline gears, the habitat preferences of the main target species caught and the need to test, refine and further develop the methods used to standardise catch and effort data in pelagic fisheries.

Section 12: Conclusions

The harvest strategy adopted for the Eastern Tuna and Billfish Fishery (ETBF) relies on the calculation of a number of resource indicators determined from the catch and effort data collected from the fishery. In particular, standardised catch rates are used as an indicator of resource status or availability. However, the ETBF is a multi-species fishery having at least five principal target species – yellowfin, bigeye and albacore tunas, broadbill swordfish and striped marlin. As such, changes in operational practices associated with targeting different species makes it difficult to determine a metric of effective effort directed at any particular species. This in turn makes it difficult to interpret changes in catch rates as changes in resource availability. In order to help overcome this problem, the primary objective of this project was to increase our knowledge of the operational characteristics and fishing effectiveness of longline gears deployed in the ETBF so that the relationship between fishing practices and resultant catch rates of the principal target species in this fishery could be better determined. The second main objective was to apply and test the utility of the habitat based method of standardising catch rates in this fishery.

The longline hooks deployed in the ETBF were observed to attain a range of depths down to around 400m. The time-at-depth profiles for sets deploying less than 10 hooks-per-float (HPF) were found to be very similar, though the depth-profiles associated with those sets deploying more than 15 HPF were considerably deeper. As most sets targeting yellowfin, bigeye or swordfish generally deploy less than 10 HPF, the depths fished by hooks targeting these species were found to be similar. On the other hand, for gear configurations deploying more than 10 HPF a near linear relationship was found in the mean depth fished across all hooks and the number of HPF. This result supports the assumptions often used in the CPUE standardisation models for longline fishing that the number of HPF is a proxy for mean fishing depth, but the former result shows that this assumption may not true for across all HPF configurations.

The most common depths fished by hooks deployed in the ETBF were found to be relatively shallow, with monitored hooks spending around 34 percent of the soak time between 40-60 meters and around 75 percent of the time at depths less than 80 meters. Hooks fished depths greater than 140 meters for only 10 percent of the time. However, the greater use of sets deploying 20 or more HPF during 2007 increased the percentage of time hooks fished below 140 meters to 20 percent and below 200 meters to 10 percent. Furthermore, the depth profiles of hooks deployed in the ETBF were found to be different to those estimated for hooks deployed from Japanese longline vessels fishing across the Western and Central Pacific Ocean.

While the depths to which hooks were observed to sink were found to be highly variable for a given HPF configuration and hook number, the mean depths attained were found to be reasonably well predicted by the longline catenary equation of Yoshihara (1951). Current-speed, HPF configuration and the use of a line shooter were found to be the main factors influencing variation from the predicted depth.

Significant differences in the catch rates of the five principal target species between gears with different HPF configurations were observed, though for each HPF configuration the relative catch rates-by-depth profiles were usually similar for these species. This indicates that the relative availability of these species with depth was similar over the range of depths fished by each gear configuration. Only for sets with 30 HPF was it observed that the catch of bigeye tuna generally occurred on deeper hooks than for the other species. Nevertheless, after combining the results across all gear configurations it was possible to discern major differences in the availability-by-depth for the five principal target species. Availability of yellowfin, swordfish and striped marlin was generally greatest in the top 40 meters, whilst availability for albacore was estimated to be relatively low in the upper parts of the water column and to be highest below 150 meters. Bigeye tuna availability was found to be more evenly distributed with depth, though with a tendency for higher availability at deeper depths. These results should be of particular interest to fishers as this knowledge will assist them better understand the factors that control the depths fished by hooks and how effective each gear configuration is at targeting a given species. Individual improvements in fishing effectiveness will, in turn, assist improving the economic efficiency of the entire fishery.

The information gained from this study on the depth distributions of the fishing gears, together with the improved understanding of the depth preferences of bigeye tuna gained through the deployment of archival tags in the ETBF in recent years, provided the opportunity to apply the habitat-based (HBS) method to standardising the catch rates of bigeye tuna in the ETBF. This method has the advantage of making direct use of the information on the depths of hooks and fish, and provides an alternative to the statistical approaches of the GLM and GAM methods. The large amount of data available for the ETBF helped to overcome a number of problems which have limited the use of this approach in other fisheries. Both the deterministic and statistical HBS models were applied and two approaches were also used to infer the spatial distribution of the habitat across the fishery. The first made use of the Ocean Global Circulation Model (OGCM) data, as used in previous application of the HBS model, whilst the second applied the depth and temperature distributions inferred from the tag-data to the entire fishery. Furthermore, the availability of information on set-time allowed the addition for the first time of a diurnal habitat component to the HBS model.

Comparison of the resulting indices of bigeye availability calculated for each model indicated that the deterministic HBS model (which relies to the greatest extent on the OGCM data) was the most dissimilar, while the results from the statistical HBS model and the two models using the tag-based depth and temperature distributions were quite similar. It is likely that deterministic HBS model is limited by the poor resolution of the OGCM data within the ETBF region while the statistical HBS model has the freedom to modify the tag-based temperature-preference profile of the fish to overcome such limitations. For smaller regional fisheries such as the ETBF this results implies that one might best avoid using the OCGM data and just assume a single habitat profile across the entire fishery based on information obtained directly from archival tags. Where such tag data is spatially extensive, it may also be possible to estimate separate profiles for each sub-region of the fishery. This approach would also be preferable for large regional fisheries such as that within the WCPO but will require a systemic program of archival tagging in order to collect the required data. This will be an important consideration for the managers of these fisheries.

The results also indicated that addition of the diurnal component to the model makes a significant improvement to the result. This is not unexpected, as it is well known that the depth and temperature preferences for bigeye tuna are significantly different between the day and night and there have been shifts over time in the proportion of sets in the ETBF deployed during the day and night.

Whilst the HBS method is able to make direct use of information to match the depths and temperatures fished by hooks with the habitat of the species of interest, it is currently limited in that it does not incorporate other factors which are known to also influence the catchability of a longline hook such as bait type, use of lightsticks, etc. As such there remains a role for the use of the more traditional statistical GLM in standardising catch rates. However, the development of a third approach, which is able to combine the use of the currently disparate data sources used by the HBS and GLM methods, would be seen as an important advance and should remain the focus of ongoing research. This is especially the situation given the central role played by standardised catch rates as indices of resource abundance in stock assessments and for the harvest strategy adopted for the ETBF.

Finally, the results of this study reaffirm the critical need to collect a range of information from the fishery on those fishing practices which influence the performance of the fishing gears and the resulting catch rates. By undertaking the first extensive survey of the depths fished by the longline gears deployed in the ETBF this study has provided a baseline against which future changes in fishing practices and changes in fishing effectiveness can be compared. This will be an important to understand changes in the fishing effectiveness and prevent biases entering the calculated indices of stock status due to effort creep.

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Appendix 1: Intellectual Property

No intellectual property is claimed.

Appendix 2: Project Staff

Robert Campbell[1]	10-20%
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Appendix 3: Instructions for the Deployment of Hook Timer and Temperature-Depth Recorders

CSIRO Marine and Atmospheric Research
Hobart

1. Introduction

The main objective of this project is to understand the relationship between the deployment of longline gears and the resulting catch. In order to better understand this relationship information is required on the following components of the fishing process:

1) the depths fished by the longline gears,
2) the relationship between variation in depths obtained by the gears and variation in deployment strategies (e.g. setting speeds, line configuration),
3) the place along the longline gear that fish are caught,
4) the times during the total soak that fish are caught,
5) the habitat preferences (e.g. time-at-depth and temperature profiles) of the main target species.

Apart from component 5, information on which is gained from archival tagging data, information on all other four components is dependent on the data collected and recorded by observers. Information on setting practices (component 2) and the resulting catch and position along the line (component 3) are recorded on the standard observer forms. On the other hand, temperature-depth recorders are required to gather information on the depths obtained by the hooks (component 1), while hook-timers are required to gather information on the times at which fish are caught (component 4).

These notes provide instructions on how the temperature-depth recorders and hook-timers are to be deployed during a longline set and what information related to their deployment and retrieval needs to be recorded. Please note that these instructions are somewhat flexible as we hope to find a manner of deploying the gear monitors which works well for both the observer and the crew.

2. Hook-Timers

There should be about 100 Hook-Timers (HTs) per observer per vessel. The purpose of these units is to determine the time that a fish was caught on a hook. When a fish is caught the action of struggling to free itself will activate the timer (via release of the magnet attached to the pull out stopper) which will then start recording the elapsed time. When the timer is retrieved during the line haul, the time recorded by the timer will indicate the elapsed time since the fish was originally caught on the hook.

Deployment

The branchline should be attached to the bottom of a rigged HT then the combined HT-branchline clipped onto the mainline as usual (Figure 1). During previous surveys where HTs have been used, it was been found easiest to attach the HTs as the line was being deployed for the first time. Once the HTs have been attached to a branchline, they can then just stay attached for the rest of the cruise. (Note, if this causes problems with storage of the branchlines in the bins, then detach the hook timers and store them separately.)

Figure 1. Deployment of rigged hook-timer and branchline.

We do not expect a preference along the line as to where fish will be hooked. As such, the HTs can be deployed in a relatively random manner or uniformly (ie every 10-th hook if setting 1000 hooks) along the entire longline. Alternatively, as there is a possibility that the beacons may act as FADs, then you may like to deploy a relatively higher percentage around the beacons (ie on 2 or 3 float sections ether side of the beacons).

If it is easiest not to have the hook-timers attached to the branchlines between sets, then it may also be possible to deploy them on a more opportunistic basis. For example, if there is a belief that strike rates may increase due to some event during the deployment of the line (eg. vessel steams through a school of baitfish), then you may like to deploy the HTs at a higher rate during this time.

We would like to leave some degree of flexibility with you as to how the HTs can be deployed as we would like to find a technique that works well for both yourself and the crew on the boat. However, try and ensure that the HTs do not end up too bunched along the line or on the same hook position between floats, as it is important that all hook depths are sampled (relatively equally) by the HTs.

Finally, no information pertaining to the time of deployment or position of each HT needs to be recorded during deployment as data will only need to be recorded for those timers which have been activated and this can be done upon line retrieval.

Retrieval

Only the data (the elapsed time shown on the clock) associated with those HTs which have been triggered upon retrieval needs to be recorded. Observer data collected to date indicates that, on average, 38.5 fish are caught per 1000 hooks. Hence, the number of HTs which can be expected to be triggered per set is, on average, around 3 or 4.

There are two events with can arise:

1) Hook-timer triggered and a fish landed on the associated hook
2) Hook-timer triggered and no fish landed on the associated hook.

The second event is of interest because it is believed that fish have the ability to sometimes get off a hook and this data helps to model this occurrence.

Upon retrieval the snoods with HTs, if not activated, should just be put back in the snood bins as usual by the crew.

If a HT has been activated (whether there is a fish on the hook or not), then record the time displayed on the hook timer in the Sample Number column on the Biological Data form, and write the unique code HT (Hook Timer) in the Sample Code column of the same sheet. The time retrieved, hook position, species ID and other biological information should be recorded as normal. If a hook timer is activated and the fish has escaped, again record the time-retrieved and the hook position and write UNK (unknown) in the species column and E (escaped) in the fate column. The HT can then be reset and hung up with the other snoods in the snood bin (this is best left for the crew to do).

The comments column should be used to differentiate between a hook timer which is believed to have been activated by tangles with the fishing gear and a fish that has escaped. Also, please indicate if the hook is missing.

Collation of the Data

Although all the data has been recorded on the Biological Data form, as there can be a period of delay before the observer data is entered into the AFMA database and sent to CSIRO it would be useful if the HT data could be collated after each set and sent back to CSIRO after each trip. For this purpose an additional observer form has been created – see copy of HOOK TIMER SUMMARY Form provided in the Appendix. The data can be transcribed directly from the Biological Data form and either written on a printed form or entered directly into the associated Excel spreadsheet sent to you along with these instructions. When the latter option is used, the Bite-Time is automatically calculated.

Note: there is no need to use a new sheet for each set: the data for consecutive sets can follow on from the previous set on the same sheet.

3. Deployment of Temperature-Depth Recorders

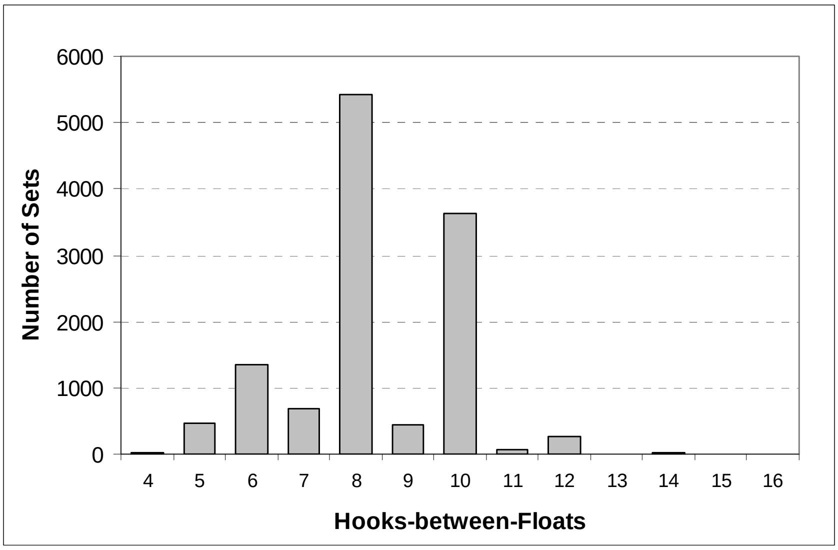
There should be about 12 or 13 Temperature-Depth Recorders (TDRs) per observer per vessel. The purpose of these units is to determine the time versus depths-fished and temperature profiles for selected hooks along the longline. Furthermore, by placement of TDRs at various hook positions (both along the longline and between floats) the variation profiles due to different hook positions can be observed. This information will also help determine the associated shape of the line between the floats. Consequently, TDRs will need to be deployed on some of the shallowest hooks, some of the deepest hooks, and some of the intermediate-depth hooks.

Deployment

Given the small number of TDRs available for deployment, and the need to ensure an adequate coverage of the various hook positions along the line, the TDRs will need to be deployed in a structured manner.

In order to help guide determination of the best approach, it is useful to consider the line configurations adopted across the ETBF. A histogram of the number of sets which deployed various line configurations (e.g. number of hooks between floats) in 2003 is shown in Figure 2. The most common configurations are 8 and 10 hooks between floats, which together account for 73% of all sets. Note: in the following we use the Japanese term "basket" to describe the single set of hooks which are deployed between two floats or within a float section.

Figure 2. Histogram of the number of longline sets deployed in the ETBF during 2003 which deployed various line configurations (e.g. number of hooks between floats).

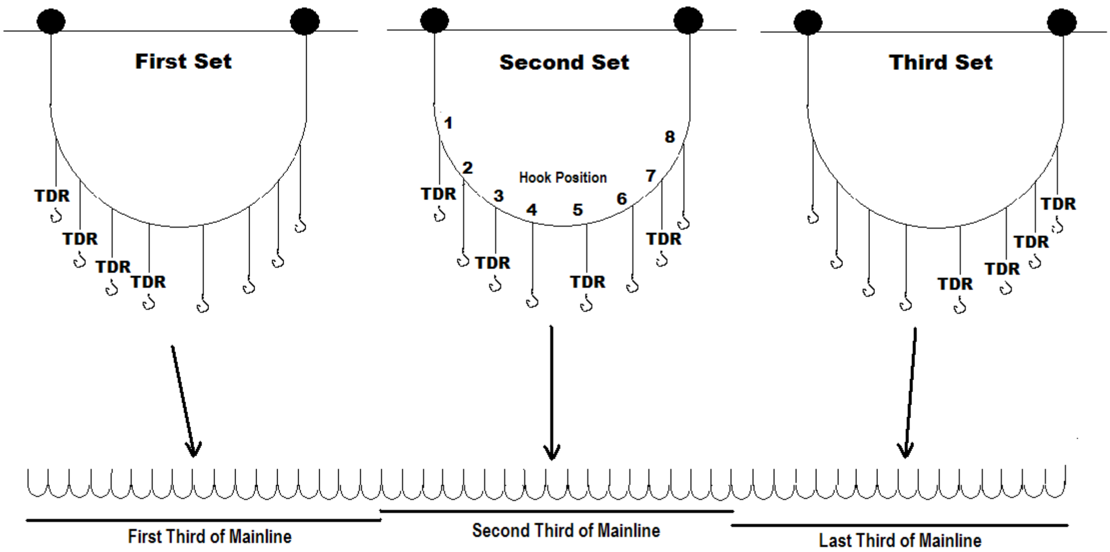


If we consider the most common configuration first, that of deploying 8 hooks between floats, then the following structured approach for deployment of the 12 TDRs along the mainline is recommended (See Figure 3):

Divide the 12 TDRs into three groups of four. Each group of TDRs is then deployed in the following manner:

1) The first group of 4 TDRs should be deployed within a single basket above the first four hooks (i.e Hook positions 1, 2, 3 and 4). The basket should be somewhere near the middle section of the first third of the mainline.
2) The second group of 4 TDRs should be deployed within a single basket on alternative hook positions starting with the first hook (i.e Hook positions 1, 3, 5 and 7). The basket should be somewhere near the middle section of the second third of the mainline (i.e. near the middle of the entire mainline).
3) The third group of 4 TDRs should be deployed within a single basket above the last four hooks (i.e Hook positions 5, 6, 7 and 8). The basket should be somewhere near the middle section of the last third of the mainline.

Figure 3. Schematic of the recommended deployment of TDRs when there are eight hooks between floats.



The structured manner described above for deploying the TDRs provides an even coverage of hook-depths. In particular, data is obtained for three of the shallowest hooks (positions 1 and 8), three of the deepest hooks (positions 4 and 5) and three each of the two intermediate-depth hooks (positions 2 and 7 and positions 3 and 6). Furthermore, by selecting baskets relatively evenly along the mainline, the groups of TDRs are not all in the same section of line so that indicative sections of the entire line are sampled.

Another reason for grouping the TDRs together in this manner instead of spreading them out relatively randomly over the entire line is that they can be retrieved in batches, i.e, when the first of a group is retrieved then you will know that the rest of the group will also be retrieved over the remainder of that basket and the next.

While the above structured approach provides the desired coverage of all hook positions and depths, however, it may be impractical to deploy TDRs on consecutive branchlines. For a number of reasons (i.e. the observer stands on only one side during line deployment, best to use only one person to attach the monitors, etc) it is likely to be more practical to deploy TDRs on only odd or even hooks within a single basket. In order to achieve this, the pattern of deploying the TDR within each basket indicated in Figure 3 should be spread over two consecutive baskets. Hence, the first group of TDRs should be placed on hooks 1 and 3 in the first basket and then hooks 2 and 4 in the second basket. Similarly, the third group of TDRs can be placed on hooks 5 and 7 in one basket and hooks 6 and 8 in the next. It may also suit to deploy the second group of TDRs (which are already on every odd hook) over two baskets (c.f. Table 1).

When the number of hooks-between-floats being deployed is different from eight, then the recommended structured approach for attaching the TDRs is summarised in Table 1. It can be noted that when the number of hooks-between-floats is less than or equal to eight, then all hook-depths within a group are monitored in the first and third group of TDRs. However, when nine of more hooks-between-floats are deployed, then not all hook-depths within a group are monitored, though a relatively even coverage of all hooks can be obtained given the structured manner in which all TDRs are deployed across the three groups.

Finally, when deploying all temperature-depth recorders, the TDR number, time-deployed and hook-position should be entered on the TDR Deployment Details Form (cf. Form 2 in the Appendix).

Table 1. Recommended "structured" manner for deploying temperature-depth records (TDRs) within baskets and along the mainline.

6 Hooks-between-Floats

TDR Group	Basket	Hook Position						
		1	2	3	4	5	6	
1st	1	TDR		TDR				Middle of first third of mainline
	2		TDR			TDR		
2nd	1	TDR		TDR				Middle of second third of mainline
	2				TDR		TDR	
3rd	1				TDR		TDR	Middle of last third of mainline
	2		TDR			TDR		

7 Hooks-between-Floats

TDR Group	Basket	Hook Position						
		1	2	3	4	5	6	7
1st	1	TDR		TDR				
	2		TDR		TDR			
2nd	1	TDR		TDR				
	2				TDR		TDR	
3rd	1				TDR		TDR	
	2					TDR		TDR

8 Hooks-between-Floats

TDR Group	Basket	Hook Position							
		1	2	3	4	5	6	7	8
1st	1	TDR		TDR					
	2		TDR		TDR				
2nd	1	TDR		TDR					
	2					TDR		TDR	
3rd	1					TDR		TDR	
	2						TDR		TDR

9 Hooks-between-Floats

TDR Group	Basket	Hook Position								
		1	2	3	4	5	6	7	8	9
1st	1	TDR			TDR					
	2		TDR			TDR				
2nd	1	TDR		TDR						
	2					TDR		TDR		
3rd	1						TDR			TDR
	2					TDR			TDR	

10 Hooks-between-Floats

TDR Group	Basket	Hook Position									
		1	2	3	4	5	6	7	8	9	10
1st	1	TDR			TDR						
	2		TDR			TDR					
2nd	1	TDR		TDR							
	2					TDR			TDR		
3rd	1						TDR			TDR	
	2							TDR			TDR

11 Hooks-between-Floats

TDR Group	Basket	Hook Position										
		1	2	3	4	5	6	7	8	9	10	11
1st	1	TDR				TDR						
	2			TDR			TDR					
2nd	1		TDR		TDR							
	2							TDR		TDR		
3rd	1						TDR				TDR	
	2								TDR			TDR

12 Hooks-between-Floats

TDR Group	Basket	Hook Position											
		1	2	3	4	5	6	7	8	9	10	11	12
1st	1	TDR				TDR							
	2			TDR			TDR						
2nd	1		TDR		TDR								
	2								TDR		TDR		
3rd	1							TDR				TDR	
	2									TDR			TDR

With more than 12 Hooks-per-Basket, place TDRs to ensure a relatively even coverage of all hook depths.

Retrieval

Upon retrieval of a TDR, the unit should be detached from the branchline and placed in a safe position for later collection for down loading the data. The time of retrieval, TDR number and hook position should be recorded on the Biological Data form. The TDR number should be recorded in the Sample Number column with "TD" recorded in the Sample Code column. When a fish is caught on the associated hook, the catch details should be recorded in the usual manner. When no fish is caught, write XXX in the species code column.

Collating and Down-loading Data

At the end of each set, the data recoded by each TDR needs to be downloaded to the laptop computer. For each observer cruise a new folder should be created with the name comprising the Vessel Name and Observer Trip ID. Within the trip folder, a new folder should be created for each longline set observed. The name of the folder should be Set_X where X refers to the shot number for that trip. The data from all TDRs for a single set should then be downloaded with the associated data files placed into the corresponding Set_X folder. Each file should be clearly marked to identify the TDR number.

The details on the TRD Deployment form should also be completed (i.e. the time-out should be added for each TDR).

Figure 5. Photo of rigged TDR in protective sheaf.

4. Other Issues

Please ensure that you have enough HT and TDR Data Forms before leaving on each trip. If more are required, can be please print the required number from the worksheets in the associated Excel file.

If entering the HT and TDR data into the Excel spreadsheets, it is probably best at the start of each trip to make a copy of the original file and name the copy with the Trip ID details. All data can then be entered into the trip file, leaving the original version of the file containing the forms to be used and copied for the next trip. Also, within the trip file make a few extra copies of each worksheet before the first set so that enough pages of each data form are available for the entire trip.

It may also be practical to externally number each TDR and its associated sheath with numbers (say 1-12) with a waterproof marker or paint. This number and manufacturer's TDR ID number can then be recorded together on the TDR Deployment Form.

5. Sending Data to CSIRO Marine Research

At the end of each trip, the trip folder containing all the TDR files for all sets should be burnt onto a CD and mailed, together with the completed TDR Deployment forms for each set and the completed Hook-Timer Summary forms for the trip, to the following address:

Robert Campbell
CSIRO Marine Research
PO Box 1538
Hobart TAS 7001

We will endeavour to supply CDs and padded post bags for this purpose. Please include any written trip reports with the above data.

Alternatively, the data and completed Excel worksheets containing the HT and TDR information can be zipped into a single file and emailed to the following address:

Robert.Campbell@csiro.au

Finally, as stated in the Introduction, these instructions are somewhat flexible as we hope to find a manner of deploying the gear monitors which works well for both the observer and the crew. As you are in the best position to assess the practicality of these instructions, please pass on any comments you may have to improve them.

Many thanks.

Form 1. Example of completed Hook-Timer Summary Form

AFMA Australian Fisheries Management Authority

OBSERVER PROGRAMME

CSIRO HOOK TIMER (HT) SUMMARY

OBSERVER NAME	HANDY OBSERVER	OBSERVER TRIP ID	100
VESSEL NAME	GOOD SAILING	OBSERVER PROJECT	ETBF Gear Monitoring

SHOT NUMBER	DATE (DD/MM/YY)	HOOK POSITION	HOOKS BETWEEN FLOATS	TIME - OUT (HH:MM)	ELAPSED TIME (HH:MM)	BITE - TIME (HH:MM)	SPECIES	LIFE-STATUS
1	12/10/2004	3	8	10:30	17:17	17:13	SWO	3
1	12/10/2004	5	8	11:15	15:34	19:41	YFT	1
2	13/10/2004	2	7	7:23	5:45	1:38	UNK	
2	13/10/2004	1	7	7:50	12:56	18:54	DOL	5
2	13/10/2004	5	7	8:34	13:04	19:30	UNK	
3	14/10/2004	6	8	10:12	15:45	18:27	SWO	1
3	14/10/2004	2	8	11:23	4:04	7:19	SWO	2
4	15/10/2004	5	9	9:06	3:45	5:21	YFT	3
4	15/10/2004	1	9	9:15	17:23	15:52	UNK	
4	15/10/2004	7	9	9:56	17:45	16:11	UNK	
4	15/10/2004	5	9	10:56	18:36	16:20	BET	2
5	16/10/2004	6	8	10:45	18:21	16:24	BSH	1
5	16/10/2004	4	8	11:34	5:28	6:06	RUD	5
5	16/10/2004	1	8	11:42	5:45	5:57	UNK	
6	17/10/2004	7	8	10:02	10:45	23:17	SWO	4
6	17/10/2004	5	8	10:43	17:56	16:47	UNK	
6	17/10/2004	6	8	11:12	18:34	16:38	YFT	2
6	17/10/2004	2	8	11:14	15:07	20:07	MLS	2
6	17/10/2004	8	8	11:27	5:45	5:42	YFT	1

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Form 2. Example of completed Temperature-Depth Recorder (TDR) Deployment form.

OBSERVER PROGRAMME

CSIRO TEMPERATURE-DEPTH RECORDER (TDR) DEPLOYMENT DETAILS

OBSERVER NAME	HANDY OBSERVER	OBSERVER TRIP NUMBER	100
VESSEL NAME	GOOD SAILING	OBSERVER PROJECT	ETBF GEAR MONITORING
DATE	1/01/2005	SHOT NUMBER	1
LENGTH OF FLOAT LINE (M)	25	LENGTH OF SNOOD (M) - IF VARYS RECORD BELOW	15 & 20

TDR	TDR NUMBER (Fill in first shot only if remain same)	TIME - IN (HH:MM) (24 Hour)	TIME - OUT (HH:MM) (24 Hour)	BEACON SECTION	LENGTH OF SNOOD (M) (Very Important)	HOOK NUMBER AFTER FLOAT (Very Important)	NUMBER HOOKS BETWEEN FLOATS (Very Important)
1	1001	17:00	8:00	2	20	1	7
2	1002	17:03	8:05	2	20	2	7
3	1003	17:30	9:00	3	20	3	7
4	1004	17:33	9:05	3	15	4	7
5	1005	18:00	10:00	4	15	5	7
6	1006	18:03	10:05	4	15	6	7
7	1007	18:30	11:00	5	20	7	7
8	1008	18:33	11:05	5	20	7	7
9	1009	19:00	12:00	6	20	5	7
10	1010	19:03	12:05	6	15	4	7
11	1011	19:30	13:00	7	15	3	7
12	1012	19:33	13:05	7	15	1	7
13							
14							
15							

COMMENTS

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Appendix 4: Structure of Database Tables for Storing TDR and HT Data

1. Table TDR Trips

Stores data relating to observer trips deploying gear monitors

Name	Type	Information Stored
TRIP_NUM	NUMBER(3)	Project Trip Number
TRIP_OBS	NUMBER(4)	AFMA Observer Trip Number
VSL_NAME	VARCHAR2(20)	Name of vessel
OBS_NAME	VARCHAR2(20)	Name of observer
SETS_TOT	NUMBER(2)	Total number of sets deployed
SETS_TDR	NUMBER(2)	Number of sets with TDRs
LOAD_TDR	NUMBER(3)	Number of TDR-sets
SETS_HT	NUMBER(2)	Number of sets with HTs
TRIG_HT	NUMBER(3)	Number of HTs triggered

Number of records = 52

2. Table: TDR Sets

Stores data relating to deployed TDRs

Name	Type	Information Stored
TRIP_NUM	NUMBER(3)	Project Trip Number
SHOT_NUM	NUMBER(2)	Shot Number
TDR_NUM	NUMBER(4)	TDR Number
DEPLOY_DATE	DATE	Date deployed
DEPLOY_TIME	DATE	Time deployed
RETREIVE_TIME	DATE	Date retrieved
DURATION	NUMBER(4)	Time retrieved
BEACON_SECTION	NUMBER(2)	Beacon section along mainline
FLOAT_SECTION	NUMBER(3)	Float section after beacon
FLOAT_LENGTH	NUMBER(4,1)	Length of float line
SNOOD_LENGTH	NUMBER(4,1)	Length of branch (snood) line
HOOK_NUM	NUMBER(2)	Hook number since buoy
HOOKS_PER_FLOAT	NUMBER(2)	Number of hooks between buoys
TSR_INDEX	NUMBER(8)	Unique Trip-Shot-TDR index
STATUS	VARCHAR2(2)	Indicates status of retrieved data

Number of records = 2104

3. Table: TDR Data

Stores time-series of depth and temperature data recorded by deployed TDRs.

Name	Type	Information Stored
TRIP_NUM	NUMBER(3)	Project Trip Number
SHOT_NUM	NUMBER(2)	Shot Number
TDR_NUM	NUMBER(4)	TDR Number
TDR_DATE	DATE	Date information recorded
TDR_TIME	DATE	Time information recorded
ACTIVITY	VARCHAR2(1)	S=sinking, F=fishing, H=hauled
SEQUENCE_NUM	NUMBER(4)	Sequence number (1, 2, 3,…)
DEPTH	NUMBER(7,2)	Depth recorded
DELTA_DEPTH	NUMBER(7,2)	Change in depth since last record
TEMPERATURE	NUMBER(7,2)	Temperature recorded
DELTA_TEMP	NUMBER(7,2)	Change in temperature since last record
TSR_INDEX	NUMBER(8)	Unique Trip-Shot-TDR index

Number of records = 790,644

4. Table: TDR Summary

Stores summary information relating to time-series of depth and temperature data recorded by deployed TDRs.

Name	Type	Information Stored
TRIP_NUM	NUMBER(3)	Project Trip Number
SHOT_NUM	NUMBER(2)	Shot Number
TDR_NUM	NUMBER(4)	TDR Number
DEPLOY_DATE	DATE	Date TDR deployed
DEPLOY_TIME	DATE	Time TDR deployed
RETRIEVE_DATE	DATE	Date TDR retrieved
RETRIEVE_TIME	DATE	Time TDR retrieved
TIME_INC	NUMBER(2)	Time increment between records
INIT_DEPTH	NUMBER(5,2)	Default "on-boat" depth
HAUL_DEPTH	NUMBER(5,2)	Depth monitor hauled from
DEPLOY_SEQNO	NUMBER(4)	TDR Sequence No. at deployment
FISH_SEQNO	NUMBER(4)	TDR Sequence No. at end of sink
HAUL_SEQNO	NUMBER(4)	TDR Sequence No. at start of haul
RETREIVE_SEQNO	NUMBER(4)	TDR Sequence No. at end of haul
SET_STATUS	VARCHAR2(2)	Indicator of status of data
NFISH_INC	NUMBER(4)	Number of records whilst "fishing"
AVG_DEPTH	NUMBER(6,2)	Average depth fished
AVG_TEMP	NUMBER(6,2)	Average temperature fished
TSR_INDEX	NUMBER(8)	Unique Trip-Shot-TDR index

Number of records = 2,050

5. Table: Hook-Timer Data

Stores information relating to deployment of triggered Hook-Timers.

Name	Type	Information Stored
TRIP_NUM	NUMBER(3)	Project Trip Number
SHOT_NUM	NUMBER(2)	Shot Number
DEPLOY_DATE	DATE	Date HT deployed
HOOK_NUM	NUMBER(2)	Hook-number HT attached to
HOOKS_PER_FLOAT	NUMBER(2)	Number of hooks between floats
TIME_OUT	DATE	Time HT deployed
TIME_ELAPSED	DATE	Time elapsed on trigged HT
TIME_BITE	DATE	Estimated time HT triggered
SPECIES	VARCHAR2(3)	Species caught on hook
LIFE_STATUS	NUMBER(1)	Life-status of associated fish
VOYAGE	NUMBER(4)	AFMA Observer Trip Number
SHOT_ID	NUMBER(6)	Unique Trip-Shot index

Number of records = 683

Appendix 5: Derivation of the Longline Catenary Equation

A catenary is the name of the curve attained by a heavy uniform chain or cable suspended vertically between two points. Consider the representation of a cable (e.g. longline) of total length 2L suspended between points A and B shown in Figure 1. The resulting catenary curve is given by the following equation:

$$y = m.\cosh(x/m) \qquad (1)$$

where x=0 corresponds to the vertex and *m* is a parameter that determines how quickly the catenary "opens up."

Given the above representation, points A and B have the following coordinates:

$$A: [x, y] = [H, y(H)] = [H, m.\cosh(H/m)]$$

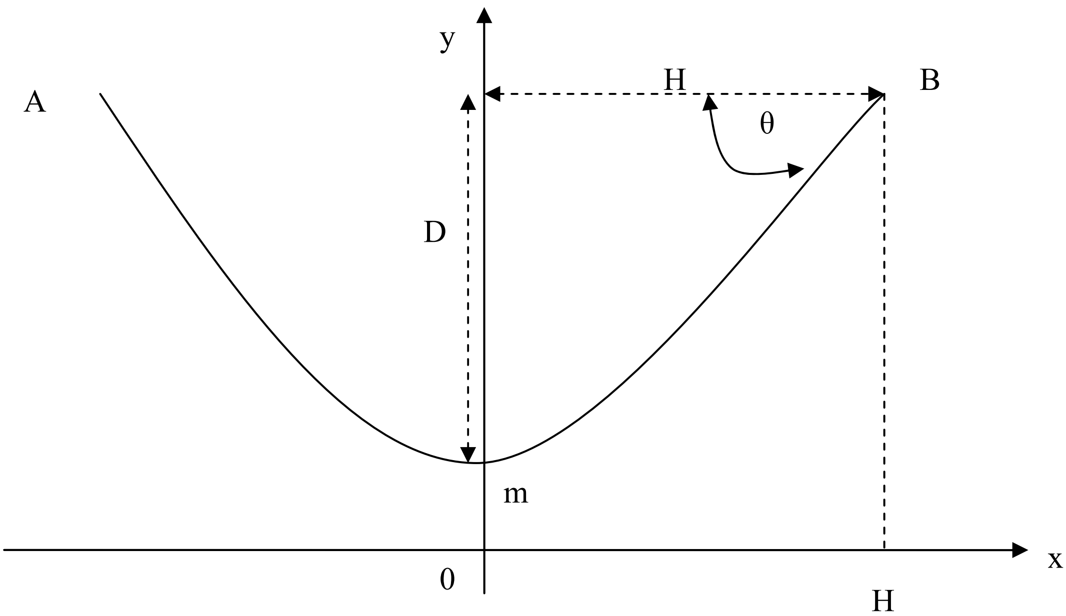
$$B: [x, y] = [-H, y(-H)] = [-H, m.\cosh(-H/m)] = [-H, m.\cosh(H/m)]$$

The maximum depth of the catenary is also given by:

$$D = y(H) - m = m.\cosh(H/m) - m = m.[\cosh(H/m)-1] \qquad (2)$$

Given the above definitions, we seek whether it is possible to find a representation of the horizontal distance (2H) between the two suspension points A and B in terms of the length of the chain (2L) and the maximum depth, D.

Figure 1. Representation of the catenary geometry of a chain (longline) suspended between points A and B.



The length of a plane curve between points x=a and x=b is given by the following integral:

$$L = \int_a^b ds = \int_a^b \sqrt{(dx)^2 + (dy)^2} = \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx$$

For the above catenary curve, let u = x/m so that:

dy/dx = (dy/du).(du/dx) = m.sinh(u).(1/m) = sinh(u) =sinh(x/m)

It follows then that the length of the catenary curve between the points x=-0 and x=H is given by:

$$L = \int_0^H \sqrt{1+\left(\frac{dy}{dx}\right)^2}\,dx = \int_0^H \sqrt{1+\left(\sinh\frac{x}{m}\right)^2}\,dx$$

Using the relation $\cosh^2(u) = 1 + \sinh^2(u)$ this can be written as:

$$L = \int_0^H \sqrt{\cosh^2\left(\frac{x}{m}\right)}dx = \int_0^H \cosh\left(\frac{x}{m}\right)dx$$

Again, letting u=x/m we have dx=m.du so:

$$L = \int_0^{H/m} m.\cosh(u)du = m.[\sinh(H/m) - \sinh(0)] = m.\sinh(H/m)$$

From this it follows that the distance H, representing half the horizontal distance between the suspension points A and B can be represented in terms of half the total length of the chain, L, and the distance m as follows:

$$H = m.\sinh^{-1}\left(\frac{L}{m}\right) \qquad (1)$$

As seen above, the maximum depth of the catenary is given by D = m.[cosh(H/m)-1]. Solving for H gives:

$$H = m.\cosh^{-1}\left(\frac{D+m}{m}\right) \qquad (2)$$

From equations (1) and (2) we have:

$$\sinh\left(\frac{H}{m}\right) = \frac{L}{m} \qquad \text{and} \qquad \cosh\left(\frac{H}{m}\right) = \frac{(D+m)}{m}$$

Using the relation $\cosh^2 u - \sinh^2 u = 1$ and following through the algebra we find:

$$m = \frac{\left(L^2 - D^2\right)}{2D} \qquad (3)$$

Substituting into (1) and (2) gives:

$$H = \frac{L^2 - D^2}{2D}\sinh^{-1}\left(\frac{2LD}{L^2 - D^2}\right) = \frac{L^2 - D^2}{2D}\cosh^{-1}\left(\frac{L^2 + D^2}{L^2 - D^2}\right) \qquad (4)$$

which by using the relation $\cosh^{-1}u = \ln[u + \sqrt{(u^2-1)}]$ can also be expressed in the form:

$$H = \frac{L^2 - D^2}{2D}\ln\left(\frac{L+D}{L-D}\right) \qquad (5)$$

The angle, θ, subtended by the horizontal and the tangent to the chain at the suspension point A can also be found:

$$\tan\theta = \frac{dy}{dx}(H) = \sinh\left(\frac{H}{m}\right) = \frac{L}{m} = \frac{2LD}{L^2 - D^2}, \text{ using (1) and (3)} \qquad (6)$$

Substituting this into equation (4) we obtain:

$$H = L.\cot\theta.\sinh^{-1}(\tan\theta)$$

From this equation, the sag ratio S can then be calculated as follows:

$$S = \frac{H}{L} = \cot\theta.\sinh^{-1}(\tan\theta)$$

which after using the relation $\sinh^{-1}u=\ln[u+\sqrt{(u^2+1)}]$ can be expressed in the form:

$$S = \frac{H}{L} = \cot\theta.\ln\left(\tan\theta + \sqrt{\tan^2\theta + 1}\right) = \cot\theta.\ln(\tan\theta + \sec\theta)$$

Depth along catenary

The depth at any point x_j a fraction f along the catenary is given by the following expression:

$$depth, d = y(H) - y(x_j)$$

where x_j is the solution to the following equation:

$$L_j = f.2L = \int_{-H}^{x_j} ds = \int_{-H}^{x_j} \cosh\left(\frac{t}{m}\right)dt = m.\left[\sinh\left(\frac{x_j}{m}\right) - \sinh\left(\frac{-H}{m}\right)\right]$$

Using the relation sinh(-x) = -sinh(x) and the previous result that sinh(H/m)=L/m we obtain:

$$2fL = m.\sinh\left(\frac{x_j}{m}\right) + L \qquad \Leftrightarrow \qquad x_j = m.\sinh^{-1}\left(\frac{L}{m}(2f-1)\right)$$

Hence $y(x_j)$ has the following form:

$$y(x_j) = m.\cosh\left(\frac{x_j}{m}\right) = m.\cosh\left[\sinh^{-1}\left(\frac{L}{m}(2f-1)\right)\right]$$

$$= \frac{L}{\tan\theta}\cosh\left[\sinh^{-1}\{\tan\theta(2f-1)\}\right], \text{ using (6)}$$

Using the relations $\cosh(x)=(e^x+e^{-x})/2$ and $\sinh^{-1}u=\ln[u+\sqrt{(u^2+1)}]$ and after some algebra we find $\cosh(\sinh^{-1}x) = \sqrt{x^2+1}$ so that:

$$y(x_j) = \frac{L}{\tan\theta}\left[(2f-1)^2\tan^2\theta + 1\right]^{1/2} = L\left[(2f-1)^2 + \cot^2\theta\right]^{1/2}$$

Given $y(H) = y(x, f=0) = L\left[1+\cot^2\theta\right]^{1/2}$ we obtain the following expression for depth, d:

$$d(x_j = 2fL) = L\left\{\left[1+\cot^2\theta\right]^{1/2} - \left[(2f-1)^2 + \cot^2\theta\right]^{1/2}\right\}$$

For each longline section with N branchlines evenly distributed between the two floats the fraction along the longline that the *jth* branchline is attached is given by:

$$f = \frac{j}{N+1}$$

The depth of the attachment point of the j-th branchline along the longline between the floats is therefore given by:

$$d(j) = L\left\{\left[1+\cot^2\theta\right]^{1/2} - \left[\left(2\frac{j}{N+1}-1\right)^2 + \cot^2\theta\right]^{1/2}\right\}$$

This equation is the same as that derived by Yoshihara (1951).