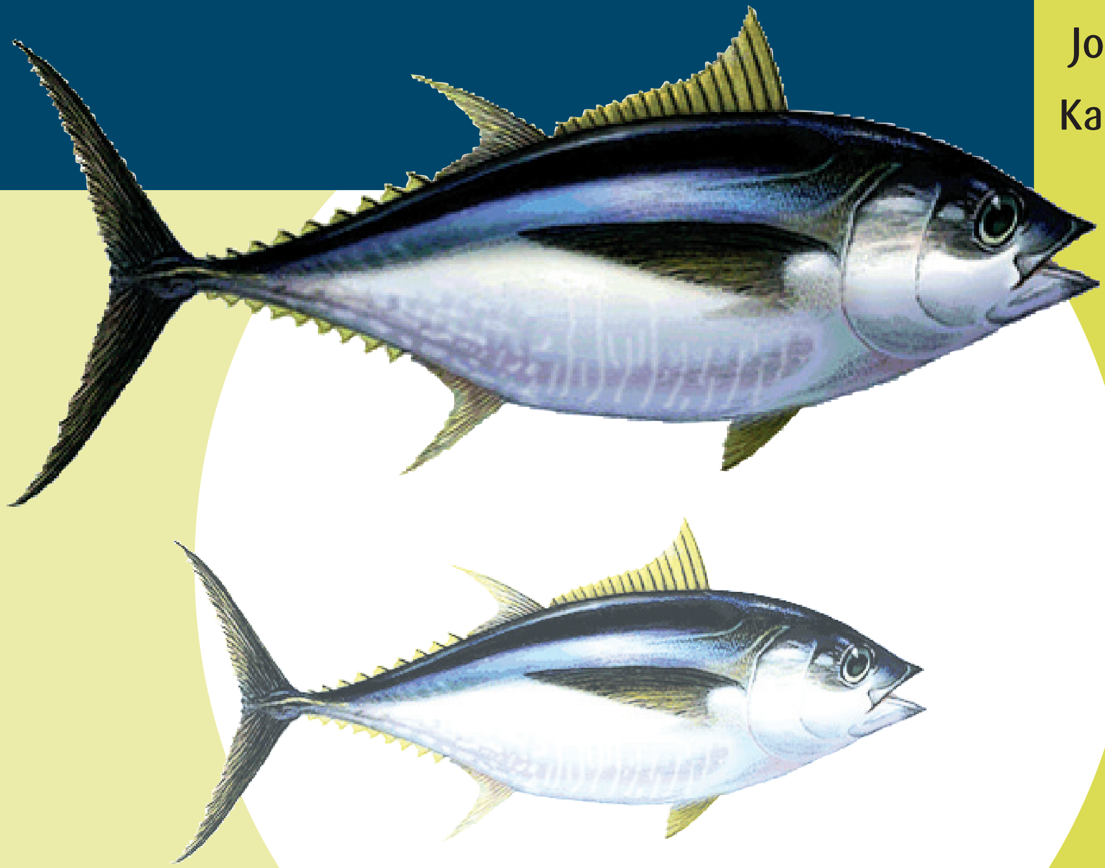

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Migration and habitat preferences of bigeye tuna, *Thunnus obesus*, on the east coast of Australia

— a project using archival and conventional tags to determine key uncertainties in the species stock structure, movement dynamics and CPUE trends

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1 NON-TECHNICAL SUMMARY

1999/109 Migrations and habitat preferences of bigeye tuna, *Thunnus obesus*, on the east coast of Australia – a project using archival and conventional tags to determine key uncertainties in the species stock structure, movement dynamics and CPUE trends.

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1.1. Objectives

1. Determine the seasonal and long-term migration patterns of bigeye on the east coast of Australia and determine links between populations on the east coast and those of the broader Western Pacific Ocean.

2. Determine the links between the rapidly expanding bigeye fisheries in south-east Queensland/northern New South Wales and those of the Coral Sea.

3. In collaboration with the South Pacific Commission Oceanic Fisheries Program, examine the patterns and extent of movement of bigeye throughout the WPO and determine the structure of bigeye stocks throughout this region.

4. Determine the habitat preferences (depth, water temperature, oxygen concentrations) of bigeye and examine temporal and spatial variability of these parameters.

5. Examine the hypothesis that seasonal variability in CPUE of bigeye on the east coast of Australia reflects changes in catchability rather than availability (*i.e.* that at times when bigeye are not being caught by longliners they are feeding and living at greater depths than those currently fished by longliners, rather than having migrated out of the area).

6. Using strontium chloride injections and conventional tags, mark 200-500 bigeye for subsequent use in validation of age estimates based on otolith banding patterns.

1.2. Outcomes achieved to date

This project, the first major investigation into the habits of bigeye tuna in the Coral Sea/Western Pacific Ocean (WPO), has substantially increased our understanding of the behaviour and movements of the species in this region.

The study supports those hypotheses put forward previously that residency in Coral Sea bigeye populations is high. The majority of tagged fish remained within the Coral Sea and of those individuals that undertook large-scale movements, most were to neighboring waters and were followed by a return to the Coral Sea.

The behaviour of bigeye in the Coral Sea/WPO varies on an individual basis and also temporally and spatially. Thus, defining “typical” bigeye behaviour at any time or space scale is problematic. Despite this complexity, the substantial data provided by this project has enabled a more comprehensive integration of the habitat preferences of this species into stock assessment and fishery interaction models and has highlighted the vulnerability of these models to variability in the behaviour of bigeye.

The limited movement of bigeye tuna within the Coral Sea is an important and timely consideration for the sustainable management of this species given recent concerns over the status of stocks in the eastern tuna and billfish fishery (ET&BF) and throughout the wider Pacific Ocean. The vulnerability of catch per unit effort (CPUE) models to variability in behaviour and uncertainty in position estimates has highlighted key areas for further development and future focus. Concentration of effort in these areas will ultimately provide more robust estimates of relative abundance and facilitate a more comprehensive understanding of relationships between targeting practices, the distributions of the fishery and the behaviour and distribution of bigeye tuna within the Coral Sea.

This study has played an important role in informing the Australian Fisheries Management Authority’s (AFMA) process of developing Total Allowable Effort (TAE) options for the ET&BF. An important consideration in this process has been the degree of connectivity between bigeye populations in the broader WPO and those exploited by Australian domestic fisheries. In this context, the patterns of residency in Coral Sea bigeye suggest that AFMA’s management of bigeye in the eastern Australian Fishing Zone [AFZ; as distinct from regional fisheries management organizations’ (RFMO) efforts to control effort and/or catches throughout the Central/WPO] will have a direct impact on local populations and on the sustainable development of the ET&BF.

The demonstration of high levels of residency in WPO bigeye follows similar findings for bigeye in other parts of the world. The growing evidence for restricted movement of Pacific Ocean tunas, particularly in sub-equatorial regions, raises the issue for the newly established Western and Central Pacific Fisheries Commission of how best to manage across the broad range of these fisheries for the sustainability of regional/localised populations. Localised depletions have the potential to significantly affect the viability of island and coastal state fisheries, yet fishery-wide controls of effort or catch will be unlikely to prevent localised depletions of these stocks.

1.3. Non-Technical Summary

This study investigated the movement patterns and behaviour of bigeye tuna tagged with conventional and archival tags off the north eastern coast of Australia with the aims of (i) increasing our understanding of the link between bigeye in the Coral Sea and the larger Pacific Ocean; (ii) providing data that would allow an objective analysis of bigeye CPUE trends and the variability in these and (iii) providing information on the links between bigeye in the Coral Sea and those targeted in the rapidly expanding south-east Queensland/northern NSW fisheries.

Tuna were tagged during four tagging operations carried out between October 1999 and October 2001. In total 161 archival tags (ATs) and 269 conventional tags (CTs) were deployed on bigeye tuna during these operations and of these 17 ATs (10.6 %) and 66 CTs (24.5 %) have been recaptured to date. Tuna were recaptured between 9.6 to 7,873.2 nautical miles (nmi) from their place of release, with 90 % of all tags recaptured within 150 nmi of their release position. Time at liberty varied from 16 to 1,441 days and growth of individual fish during time at liberty varied from 0 to 68 cm with individuals growing 0-11.3 cm/month. Returns were seasonal in nature, reflecting CPUE within the ET&BF. Of the conventional tags released, 189 were injected with 5 ml of strontium chloride (SrCl). Otoliths collected from SrCl marked fish after recapture have already been included in analyses validating age estimates and establishing the formation of annual increments in the otoliths of bigeye (Farley et al. 2003).

Of the 17 ATs recaptured, data on light level, water temperature, depth and internal (body) temperature were able to be retrieved from 14 of the tags. Light data were used to assess the movements of individuals while at liberty - daily estimates of position were generated from light levels using standard astronomical equations. Estimates of longitude derived using this geolocation technique were used but because of substantial errors in latitude estimates, latitude was derived using sea surface temperature matching techniques coupled with a movement filter. For each day at a given longitude median water temperatures collected by individual tags across 0-20 m were matched with sea surface temperatures (SSTs) derived via remote sensing. The resulting positions were then assessed for the likelihood the fish could have travelled to that position from any of the previous day's positions. If the distance between positions from one day to the next were less than a maximum distance of 1°, taking into account the uncertainties associated with the light-based longitude estimate (approximately 1°) and the SST-based latitude estimate (estimated to be 3°), the position was accepted and stored for use in calculating the following day's possible positions. Longitudes for which there were no corresponding match between water temperatures and satellite derived temperatures (and therefore no latitude) were removed from analyses. Calculated position estimates suggest that for the large part, bigeye tuna remained within the area of release for the entire time at liberty with individuals released within the north-western Coral Sea largely remaining in the north-western Coral Sea and those released in the south-western Coral Sea remaining in the south-western Coral Sea. Only three fish with ATs and two fish with CTs were confirmed as undertaking large scale movements. All five moved east and into the greater Coral Sea, with two confirmed as returning to waters close to their release location. Data from one tag suggested that this east-west movement was repeated and may be cyclic in nature. A further two fish on which ATs were deployed initiated eastward movements, however, the extent of these movements could not be assessed due to tag failure.

All individuals demonstrated a distinct diurnal pattern in behaviour and habitat preferences for a large proportion of time at liberty. During the day individuals were mostly distributed between 250-500 m, at water temperatures of 11 - 20°C and at dissolved oxygen levels of 2-4.5 ml/L^{-1}.

Daytime diving behaviour was typified by intermittent brief excursions from deeper waters up into shallower waters to re-warm muscles after time spent in cooler waters. At night the majority of time was spent at depths of less than 200 m, at water temperatures greater than 22°C and dissolved oxygen levels of 3-5 ml/L^{-1}. Individuals made irregular excursions to depths greater than 985 m, experiencing temperatures as low as 2.5°C and dissolved oxygen levels of 1.5 ml/L^{-1}. Individuals spent the majority of time in waters with dissolved oxygen levels of 2 ml/L^{-1} or more suggesting oxygen was not a limiting factor on the distribution of individuals. Shifts in the depth and water temperature preferences of bigeye tuna appeared to be closely related to seasonal shifts in the thermal structure of their oceanic environment; however these associations were marked by considerable individual variability. Separating seasonal variability from that associated with spatial variability was difficult due to the limited movements made by individuals and difficulties in comparisons with those data collected in other parts of the Pacific Ocean. Further data from individuals in the southern part of the fishery are required and collaborations with other institutions collecting data from other parts of the Pacific Ocean should be encouraged to ascertain the presence of spatial variation in behaviour and habitat preferences.

Bigeye demonstrated considerable variability in diving behaviour in association with the lunar cycle, often shifting preferred depths on those nights around the full moon to those slightly deeper than those throughout the rest of the lunar cycle. However, this was not consistent across individuals or consistent across lunar cycles within individuals (*i.e.* individuals did not demonstrate this shift during all lunar cycles and not all fish demonstrated the same shift during the one lunar cycle). The considerable individual variation evident in both depth and water temperature preferences suggests bigeye are quite flexible both in terms of their physiology and ability to cope with such large temperature extremes and in their foraging strategies. This allows bigeye to maximise their ability to successfully forage in a patchy environment whilst minimising competition with other tropical and subtropical tuna species for prey resources.

Movement and behavioural data were analysed in association with catch and effort data from the Australian domestic longline fishery in an effort to investigate observed variation in bigeye catchability. Trends in the catch rates of bigeye from 1994 to 2003 were examined in relation to changes in the spatial and vertical distribution of bigeye on a diurnal and seasonal basis and with respect to the lunar period. Shifts have been observed in effort within the Australian domestic longline fishery in relation to the time of day and period of the lunar cycle over this period resulting in an increased the efficiency of longline fishing effort with respect to targeting bigeye. In both the northern part of the fishery (north of 19°S and east to 160°E) and the southern part of the fishery (between 19°S and 35°S and east to 160°E) there has been a gradual shift in setting times from day sets to evening/night sets through time and increases in catch rates associated with this clearly reflect the greater overlap in the vertical distribution of the fishery and bigeye at night (both are distributed largely between 50-150 m). Average weekly catch rates of bigeye, particularly during the night, in both parts of the fishery generally increase on the full moon, while catch rates are lowest during the new moon. The increase in catch rate of bigeye during the full moon is consistent with the high overlap between the night-time depth distribution of bigeye and the assumed depth range of the longline gear. Conversely, during the new moon, bigeye spend a higher proportion of their time in shallower water (less than 50 m) and, consequently the overlap with the depth distribution of longline gear (and therefore their catchability) is lower. High variability in the diurnal and seasonal patterns of the relationship between bigeye behaviour and catch trends reflect the high individual variability observed in the behaviour of bigeye. Such variability also suggests that those factors influencing the relative catchability of bigeye are complex. There are likely to be a range of other environmental, behavioural, and operational factors than those covered in this study that also influence the catchability of bigeye; for example, seasonal differences of the feeding behaviour or differences in fishing gear configuration/deployment; data for which are limited. Spatial assessments of the interaction between bigeye and the longline fishery were limited due to the uncertainty around geolocation derived position estimates and small sample sizes. Sets with very high catch rates, generally occurred in discrete locations during individual months, suggesting CPUE during these periods is largely attributable to localised aggregations of bigeye. However, the data are confounded by the fact that recovery of tags is fishery-dependent and, therefore, increased fishing activity in one area will increase the probability of fish in the area being captured.

In general, purely statistical models used for standardising nominal CPUE in a fishery do not lend themselves to the inclusion of information on the preferred habitat of the species in mind. In an effort to determine an optimal method of standardising CPUE data, and at the same time, make progress toward understanding the effect of between-individual behavioural differences on how well a model adjusts nominal CPUE, two habitat based standardisation methods (HBS and stat-HBS) were compared to a model (generalised linear model – GLM) commonly used for standardising nominal CPUE using two spatial scales of data (data collected at 5° and 1° spatial scales). Gear configuration data from the Japanese longline fishery from 1975 to 2003 (these data were not available for the Australian domestic longline fishery) were combined with modeled oceanographic data from Global Circulation Models (GCM) and archival tag data and the relative preference of bigeye for different depth and temperature regimes in different areas of the western Pacific Ocean estimated and incorporated into the models. The models were then compared on the basis of how well they then adjusted nominal CPUE given the preferences of individuals through space (both horizontal and vertical) and time for a particular area of the western Pacific fishery. Of the three models, the HBS performed poorly relative to the stat-HBS and GLM approaches in standardising CPUE and is not recommended for CPUE standardisation. The fine scale analysis found that considering 1° CPUE data improved model fit, but more work is required to determine whether greater model flexibility or "overfitting" is occurring. Although the stat-HBS and GLM approaches appeared to adjust nominal CPUE in a more accurate manner than the HBS, the results from all models were biased by limitations of the archival tag data. These limitations include data availability within some of the spatial strata (*e.g.* the area of highest catch contained the least amount of archival tag derived data), uncertainties associated with position estimates generated via geolocation and individual variability in the habitat preferences of bigeye. Poor performance could also be associated with poor characterisation of habitat through space and time by the oceanographic models or a poor understanding of the factors driving variability in bigeye behaviour.

This study has demonstrated that bigeye tuna are in general, highly residential animals, suggesting only low levels of dispersal and mixing between populations both within ET&BF and with populations outside the ET&BF across the larger Pacific Ocean. Integration of data on the habitat preferences of bigeye tuna into CPUE models has highlighted the vulnerability of these models to variability in these parameters. This study has provided essential data for the development and testing of models of a more robust nature, enabling more accurate and objective analyses of bigeye CPUE trends. Confirmation of hypotheses put forward on the limited movement of bigeye tuna within the Coral Sea is an important consideration for the sustainable management of this species and the limited data this study provides on movements within the ET&BF are also important for the management of this species within Australian waters.

KEYWORDS: Bigeye tuna, *Thunnus obesus*, migration patterns, habitat preferences, habitat-based CPUE standardization.

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3. BACKGROUND

3.1. The Eastern Tuna and Billfish Fishery for bigeye and concerns about regional stocks.

During the 1990’s, catches of bigeye on the east coast of Australia rapidly increased from around 20 tonnes to peaks of 1031 tonnes in 1998 and 1050 tonnes in 2001 (Ward & Bromhead 2004). The gross value of the fishery also followed this trend, increasing to well over $AU25 million. As a consequence, together with swordfish, bigeye have replaced yellowfin tuna as the most valuable components of the Eastern Tuna and Billfish Fishery (ET&BF).

This very rapid rise in bigeye catches was largely a result of a number of factors:

1. a rapid expansion of longline effort off Mooloolaba and northern New South Wales,
2. significant investment in new and larger boats capable of fishing further offshore,
3. shifts in targeting practices of longliners away from yellowfin tuna to bigeye tuna and broadbill swordfish,
4. advances in the efficiency of gear and methods for targeting bigeye and swordfish.

Commanding prices close to those paid for premium grade southern bluefin tuna (SBT), bigeye tuna are now targeted throughout the year, from Cairns to southern New South Wales.

Bigeye tuna have been targeted by longline fisheries throughout the Pacific Ocean for well over 40 years. Total longline catches are currently in the order of 40,000-70,000 tonnes per year in the Eastern Pacific Ocean (EPO) and 60,000-80,000 tonnes per year in the Western and Central Pacific Ocean (W/CPO; Lawson 2004). The combined value of Pacific longline fisheries is therefore substantial, with those catches from the South Pacific region of the W/CPO alone yielding US$1 billion in 2001 (Hampton et al. 2004). Additional to substantial longline catches, purse seine fisheries in the mid-1990’s began to take significant catches of bigeye in both the EPO and W/CPO (in an effort to supplement their catch of skipjack and yellowfin for the canning market), resulting in increases in total bigeye catches from 161,000 in 1993 to 222,000 tonnes in 2002 in the EPO and 80,000 tonnes in 1993 to 124,000 tonnes in 2002 in the W/CPO (Lawson 2004).

In the late 1990’s catch rates of bigeye in the Japanese longline fishery in the EPO demonstrated significant declines from those in the previous decade. The Japanese took the unusual step of drawing attention to these declines and called for a cessation of purse seine targeting of juvenile and adult bigeye found in association with floating objects and fish attracting devices (FAD’s). Similar declines to those in the longline fleet were also demonstrated by catches in the purse seine of the W/CPO prompting concerns (Hampton et al. 1998). However, the models used for standardization of bigeye catch per unit effort (CPUE) at the time (and to a large extent currently) relied on some critical assumptions about bigeye behaviour – assumptions that are based on scant data collected through the ultrasonic tracking of a few animals. Not only are there concerns as to how representative scant data are to that of the greater population, CPUE models can also be highly susceptible to assumptions about behaviour. Submitting alternate hypotheses on depth and temperature preferences to such models in bigeye have been demonstrated to result in either a stable or a collapsing stock situation (Hampton et al. 1998).

With rapid expansion of effort and bigeye catch off the eastern Australian Fishing Zone (AFZ), and the possibility that stocks in the W/CPO are being fished down at a rapid rate, it is essential that we understand the links between the fish caught in the Coral and Tasman Seas and those caught in the wider W/CPO. It is also critical in a pan-Pacific context that we understand which of the two habitat preference hypotheses proposed in Hampton & Gunn (1998) is correct.

3.2. What do we know about bigeye stocks in the eastern AFZ?

The 1997 ET&BF Fisheries Assessment Group (FAG) examined available data on bigeye biology and the results of a tagging study in the western Coral Sea (Hampton & Gunn 1998) and discussed the potential for localised depletion of bigeye and swordfish in the eastern AFZ. Although there are still many gaps in our understanding of the longevity and productivity of bigeye, recent investigations in the age and growth of bigeye have revealed that this species is more akin to SBT in its age and growth characteristics, living to at least 15 years (Farley et al. 2003).

Genetic studies of bigeye in the Pacific Ocean, including analysis of samples collected in the eastern AFZ have been unable to reject the null hypothesis that bigeye from the Pacific Ocean belong to a single genetic unit (Grewe & Hampton 1998). Although being unable to reject the null hypothesis does not confirm the existence of a single pan-Pacific bigeye stock, it does suggest that there is sufficient mixing between the EPO and the WPO to allow gene flow across the Pacific basin.

While Grewe & Hampton (1998) found no evidence of genetic heterogeneity across the Pacific, the results of a large tagging study in the Coral Sea (Hampton & Gunn 1998) suggest that the majority of bigeye in this area have a localised distribution. Of the tags returned, 90 % have been recaptured within the eastern AFZ. The remaining 10 % have been recaptured at widely spaced locations throughout the W/CPO. The results of the tagging study suggest either long residence times for the majority of fish, or possibly a cyclic migration pattern with fish returning to the Coral Sea each year. However, it is not possible to determine which of these two hypotheses is correct with conventional tagging data alone.

Archival tags deployed on SBT have demonstrated that large scale cyclic migrations from the Great Australian Bight out into the Indian Ocean and Tasman Sea are common in juveniles (Gunn et al. 1994) Fish have been observed to return to within 180 km of their release position after 8 months, swimming distances of more 5,000 kms over that period. It is possible that Coral Sea bigeye may undertake similar migrations and that observed pulses in returns of conventional tags in this area (Hampton & Gunn 1998) reflect the seasonal return of migratory fish to the area. Understanding whether fish are residents, or are undertaking large-scale cyclic migrations into the Pacific, is critical in terms of developing harvest strategies for ET&BF.

The exploitation rates (ratio of fishing mortality rate to attrition rate plus fishing mortality rate per year) for fish tagged in the Coral Sea have been observed to be moderately high (0.2–0.3), despite a low level of effort in the north-eastern AFZ (Hampton & Gunn 1998). Moderate exploitation rates in a small fishery, if combined with long residence times and the probability of low productivity, provide the potential for localised depletion of Coral Sea bigeye populations.

It is critical that we understand the impact of the rapid expansion of the southern Queensland and northern NSW bigeye fishery on populations along the east coast, given the possibility of localised depletion of bigeye populations in the Coral Sea and possible declining populations in the W/CPO. If the Coral Sea and southern Queensland bigeye stocks mix freely, it could assumed that the potential for depletion of the east coast bigeye resources has been increased by the expansion and increased efficiency of domestic effort.

Therefore, before a harvest strategy for east coast bigeye tuna can be formulated, additional information in three key areas is required. Firstly, we need to know the nature and extent of the links between bigeye caught in the W/CPO and the Coral Sea. Is there enough evidence for localised distributions, despite evidence for some gene flow, to suggest that we should manage these resources separately? Secondly, we need to collect more information on the links between bigeye caught in the Coral Sea and those that are targeted in the rapidly expanding southern Queensland/northern NSW fisheries. And thirdly, we need data that will allow us to differentiate between behavioural/habitat preference hypotheses currently being used to standardise bigeye CPUE so that appropriate assumptions can be incorporated into these models and realistic predications on bigeye CPUE can be proposed.

In 1998 the ET&BF management advisory committee (MAC) recognised these requirements and subsequently assigned the following priorities to research associated with bigeye in its 1998-99 research priorities:

- Priority 1 to bigeye stock structure;
- Priority 2 to assessment of historical and current catches in the ETBF;
- Priority 5 to determination of biological characteristics of bigeye tuna required for stock assessments;
- Priority 8 to identification of fisheries interactions and;
- Priority 9 to determination and modeling the oceanographic and other factors influencing the seasonal movement and migration patterns of key ETBF species.

This project addresses elements of each of these priority areas.

3.3. Collaboration with international agencies in bigeye tuna archival tagging research.

Archival tags are now widely recognised throughout the international pelagic fisheries research community as an effective tool for examining movement and behaviour of large, pelagic higher order predator species such as bigeye tuna (Kitagawa et al. 2000; 2004; Block et al. 2001; Gunn & Block 2001; West & Stevens 2001; Schaefer & Fuller 2002; Musyl et al. 2003). The applicability of archival tags, the difficulty in tagging large numbers of bigeye with conventional tags (the species does not school on the surface to the same extent as yellowfin and skipjack) and the urgent requirement for information on behaviour and habitat preferences have prompted the development of a number of proposals focused on addressing some of the questions posed here relating to the movement patterns, habitat preferences and stock structure of bigeye tuna throughout the Pacific Ocean.

The CSIRO have been involved in the development of a large proposal involving coordinated international research on Pacific populations (Pelagic Fisheries Research Program unpublished data). This project plans to deploy 1,000 archival tags in bigeye throughout the Pacific across the period 1999-2002. The co-Principal Investigator's on this FRDC proposal are also collaborating in a parallel project based out of the South Pacific Commission (SPC) Oceanic Fisheries Program involving the tagging of bigeye with archival tags in the Coral Sea and other parts of the W/CPO. The SPC-CSIRO collaborative project plans to deploy 80 archival tags in the Coral Sea in 1998. The costs associated with this project are listed as contributions to the current proposal. The SPC-CSIRO project and the project proposed here are designed to contribute to the broader international initiatives on bigeye research in the Pacific.

The benefits to Australia of a coordinated program – pan-Pacific perspectives in bigeye movement, stock structure and behaviour – are significant in the context of understanding how bigeye on the Australian east coast are linked with those throughout the Pacific. With research coordinated throughout the region it is likely that the advice to managers will be consistent and supported strongly by all partners. Given current concerns about bigeye resources, this approach is seen as the most likely way to ensure sustainability of bigeye fisheries throughout the region.

4. NEED

The proposed project addresses a number of areas recognised as high priorities within the ET&BF Research Plan and has been rated as the highest priority project within the 1998 Eastern Tuna MAC priority setting process.

In the ET&BF there are both regional and local-scale questions that must be addressed before an operational model can be used to develop harvest strategies for east coast bigeye. This project addresses a number of these key questions:

1. In a climate of rapidly increasing effort on bigeye within the ET&BF, concern over the sustainability of bigeye resources in the EPO and W/CPO, and the development of a management plan and harvest strategy for bigeye in the eastern AFZ, it is essential that we understand the stock structure of bigeye in our region. Bigeye stock structure has been listed as Priority 1 in the ET&BF Research Priorities. The proposed project, in combination with similar and collaborating projects in other parts of the Pacific Ocean seeks to define links between bigeye populations throughout the Pacific.

2. Assessments of the sustainability of bigeye populations in the AFZ and in the broader Pacific urgently require more information on the behaviour and habitat preferences of bigeye (Hampton et al. 1998). Assessment of historical and current catch data in the ET&BF and surrounding region is Priority 2 in the ET&BF Research Priorities. The proposed project is designed to collect data that will allow objective analysis of bigeye CPUE trends through incorporation of information on habitat preferences, and variation in these on seasonal and annual time scales.

3. The interpretation of tagging data from the Coral Sea, used by Hampton & Gunn (1998) to estimate exploitation rates of bigeye in this area, requires additional information on the habitat preferences and seasonal migration patterns of bigeye in the Coral Sea/Tasman Sea basin. Determining the links between bigeye fisheries in Area E and those on the southern Queensland/northern NSW coasts is also essential in interpretation of the tagging data and understanding the likely impacts of increased effort in different areas of the ET&BF; these are Priorities 5, 7 and 8 of the ETBF Research Priorities.

4. The strontium marking of conventionally tagged fish will provide material for the validation of age estimates produced by CSIRO's FRDC Pilot Project developing and assessing methods to age bigeye; this is Priority 5 of the ET&BF Research Priorities.

In addition (and perhaps in competition) to the fisheries management issues, a significant spin-off from the proposed project will be a quantum leap in our understanding of the behaviour and seasonal movement of bigeye in the eastern AFZ (and broader Pacific). These advances will allow fishermen to more effectively and efficiently target bigeye in the future.

5. OBJECTIVES

1. Determine the seasonal and long-term migration patterns of bigeye on the east coast of Australia and determine links between populations on the east coast and those of the broader Western Pacific Ocean.

2. Determine the links between the rapidly expanding bigeye fisheries in south-east Queensland/northern New South Wales and those of the Coral Sea.

3. In collaboration with the South Pacific Commission Oceanic Fisheries Program, examine the patterns and extent of movement of bigeye throughout the WPO and determine the structure of bigeye stocks throughout this region.

4. Determine the habitat preferences (depth, water temperature, oxygen concentrations) of bigeye and examine temporal and spatial variability of these parameters.

5. Examine the hypothesis that seasonal variability in CPUE of bigeye on the east coast of Australia reflects changes in catchability rather than availability (*i.e.* that at times when bigeye are not being caught by longliners they are feeding and living at greater depths than those currently fished by longliners, rather than having migrated out of the area).

6. Using strontium chloride injections and conventional tags, mark 200-500 bigeye for subsequent use in validation of age estimates based on otolith banding patterns.

6. GENERAL METHODS

6.1. Tagging operations

Tagging operations were conducted on four occasions in the northern part of the eastern tuna and billfish fishery (ET&BF) over the period 1999-2001 (Figure 6.1). Bigeye were caught using handlines in 1999 and 2001 from the vessels “Total” and “Balance” and using longlines from the vessel “Ocean Odyssey” in 2000. Additional attempts were made to deploy tags in December 1999, September 2000 and September 2001, but all were unsuccessful due to weather conditions and poor catches of suitable fish.

Handlining operations were conducted on surface aggregations of bigeye and yellowfin tuna found in association with whale sharks. Once caught (either on handlines or longlines), fish were lifted through the trawl door, without gaffing, into a tagging cradle. To calm the fish, a wet cloth was placed over the eyes of the fish while the hook was removed and the fork length measured. Only fish less than 30 kg were made available by operators for tagging. The life status and condition of each of these fish was assessed by the person carrying out tagging operations and those that were vigorous and retained good colour were tagged.

All fish handling and tagging techniques were subsequently reviewed and approved by the Tasmanian Department of Primary Industries, Water and Environment Animal Ethics Committee.

6.2. Tagging procedures

6.2.1. Archival tags

A total of 161 archival tags (Mk7, Wildlife Computers, Redmond WA) were deployed on bigeye tuna (Figure 6.2). Each tag was roughly rectangular in shape with one tapered end, with a 20 cm stalk extending from the tag body that terminated in a light and temperature sensor. A pressure sensor and second temperature sensor were located in the main body of the tag (Figure 6.3). The stalk design had been slightly modified to increase the strength of the base as a result of previous problems with disconnection of the light sensor stalk to the main body of the tags. Each tag was printed with an identifying number and information about the reward and where to return the tag.

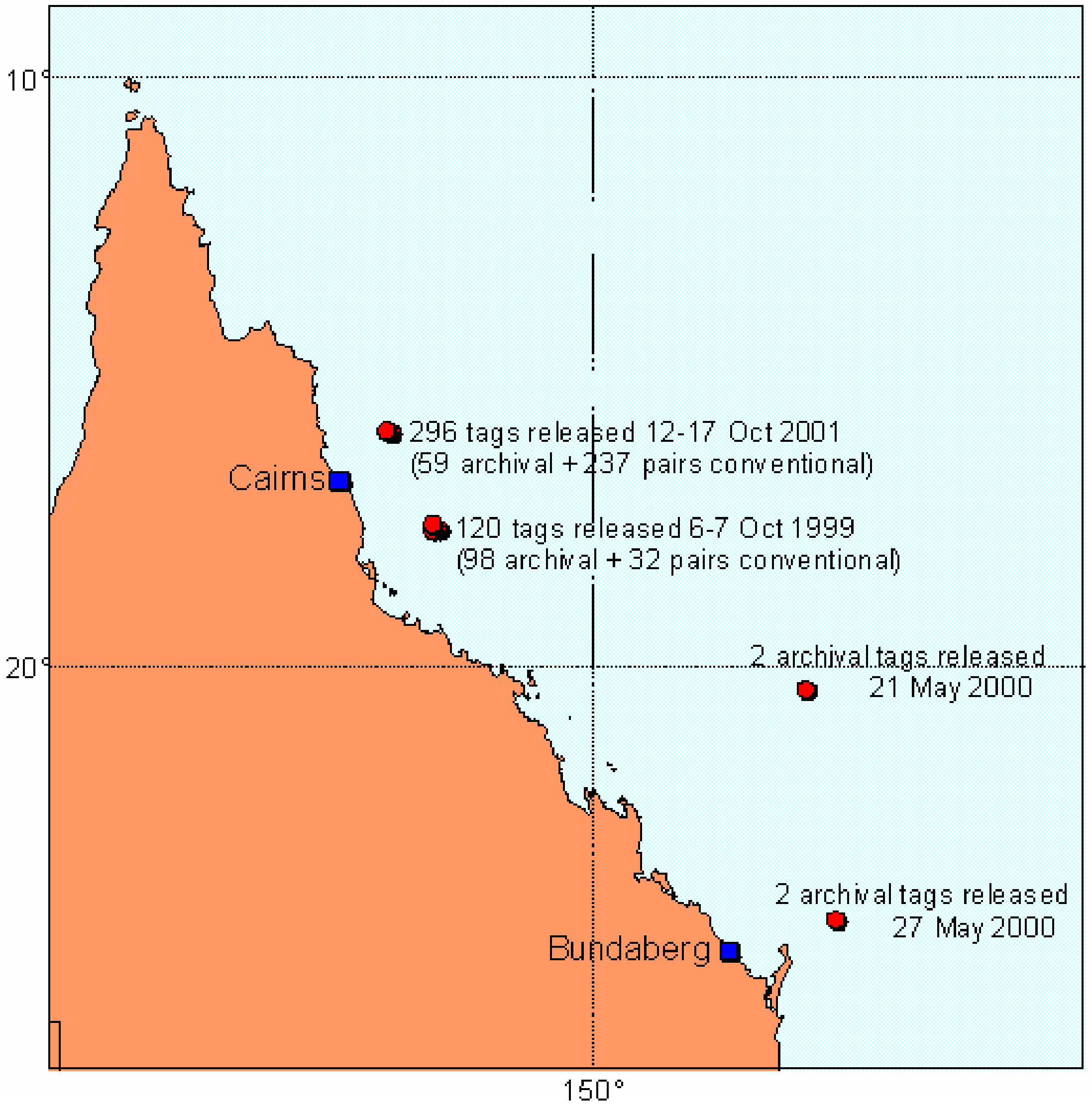
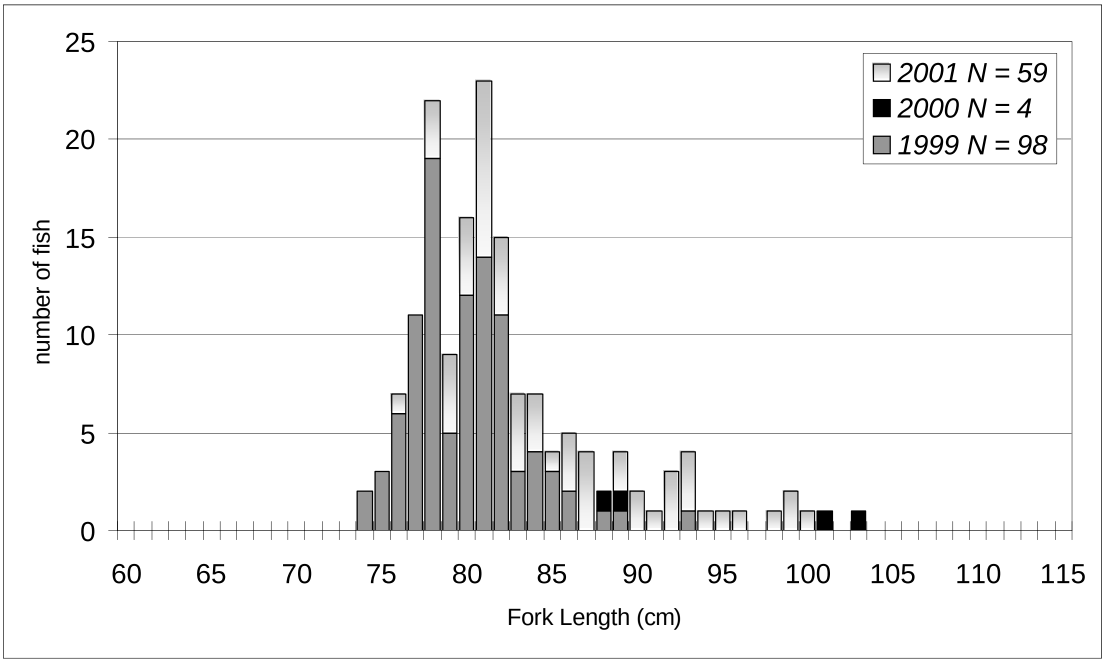


Figure 6.1. Release positions of archival and conventional tags on bigeye tuna in the ET&BF.

A.



B.

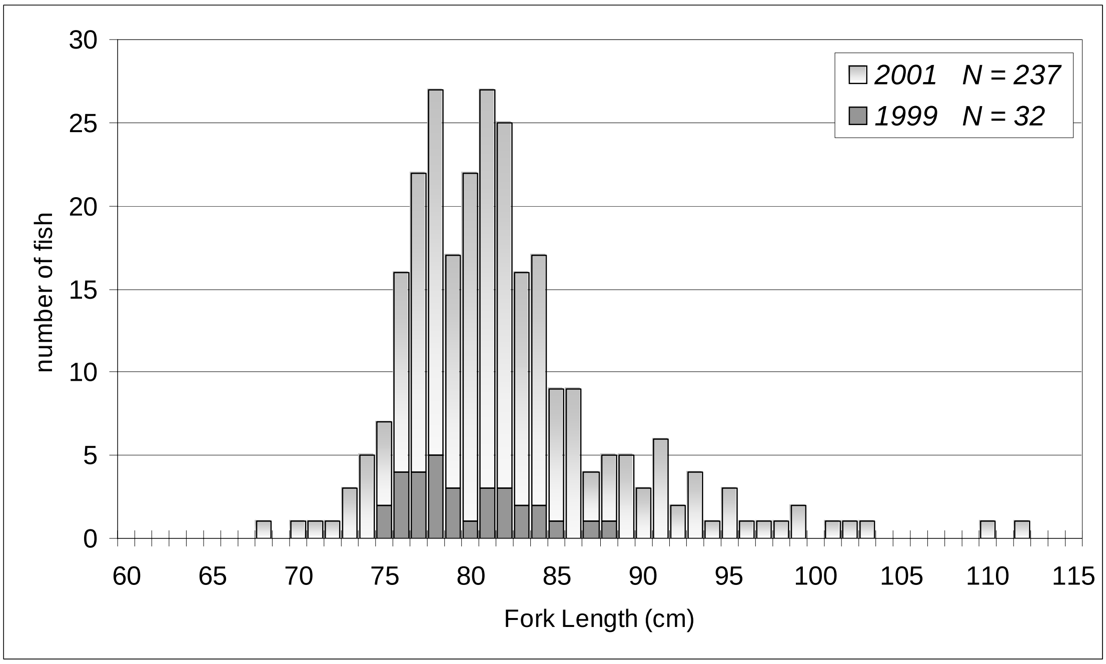


Figure 6.2. Length-frequency distribution of bigeye tuna released with (a) archival tags and (b) conventional tags in 1999-2001.

Tags were programmed to record and store internal and external temperature, light and pressure every 4 minutes. Hydrostatic pressure was measured with a resolution of 0.5 m, an accuracy of ± 1 % and saved with a resolution of 1 to 16 m, graded with depth; and temperature was measured with a resolution of 0.05°C, an accuracy of ± 0.2°C and stored with a resolution of 0.2°C. Up to 4 years of data could be stored by the tag recording the data at this resolution.

Tags were placed internally through an incision approximately 4 cm long on the ventral surface of the fish between the anal and pelvic fins. The incision was made through the skin, fat and muscle to the peritoneum and the depth of this cut varied with the size and condition of the fish. The peritoneum was then torn using a gloved finger to avoid introducing the knife blade into the body cavity and risking cutting the gut or internal organs. A broad-spectrum antibiotic (2.5 ml) was syringed directly into the body cavity. The tag was inserted, orientating the stalk in a posterior direction towards the tail. The incision was closed with an absorbable suture (Figure 6.3). The archival tagging procedure usually took less than one minute. Recovered fish were reported by processors to have little evidence of infection, although incisions remained partially open around the trailing stalk. In the case of the four fish caught during longlining operations (May 2000), individuals were additionally tagged with a pair of conventional tags (see below) as an alert mechanism for recapture. Any potential additional stress caused by the extra tags was considered to be negligible due to the larger size of these fish in comparison with those caught during handlining operations. All other fish were tagged only with an archival tag.

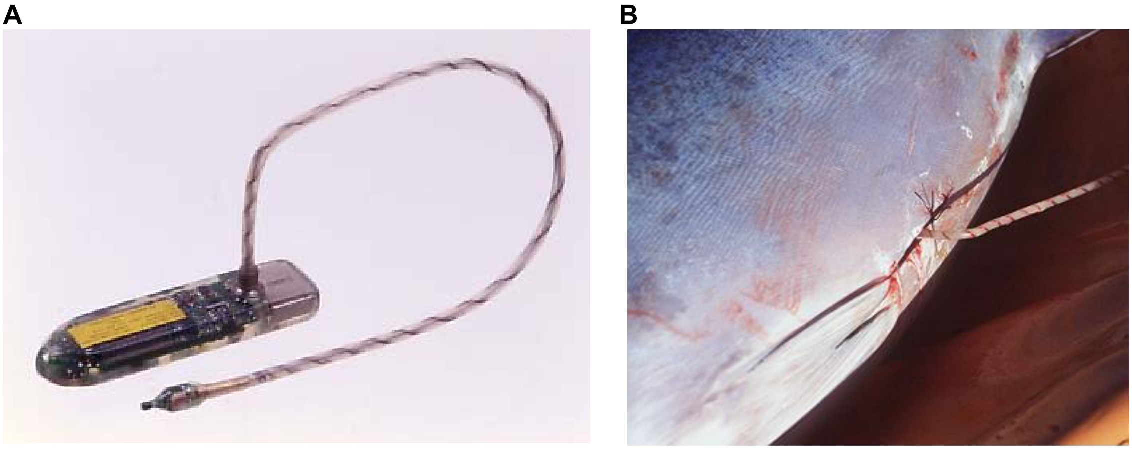


Figure 6.3. Archival tagging of bigeye tuna (a) Mk7 archival tag; (b) the ventral surface of a tuna after internal placement of an archival tag: the tag stalk can be seen emerging from the body through the sutured incision.

6.2.2. Conventional tags

During the same operations, 269 pairs of conventional dart tags (Hallprint, Australia) were deployed on bigeye throughout the ETBF (Figure 6.2). Two conventional tags (CTs), were attached to each fish using a sharpened hollow stainless steel applicator. Tags were placed on either side of the second dorsal fin about 4 cm behind the origin of the fin and 1 cm below the mid-dorsal body line, and at an angle of 45° to the body with the dart towards the head of the fish. The dart head was inserted through, and anchored in, the basal bone elements (pterygiophores) of the fin rays (Figure 6.4). The streamer was printed with an identifying number and return information.

Of the fish released with CTs, 189 were injected with 5 ml of strontium chloride solution for age validation, resulting in a dosage of strontium of approximately 250 mg kg^{-1} of fish. Capture, tagging, strontium chloride injection and returning the fish to the water took approximately 30 seconds.

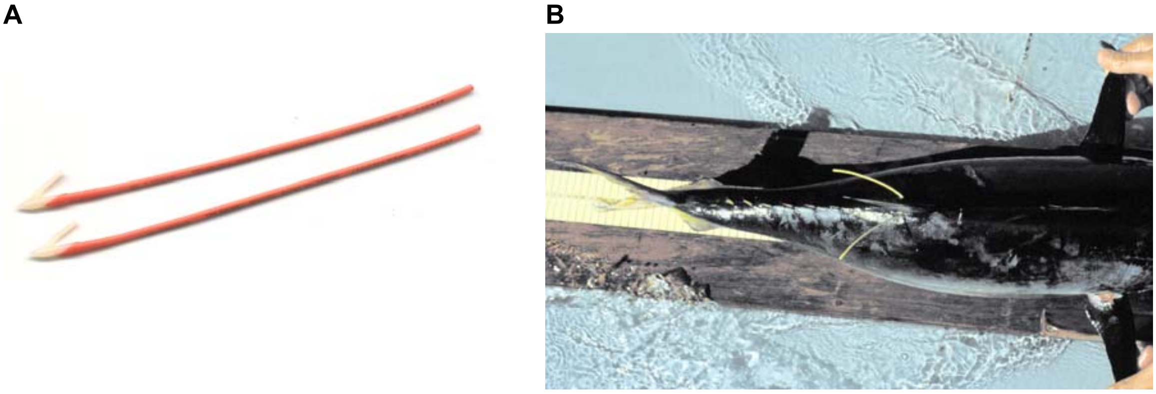


Figure 6.4. Conventional dart tagging of bigeye tuna (a) detail of the tags; (b) placement of tags on a tuna.

6.3. Recovery procedures

Posters detailing the objectives of the tagging program, the deployment of tags, the rewards given for returns and how to return tags were distributed to all operators in the ET&BF and, in several languages, to vessels outside the ET&BF working around the Coral Sea rim. Rewards for returning archival tags (ATs) comprised either a cash reward of $250 or alternatively rewards in-kind: t-shirts, caps, jackets, cups and bags that featured original images of tuna. Rewards for the return of CTs comprised one of a t-shirt, cap or cup. Additional information on the objectives of the program and updates on its progress were distributed to fishers in the ETBF by mail, newsletters and port visits and to the general public through media articles.

6.4. Data retrieval and initial processing

On return to CSIRO, ATs were firstly checked for any physical damage that may have compromised data collection and storage. Each of the four sensors was then tested to assess for correct functioning. Any drift in the internal clock of the tag was corrected (assuming a constant and progressive drift in time across time at liberty) and the data were then downloaded using Mk7 host software (Wildlife Computers, Redmond, WA). Tags from which data failed to download were returned to the manufacturer for further attempts at data retrieval. Once downloaded, data were visualised using in-house software (Arctag, CSIRO Marine Research) to determine the exact time of release and recapture. Data collected by the tag either side of release and recapture were removed and the file was checked for erroneous data and post-processing depth drift. Any drift present in the depth data was corrected using standard zero offset correction (ZOC) techniques. Erroneous data, typically caused by faulty sensors or the battery failing were flagged to ensure they were not used in subsequent processing or analyses before the complete dataset for each tag was archived in a central database. Details of CT returns were also archived in a central database.

7. RESULTS AND DISCUSSION

7.1. Movement of bigeye tuna (*Thunnus obesus*) determined from archival tag light-levels and sea surface temperatures

N. P. Clear, K. Evans, J. S. Gunn, S. Bestley, K. Hartmann, T. Patterson

7.1.1. Introduction

A rapid rise in the catches of bigeye tuna (*Thunnus obesus*) off the east coast of Australia from 20 to 1,050 tonnes during the 1990s has increased the value of this fishery to over $AU25 million (Ward & Bromhead 2004) and resulted in bigeye catches becoming one of the most valuable components of the east coast tuna and billfish fishery (ET&BF). The expansion of the fishery both spatially and temporally, rapid increases in catch rates and recent debate over potential declines in bigeye stocks (Hampton et al. 1998) have prompted questions relating to the links between bigeye throughout the Pacific Ocean, and in particular, between those fish in the western and central Pacific Ocean (WPO and CPO). Population studies on bigeye in the Pacific Ocean have found little evidence of genetic heterogeneity (Grewe & Hampton 1998) and, as a result, bigeye tuna caught off the east coast of Australia have been assumed to belong to a Pacific-wide stock. However, in general, little genetic differentiation is expected from highly migratory fish sampled from within ocean basins and hence some regionalisation could not be ruled out.

Conventional tagging programs carried out in the Australian fishing zone (AFZ) of the Coral Sea have provided some insights into the relationship between the stocks of tuna in the western Pacific and those of the broader Pacific Ocean (Miyabe 1994; Hampton & Gunn 1998). Longer-term recaptures of fish over 2,500 km from their point of release have indicated that bigeye are capable of large-scale migrations, and provide evidence that mixing (and gene flow) across the western Pacific could occur. However, the majority of fish tagged as part of these studies (> 90 %) were recaptured within the Coral Sea, suggesting the possibility of widespread residency throughout the population.

The spatial distribution of recaptures and a marked seasonality in recaptures reflecting seasonality in catch rates within the fishery led to the proposal of two possible scenarios for bigeye in the ET&BF: either (1) long residence times for the majority of fish with fish demonstrating seasonal changes in behaviour, resulting in seasonal changes in their availability to the fishery, or (2) a possible cyclic migration pattern with fish returning to the Coral Sea each year (Hampton & Gunn 1998). A lack of any recaptures south of 25°S also prompted questions as to the links between those fish in the northern part of the Coral Sea and those further south in the southern Coral and Tasman Seas.

Archival tags (ATs) are widely recognised throughout the international pelagic fisheries research community as an effective tool for examining movement and behaviour of large, pelagic higher order predator species that remain constantly submerged (and therefore are not suitable for satellite telemetry) such as bigeye tuna (Kitagawa et al. 2000; 2004; Block et al. 2001; Gunn & Block 2001; West & Stevens 2001; Schaefer & Fuller 2002; Musyl et al. 2003; Teo et al. 2004). In an effort to test the hypotheses proposed in Hampton & Gunn (1998) and to resolve those issues concerning the relationships between bigeye stocks both within the AFZ and across the broader WPO, an archival tagging program was initiated to gather additional information on the long term movements and behaviour of bigeye. However, in determining reasonable estimates of distribution and movement of bigeye tuna within the Coral Sea and broader WPO, a number of issues relating to the accuracy of position estimates derived from light-level geolocation data needed to be addressed.

Previous studies investigating the accuracy of light level geolocation estimates have demonstrated that estimates of latitude are less accurate than those of longitude and that both are compromised by the diving behaviour of fish species through degradation of light attenuation curves used in calculating surface light levels at depth (Gunn et al. 1994; Welch & Eveson 2001; Beck et al. 2002; Bradshaw et al. in press; Schaefer & Fuller 2002; Itoh et al. 2003; Musyl et al. 2003). Poor estimation of surface light levels when at depth is manifest in a compromised calculation of longitude and particularly latitude. Latitude estimates are further compromised during periods surrounding the equinoxes, when differing latitudes have a similar day length. During these periods, it is therefore difficult to discern latitude on the basis of day length as employed in light-based geolocation estimation.

In an effort to improve light-based geolocation estimates, particularly those associated with latitude, several studies have incorporated environmental data into position estimation calculations as a means of reducing the potential area in which an individual could be found (and therefore the error around the estimate). These have included bathymetry (West & Stevens 2001; Beck et al. 2002), tidal data (Hunter et al. 2003), sea surface temperature, temperature-at-depth, sea surface height, chlorophyll and ocean currents (Inagake et al. 2001; Beck et al 2002; Bradshaw et al 2002; Itoh et al. 2003; Kitigawa et al. 2004). Other techniques employed to reduce errors in light-based position estimates have included the application of models such as state-space Kalman filter statistical models which provide best-estimate predictions of the location of an animal given the light-based geolocation estimates provided to the model (Sibert & Fournier 2001; Sibert et al. 2003).

Here we present the results of investigations into the seasonal and long-term movements of bigeye tuna tagged in the western Coral Sea, providing insights into the relationships between stocks both within the ET&BF and with that of the broader WPO, information that is essential for the effective future management of these populations. Additionally, we present here the results of investigations into the use of remotely sensed sea surface temperatures as a means of improving latitude estimation and in doing so, highlight issues pertinent to the use and future improvement of geolocation techniques in resolving the movement patterns of deep diving species such as bigeye tuna.

7.1.2. Methods

7.1.2.1. Conventional tags

A total of 269 conventional tags (CTs) were deployed on bigeye tuna off the north-east coast of Australia during the period 1999-2001. Full details of conventional tags, tagging operations and locations and recapture are presented in Chapter 6.

7.1.2.2. Archival tags

A total of 161 ATs were deployed on bigeye tuna off the north-east coast of Australia during the period of 1999-2001. Full details of ATs, tagging operations, location of release, recapture and downloading of archival tags are presented in Chapter 6.

7.1.2.3. Tag returns

Recaptures of CTs and ATs were investigated for seasonality in returns in the context of fishery effort. Return rates and possible seasonality in returns were then compared with previous CT returns in the Coral Sea region (Hampton & Gunn 1998).

7.1.2.4. Light-based geolocation

Daily estimates of location were calculated using proprietary software (GeoControl v2.01.0002; Wildlife Computers, Redmond). This program firstly extracts the onboard stored light-data, correcting for any drift in the tag's internal clock. Light level curves are generated from light data collected by each AT and associated with a range of zenith angles (the angle between the vertical and observed centre of the sun) corresponding to a range of dawn, dusk and twilight values (Hill & Braun 2001). A range of day lengths corresponding to each zenith angle are generated and the latitude that best predicts these day lengths is given as the best estimate. A graphical view of each day's light level curves are generated, allowing for interactive processing of each day's data and correction of any displacement of depth attenuation curves due to dive behaviour of the animal. An approximate time of midday is input into the program as a reference point and midnight is calculated from the midpoint of the dawn-dusk events using a folding method involving overlaying the dawn and dusk light curves across one another. Standard astronomical equations are then used to calculate an estimate of longitude.

The regular crepuscular diving behaviour of bigeye tuna often severely affected the shape of the light curves displacing the attenuation of light levels with depth and therefore compromising estimation of latitude and longitude. Position estimates from days affected by such diving behaviour were not used in further analysis. Due to the interactive and thereby subjective nature of position calculations, processing of all light data was carried out by only one of the authors (KE) in an effort to standardise position estimation.

7.1.2.5. Estimating latitude using sea surface temperatures.

In an effort to address the problems associated with the calculation of latitude using light-based geolocation techniques (see Section 7.1.1.), estimates of daily latitude were derived by comparing surface temperatures recorded by ATs with remotely sensed sea surface temperatures (SST).

A daily surface temperature for each tag was estimated from the median external temperature recorded by the tag across 0-20 m. Drift in the depth sensors of the tags used occurred over a period of months and ranged from 5-10 m up to a maximum of 15-20 m. Although zero offset correction (ZOC) techniques allowed some correction of this drift, this did not correct for all drift across time at liberty. Zero correction techniques rely on data points collected at the surface able to be adjusted back to 0 m. Often in datasets collected by bigeye very few data points were collected at the surface (0 m), thereby causing ZOC techniques to be applied to only a small number of data points located large distances apart in the data record. As a result, a smaller degree of depth drift often occurred between the points at which ZOC techniques could be applied. Using a median across the top 20 m accounted for any depth drift remaining in the data record after ZOC techniques were applied and ensured that the true surface was included. Throughout the area encountered by tagged bigeye, the top 20 m appeared to be well mixed with little difference in water temperatures at the surface and 20 m. Overall, mean differences between the water temperatures in the top 1 m and the median calculated for 0-20 m were 0.06 ± 0.12°C (Figure 7.1.1.).

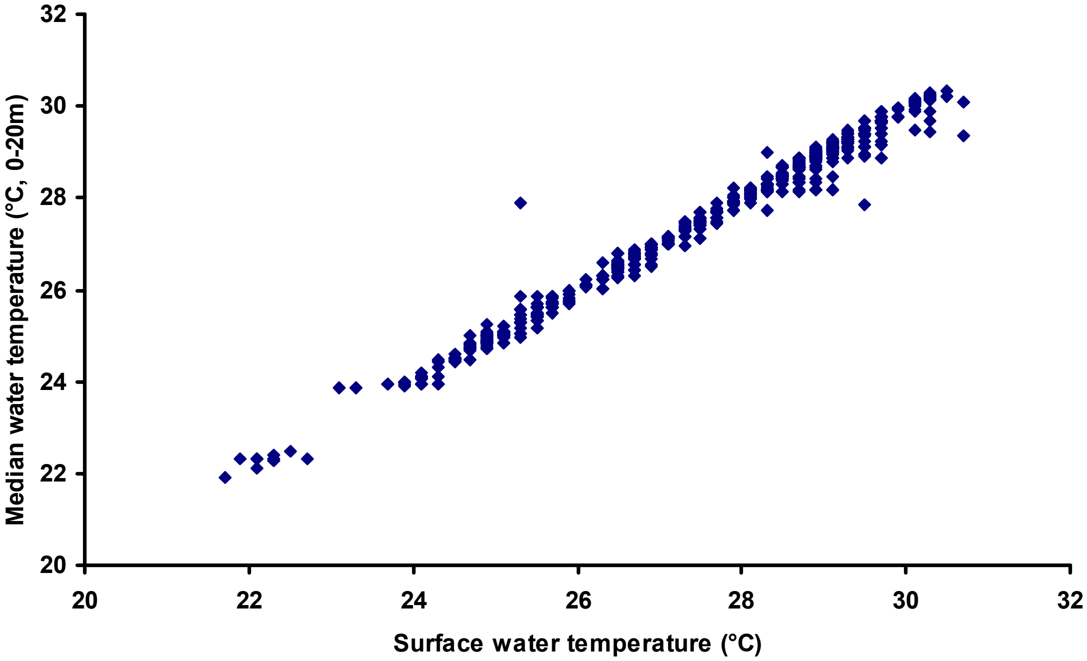


Figure 7.1.1. Difference between water temperature measured by archival tags across 0 - 1 m and the median water temperature recorded across the depths 0 - 20 m for all tags.

The matching process compared tag temperatures with an interpolated weekly SST product [optimum interpolation SST v2 (OI SST v2)] on a one-degree grid centred along a strip of longitude based on the daily longitude estimate derived from light-based geolocation. Errors associated with longitude estimation [based on those calculated in Itoh et al. (2003) and Teo et al. (2004)] and those associated with sensor error [± 0.5°C associated with OI SST v2 SSTs (Reynolds et al. 2002) and ± 0.2°C associated with the temperature sensor of the tag] were incorporated into the matching process. This resulted in the matching process searching across a strip ± 1° either side of the estimated longitude and ± 0.7°C around the calculated median SST. Due to the spatial resolution of the OI SST v2 data, the strip of longitudes searched either included the pixel in which the geolocation derived longitude lay and the closest adjacent pixel (resulting in a total of 2° of longitude included) or if the estimated longitude was exactly in the centre of a pixel then both adjacent pixels were included (resulting in a total of 3° of longitude included). No hemispheric limitation was placed on the SST matching process resulting in all SSTs between 90°N and 90°S being included in analyses.

7.1.2.6. Filtering of sea surface temperature derived positions

Initially, all latitudes at which tag SSTs matched satellite SSTs along the longitude strip were considered equally likely candidates for the latitude of the true location of an individual. In an effort to further refine the SST matching process, candidate latitudes were subjected to a movement filter. This involved determining if an individual could have reached a candidate position from any of the previous day's positions, starting with the position of release. An ellipse was generated for each candidate position determined by a 1° uncertainty in the estimate of longitude (as described above) and a 3° uncertainty in the estimate of latitude (based on error calculations around latitude estimates presented in Schaefer and Fuller (2002), Itoh et al. (2003) and Teo et al. (2004)]. If the distance between the ellipse around the previous days position and the ellipse around the current day's position was less than 1°, identified as the maximum daily swimming distance [based on daily speeds as derived from acoustic tracking studies (Carey 1992; Dagorn et al. 2000)], the position was accepted and used in the following day's calculations. The process was repeated for every day that longitude data estimates and candidate latitudes were available. If a candidate latitude was not available for a given day (due to either missing or poor longitude estimates or a lack of temperature matches) the maximum swimming distance was doubled to 2°. This was continued up to a maximum of ten days. If the recapture position of the fish was known and light data were available to the day of recapture, the filtering process was repeated backwards in an effort to further refine estimates with an exact known position. Remaining candidate latitudes were used to generate a density plot of likely positions in 1° grid squares for each day at liberty.

7.1.2.7. Comparison with position estimates as derived using Kalman filter analysis of light-based geolocation data

Latitude and longitude estimates as derived from light-based geolocation were analyzed using a modified version of a state-space extended Kalman filter statistical model to produce a most probable track for each tag at liberty. Details of the methodology associated with this model can be referred to in Sibert et al. (2003). A qualitative comparison of position estimates from the Kalman filter model and those derived using SST matching techniques was made in an effort to identify discrepancies in estimating positions between the two techniques.

7.1.3. Results

7.1.3.1. Tag Returns

7.1.3.1.1. Conventional tags

Of the 269 tags released, 66 (24.5 %) have been recovered to date (Figure 7.1.2.), 61 of which were recovered with recapture position information and 62 with a recapture date. Time at liberty ranged from 16 to 1,290 days with a mean of 369.6 ± 242.9 days (±SD). Full details of all returned CTs are provided in Appendix A. Distances between release and recapture positions (displacement) ranged from 9.6-1,116.0 nautical miles (nmi) with a mean displacement of 80.2 ± 192.0 nmi. Of those tags recovered 55 (90.2 %) were recaptured within 100 nmi of their release position.

Of the 66 CTs recovered, 57 were from fish injected with strontium, from which otoliths were collected from 23. Details of the analysis of these otoliths can be referred to in Farley et al. 2003.

7.1.3.1.2. Archival tags

Of the 161 ATs released between 1999 and 2001, 17 (10.6 %) have been recovered to date (Figure 7.1.3.). Time at liberty ranged from 47 to 1,441 days and the mean time at liberty was 578.0 ± 351.1 days (Appendix B). Displacement ranged 11.9-7,873.2 nmi and the mean distance displaced was 666.7 ± 1,915.1 nmi. Ten tags (76.5 % of all recovered) were recovered within 100 nmi of their release position and 14 of the 17 tags (82.4 %) were recovered within 250 nmi of their release positions. Of the tags released, the majority were released north of 18°S (97.5 %) with only four archival tags released in the southern part of the fishery (south of 18°S). Of the four tags released south of 18°S, one (25 %) has been recaptured to date.

7.1.3.1.3. Temporal variability in tag returns

Both CTs and ATs demonstrated a clear seasonality in returns, reflecting CPUE within the domestic Australian fishery (Figure 7.1.4.). Recaptures of tagged fish (both conventional and archival) occurred through out the year, but were highest in the month of September (CT: 35.5 %; AT: 35.3 %). Higher numbers of CT returns also occurred in the months of April (11.3 %), November (17.7 %) and December (14.5 %). One AT was recaptured in November 1999, one month after release and eight CTs were recaptured one month after release in 2001. The highest numbers of both CT and AT returns occurred in 2002 (Figure 7.1.5.), the year after the final release of tags and at a time when the highest number of tags were present within the fishery. Prior to 2002, six ATs (35.3 % of recaptures) and 11 CTs (17.7 %) had been recaptured.

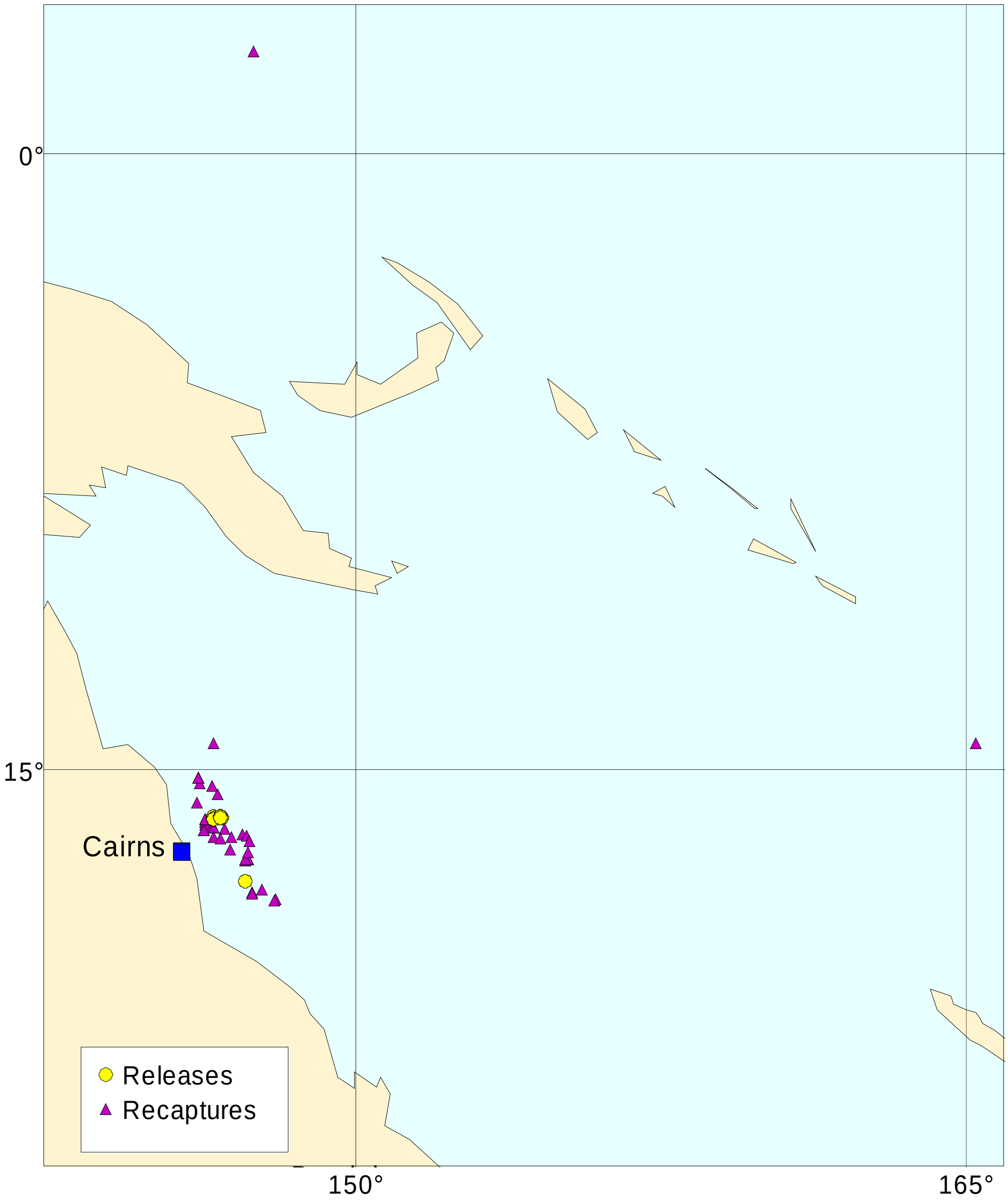


Figure 7.1.2. Release and recapture positions of conventional tags deployed on bigeye tuna in the Coral Sea.

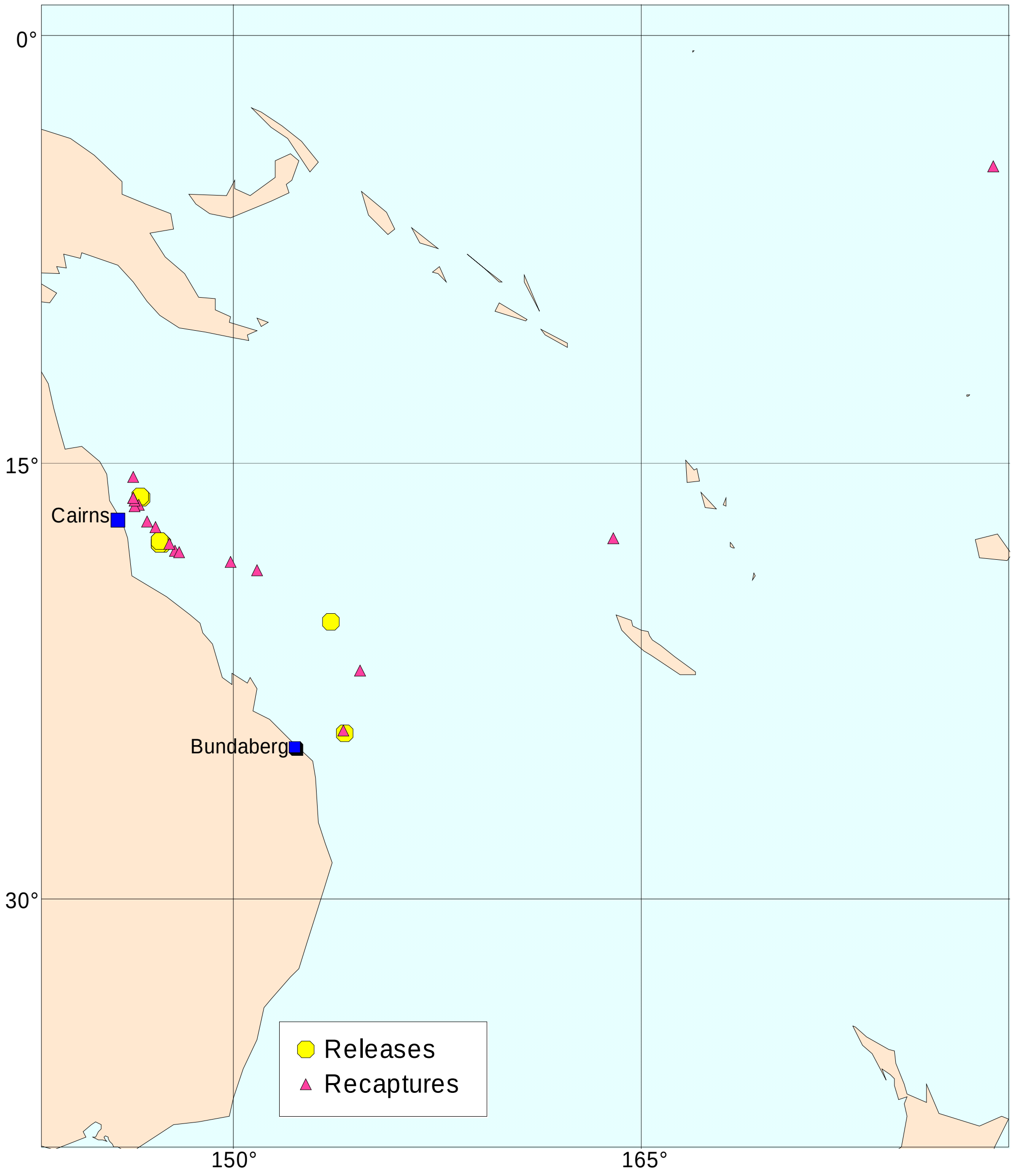


Figure 7.1.3. Release and recapture positions for archival tags deployed on bigeye tuna in the Coral Sea.

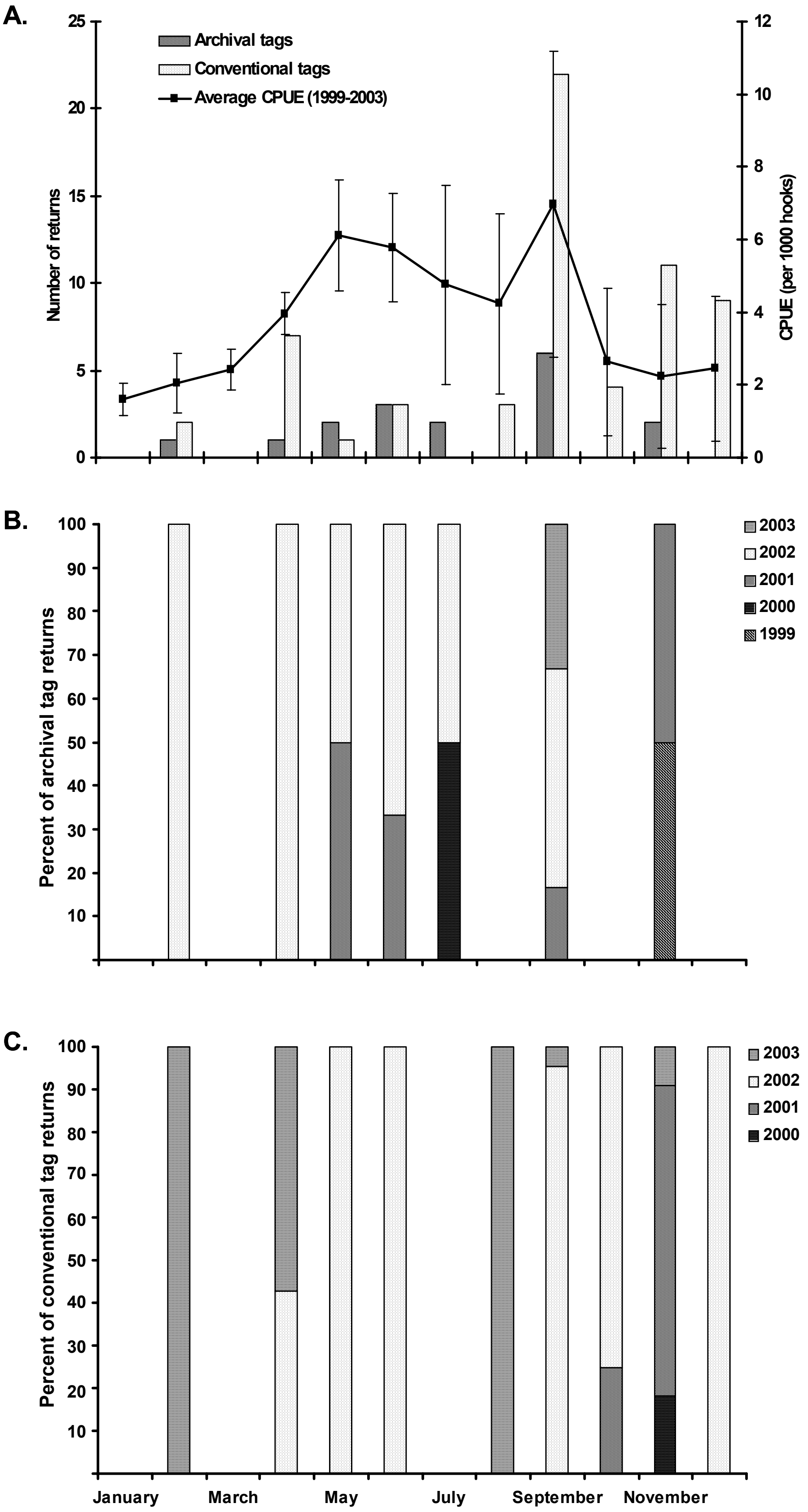


Figure 7.1.4. Conventional and archival tag returns (a) across months in relation to average CPUE for 1999-2003; (b) and (c) per year.

7.1.3.2. Longitude calculation and longitudinal movement

Of the 17 ATs recovered, a total of 3,482 days of light data were retrieved from 14 (Table 7.1.1.), with data unable to be retrieved from three due to tag failure. Of those tags from which data could be retrieved, data for the complete period at liberty were only available for four tags, with either sensor failure or tag failure occurring in all other tags (Table 7.1.1.).

A total of 3, 236 estimates of longitude were calculated using light-based geolocation techniques, representing 45.5 % days of the total 7,105 days tags were at liberty and 92.9 % of days for which light data were available(Table 7.1.1.). Maximum displacement in longitude (difference between release longitude and individual longitude estimates across time at liberty) ranged from 3.6° to 21.2°, with average displacement ranging 0.8 ± 0.6 to 13.8 ± 5.3°. Twelve of the 14 tags demonstrated an average displacement in longitude of less than 3° (range: 0.8 ± 0.6 to 2.7 ± 2.2°), suggesting the majority of tags did not make significant movements in an east-west direction during the period for which data were available. The other two tags demonstrated substantial east-west movements moving from release positions at approximately 147°E to as far as 168°E (98-353) and 163°E (99-213; Figure 7.1.5.). Both bigeye, although released in different years, initiated eastward movement in the December after their release, with 99-213 initiating a second eastward movement in the December of the following year. Although the light sensors failed on both tags, recapture positions suggest 98-353 undertook at least a second eastward migration (it was caught at 164°E) and that 99-213 returned to an area of the same longitude as that of its release (Appendix B).

One AT recovered, but from which no data were able to be retrieved, was caught at 178°E and a CT released as part of this project was recaptured at 165°E, demonstrating that these bigeye had also undertaken at least one significant eastward movement during their time at liberty. There is some indication that a number of other bigeye tagged in the western Coral Sea also initiated similar east-west movements or east-west movements of a smaller scale (Figure 7.1.5.). One tag (98-363) initiated an eastward movement, moving into an area between 150°E and 155°E what appeared to be three times, with two of these eastward movements occurring in December. Two more tags also appeared to move beyond 155°E (98-372, 99-243), again in December, however, the extent of their movement could not be confirmed due to tag failure.

The error associated with light-based longitude estimates was calculated from the difference between the release position (recorded from the tagging vessel's GPS) and the longitude estimate for the first ten days after release (Figure 7.1.6.) and for those ATs for which light data were available, the last ten days before recapture. Differences between release positions and the calculated longitude for the day of release ranged from 0.03 to 1.6° (mean±SD: 0.3 ± 0.4; n = 13) and those for the second day of release ranged 0.04 to 4.0° (0.9 ± 0.7; n = 14). Of the four tags for which light data were available on recapture, differences between recapture positions and the calculated longitude for the day of recapture (Figure 7.1.6.) ranged 0.3 to 2.5° (1.4 ± 1.5; n = 2). Differences between recapture positions and the day before recapture ranged 0.1 to 1.2° (0.5 ± 0.5; n = 4).

Table 7.1.1. Details of light data, longitude estimates and latitude estimates using sea surface temperature (SST) matching and filtering methods for all archival tags deployed in the Coral Sea 1999-2001.

Tag	DAL	Days of light data	Days of median ST (0-20m)	Light-based longitude estimates	SST-matched latitude estimates	One-way filtered latitude estimates	Two-way filtered latitude estimates
98-347	934	277	277	274	5,315	2,370	–
98-353	874	218	253	198	5,672	1,110	–
98-363	758	522	519	519	14,060	10,120	–
98-372	969	84	92	80	1,736	781	–
98-463	281	60	58	58	978	497	262
98-479	47	47	47	46	711	313	–
99-190	378	378	370	378	6,048	2,973	2,746
99-213	697	436	338	436	12,459	3,759	–
99-216	351	205	202	204	7,041	4,840	–
99-224	254	254	242	252	7,381	5,145	3,717
99-237	636	224	219	224	6,991	5,125	–
99-243	224	224	224	222	4,257	946	–
99-262	350	267	243	244	5,533	3,899	–
00-112	352	286	280	101	3,752	1,902	–
Total	**7,105**	**3,482**	**3,364**	**3,236**	**81,934**	**48,780 (8,615)^**	**6,725**

DAL: days at liberty
^: total for tags for which the two-way filter could be applied

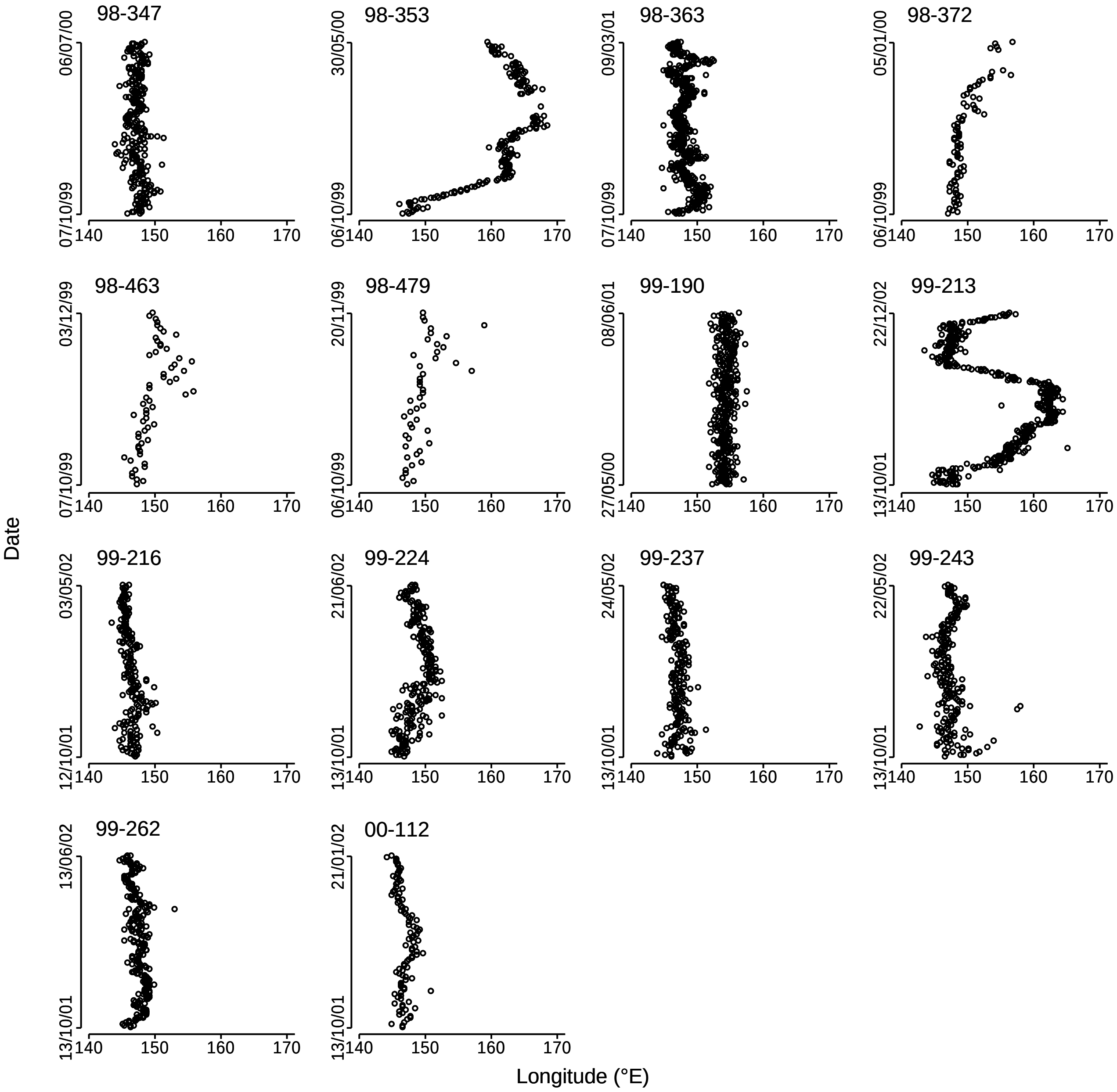


Figure 7.1.5. Longitude estimates derived from light-based analysis for all tags deployed in the Coral Sea 1999-2001.

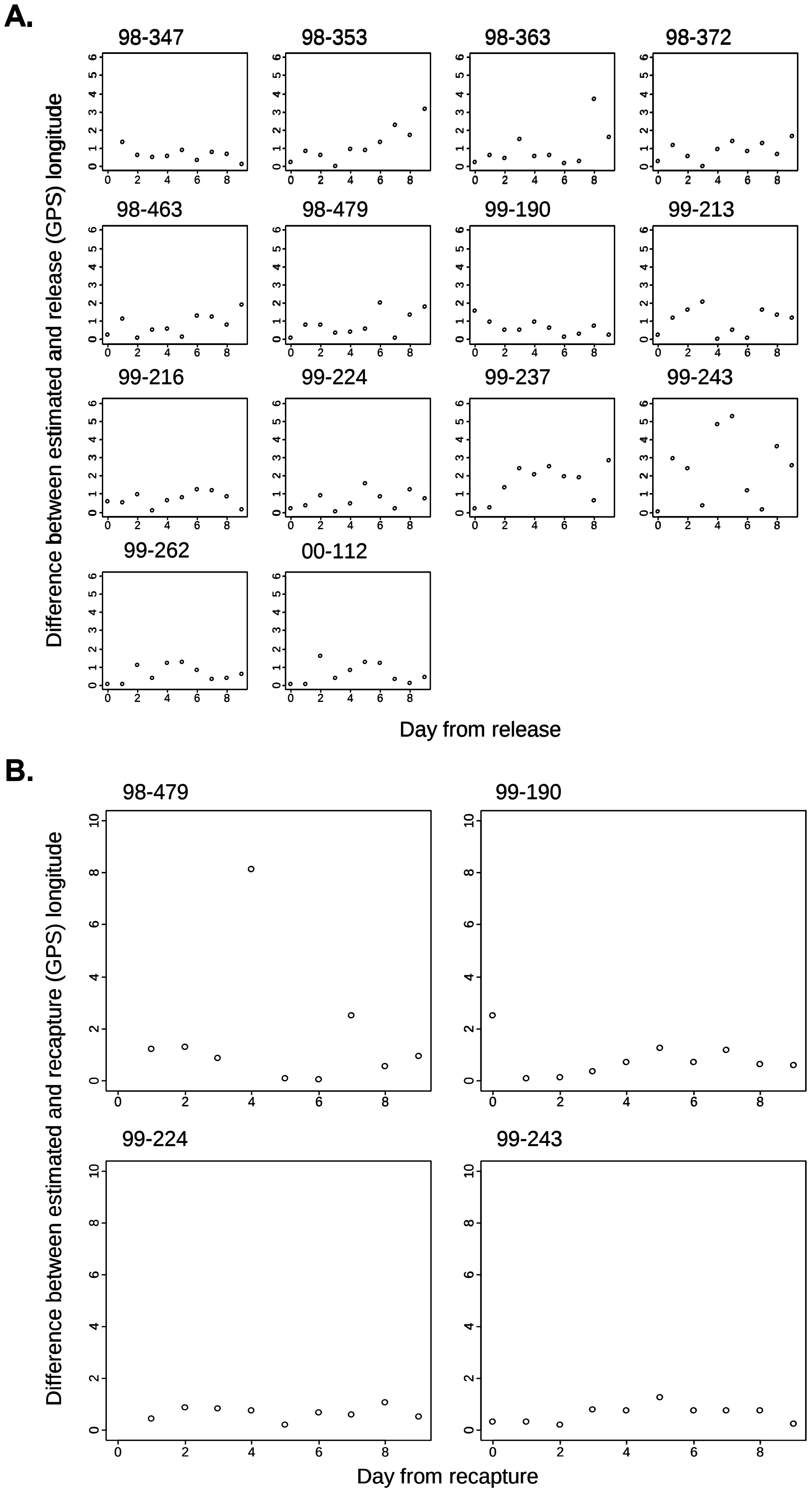


Figure 7.1.6. Difference between the (a) release and (b) recapture longitudes (as derived by GPS) and light-based longitude estimates derived from archival tags for the first and last ten days at liberty of archival tags released in the Coral Sea.

7.1.3.3. SST-based latitudes

Depth and water temperature data were available from all 14 tags for a total of 3,373 days. Of these data, a median water temperature for the upper 20 m was able to be calculated for 3,364 days (99.7 % of all days available; Table 7.1.1.). Matching between tag and satellite surface water temperatures did not result in single point estimates of latitude due to the low temperature gradient of surface waters throughout the tropics (resulting in the same water temperature occurring across large areas). As a consequence, for any given longitude estimate a number of latitudes could be considered as candidates for a tags position on any given day. A total of 81,934 candidate latitudes were calculated representing matches between remotely sensed and in situ SSTs for 3,236 light based longitude estimates. After application of the movement filter this total was reduced to 48,780 candidate latitudes (Table 7.1.1.). During the summer months, when tropical sea surface temperatures are highest and thermal gradients are lowest, candidate latitudes were contiguous along each longitudinal strip, and in some tags extended from the release area across the equator and into the Northern Hemisphere (Figure 7.1.7.). During winter months when surface water temperatures are lower and thermal gradients are highest candidate latitudes often resulted in two discontinuous bands of possible positions either side of the equator (Figure 7.1.7.).

For those tags for which light data were available for the total time at liberty, the ability to run the movement filter backwards improved latitude estimation, reducing the number of candidate latitudes, particularly those associated with a gradual drift in SST matches across hemispheres (Table 7.1.1.; Figure 7.1.7.). This also improved the error (the difference between the recapture position as derived from the tagging vessel's GPS and the latitudes estimated) around latitude estimates with mean overall error for latitude estimates the day before recapture reduced from 5.1 ± 13.0° to 0.4 ± 0.4° and those for two days before recapture reduced from 6.9 ± 14.2° to 0.8 ± 0.6° (Figure 7.1.8.). Mean error estimates for all tags calculated from the difference between the release position (recorded from the tagging vessel's GPS) and latitude estimates for the first ten days after release (Figure 7.1.9.) ranged from 0.0 ± 0.0° to 0.1 ± 0.0° (n=4) on the day after release and 0.5 ± 0.0° to 1.0 ± 0.6° (n=9) for the day two days after release.

7.1.3.4. Final position estimates and comparisons with Kalman filter analysis of light based position estimates

Density plots of position estimates produced by the use of light-based longitude estimates and filtered SST matched latitudes demonstrated in all tags (except those that moved east) that the highest frequency of matches were located in the area of release (either the north-west Coral Sea or southern Coral Sea), indicating that bigeye were largely resident in the Coral Sea during their time at liberty (Figure 7.1.10, Appendix C). Latitude estimates for the two tags that demonstrated east-west movements suggest possible movements north, particularly in those areas furthest east.

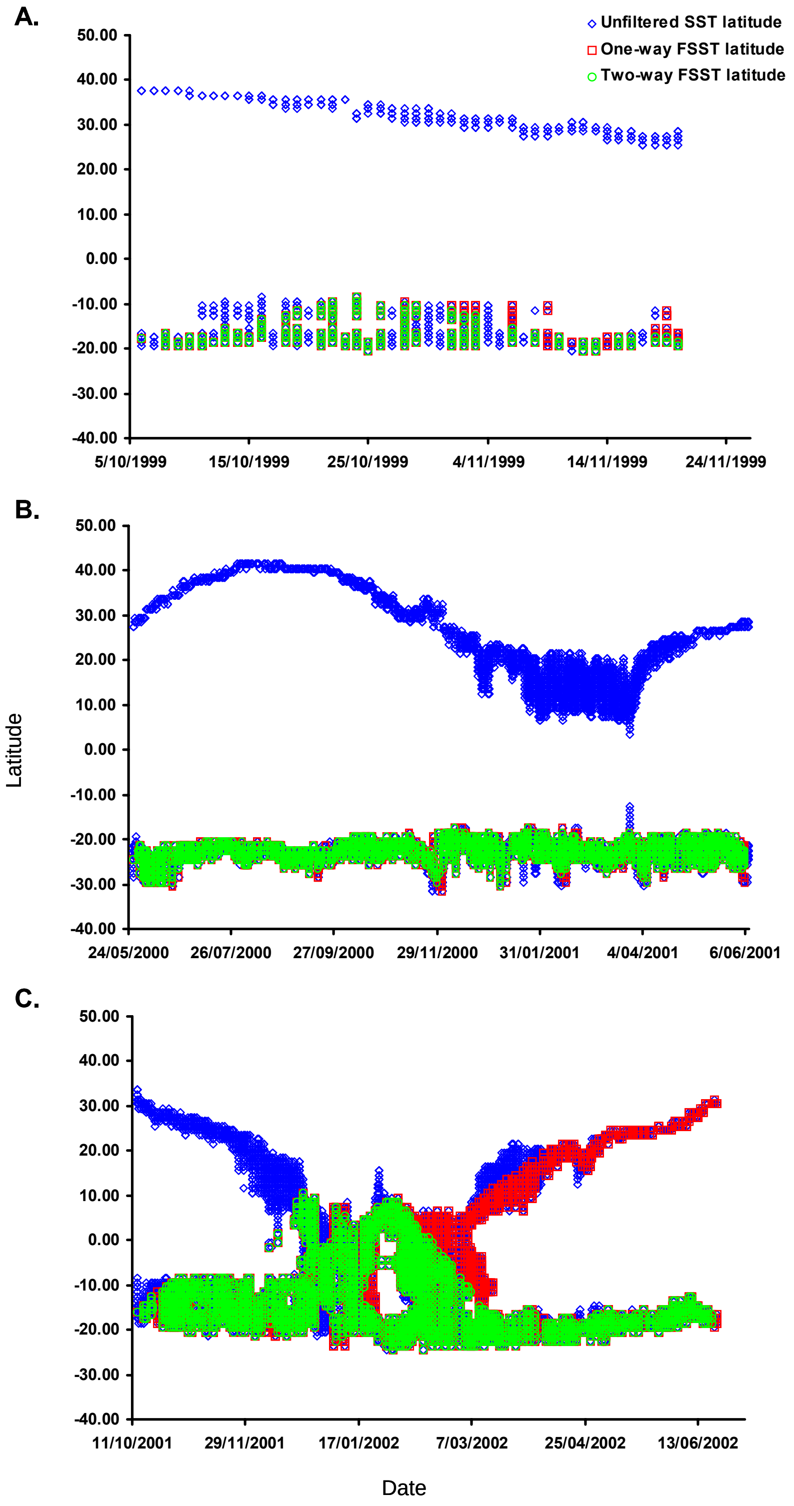


Figure 7.1.7. Latitude estimates derived from sea surface temperature (SST) matching without a movement filter, SST matching with a one-way movement filter using the known release position (one-way FSST) and SST matching with a two-way movement filter using both the known release and recapture positions (two-way FSST) for the archival tags (a) 98-479; (b) 99-190 and (c) 99-224.

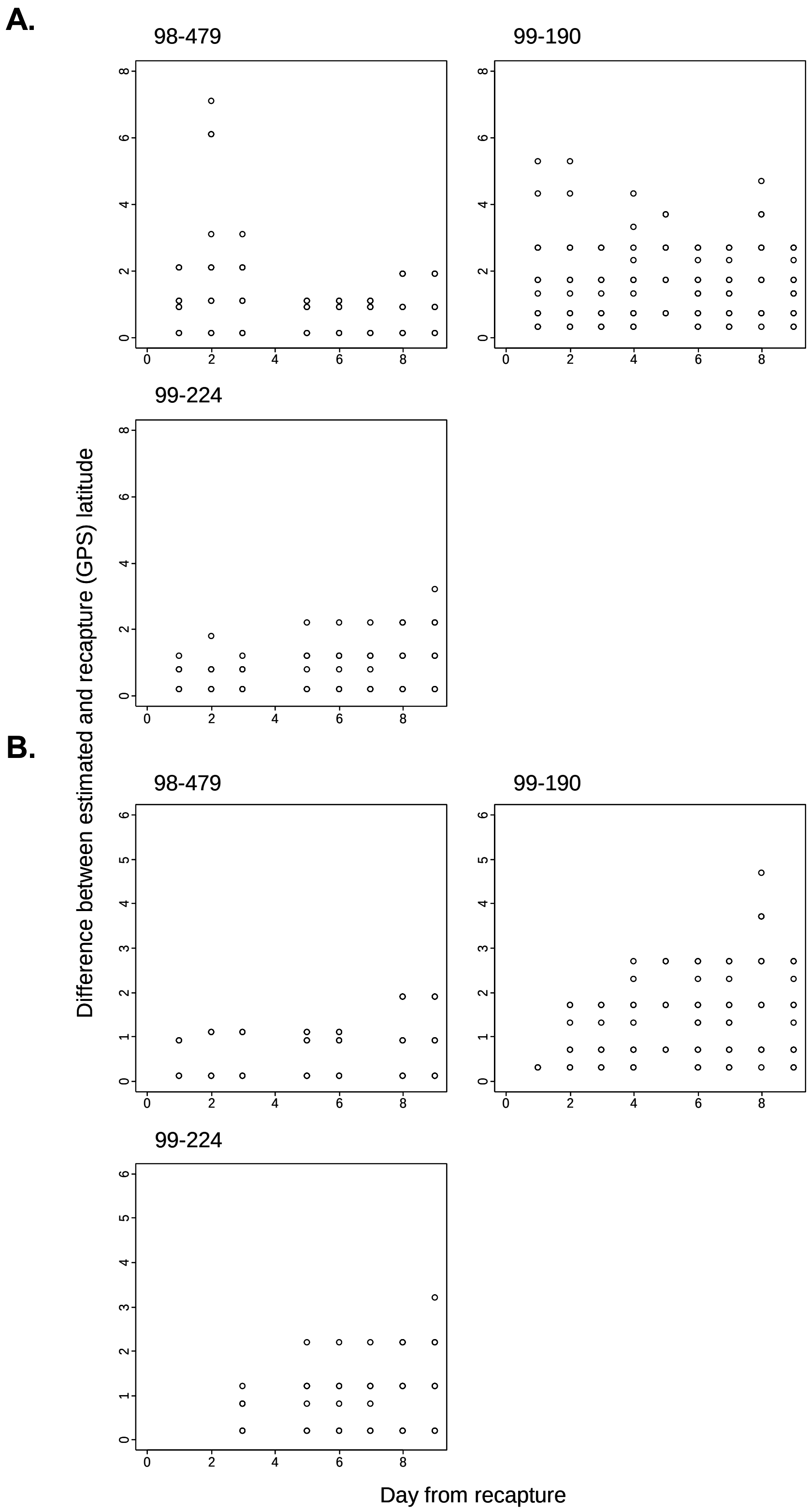


Figure 7.1.8. Difference between the recapture latitudes (as derived by GPS) and SST matched latitudes for the last ten days at liberty of archival tags released in the Coral Sea when using a movement filter (a) in only one direction (forwards) and (b) in two directions (forwards and backwards).

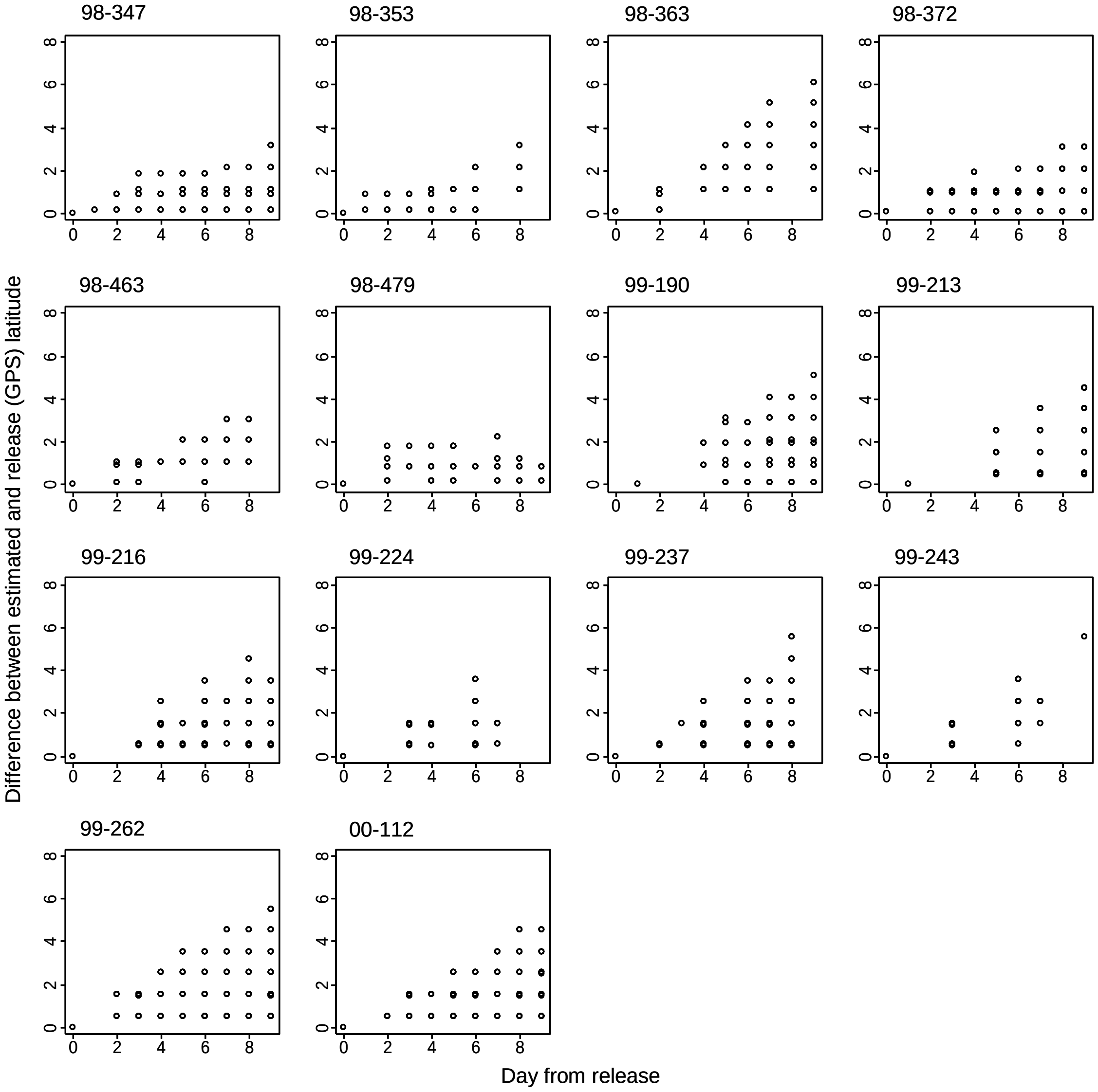


Figure 7.1.9. Difference between the release latitude (as derived by GPS) and SST matched latitude estimates for the first ten days at liberty of archival tags released in the Coral Sea.

Comparisons with those position estimates derived from a modified version of a state-space extended Kalman filter statistical model support the indication that bigeye were largely resident within the Coral Sea (Figure 7.1.11.). These results also demonstrated that the two tags 98-353 and 99-213 made substantial east-west movements. However, the additional northward movement demonstrated by filtered SST matched latitude estimation, while evident in those position estimates derived from the Kalman filter for 98-353 was not evident for 99-213.

7.1.4. Discussion

The analysis of tag data presented in this chapter has provided valuable information on the movement patterns of bigeye tuna and has provided precursory insights into the spatial interactions of this species within the ET&BF, information important for the more detailed investigations in subsequent chapters.

7.1.4.1. Recapture rates – conventional vs. archival tags

Return rates for tags released on bigeye tuna as part of this study differed substantially between the two tag types, with CT returns more than twice that of AT returns. Tag return rates reported from similar studies involving the simultaneous release of CTs and ATs have demonstrated differing patterns, with bigeye released near Hawai'i demonstrating similar tag returns between ATs and CTs (Schaefer & Fuller 2002; Musyl et al. 2003). Tag returns from southern bluefin tuna (*Thunnus maccoyii*; SBT) tagged with ATs and CTs have demonstrated an opposing pattern with higher return rates of ATs than those of CTs (CSIRO unpublished data).

The discrepancy in return rates between these studies may be a consequence of a number of possible factors such as (1) higher rates of mortality in bigeye tuna in this study as a result of the methodology used to deploy ATs; (2) a higher rate of post-tagging infection in the bigeye tuna released with ATs in this study (3) higher compliancy rates of reporting and returning of ATs throughout the Hawai'ian and SBT fishery or (4) differences in sample sizes and sampling effort.

Although it is unknown to what extent methodology (published details account a similar methodology to that used in this study) and experience differed between this study and that conducted in the waters of Hawai'i, both tagging methodology and the experience of personnel have been standardised across the bigeye and SBT tagging programs undertaken by the CSIRO. However, environmental conditions at the time of tagging are difficult to standardise across programs, particularly in differing geographic regions and differences in survival rates may occur as a result. It is possible that the need to handle individuals on deck when deploying tags may have resulted in a higher susceptibility of bigeye to overheating due to higher air temperatures in the sub-tropics in comparison to more temperate air temperatures in SBT tagging areas and may have resulted in the higher rates of returns observed in SBT. However, there was little evidence of this at the time of tagging; all fish tagged appeared lively and swam strongly away from the vessel after release. Further, the higher temperatures of sub-tropical waters may result in a higher susceptibility to post-release infection in bigeye tagged with ATs. It could be expected that incisions generated by the insertion of smaller CTs would heal more rapidly than the larger and deeper incisions resulting from insertion of ATs. In an effort to reduce this possibility of infection we flushed each incision liberally with a broad-spectrum antibiotic before insertion of the tag (therefore maximizing the possibility of absorption). Reports from processors on the state of fish with ATs when recaptured suggest little evidence of infection in individuals, although incisions were reported to remain partially open around the trailing stalk. Of those fish released in the waters surrounding Hawai'i, similar cases of failure of incisions to completely close were reported (Schaefer & Fuller 2002). Additionally, a number of individuals were reported to present signs of trans-intestinal expulsion of ATs, suggesting significant irritation of ATs in those cases. Without an ability to recover deceased fish in order to determine cause of death it is difficult to resolve these possibilities.

Archival tagging programs conducted by the CSIRO involving SBT have been in operation since the early 1990's and have involved significant communication programs detailing the deployment of tags and the rewards involved across the nations involved in this fishery. Although substantial effort was put into informing those fisheries catching bigeye in the WPO of the deployment of ATs on bigeye and the rewards involved, the number of nations involved in this fishery, the significant increased liaison effort required and the smaller time period for awareness programs could have resulted in lower levels of reporting compliancy.

Return rates of tags are dependent on both the number of tags deployed and the amount of effort associated with their recapture. Substantial differences exist in both the number of tags deployed and the amount of effort associated with each of the bigeye studies (this study; Schaefer & Fuller 2002; Musyl et al. 2003) and those investigating SBT (CSIRO unpublished data). Although resolution of these differences is beyond the scope of this study, the potential for differences in tag returns associated with these issues should be noted.

Return rates for both CTs and ATs deployed in this study were higher than those reported from the Coral Sea region in the early 1990's (6.1 %; Hampton & Gunn 1998). Whether this reflects higher exploitation rates of bigeye or depletion of stocks within the Coral Sea region is difficult to determine due to differences in sample sizes between the two studies and substantive temporal changes in effort and targeting in the Coral Sea.

7.1.4.2. Temporal variability in recapture rates and how this relates to the movement patterns of bigeye tuna throughout the western Pacific Ocean

Returns of both types of tag were highly seasonal, reflecting CPUE within the Australian domestic fishery and supporting the findings in Hampton & Gunn (1998) of seasonally variable catchability. The seasonally variable catchability observed in Hampton & Gunn (1998) was hypothesized to be the result of two possible occurrences: (1) long residence times for the majority of fish with fish demonstrating seasonal changes in behaviour, resulting in seasonal changes in their availability to the fishery, or (2) a possible cyclic migration pattern with fish returning to the Coral Sea each year.

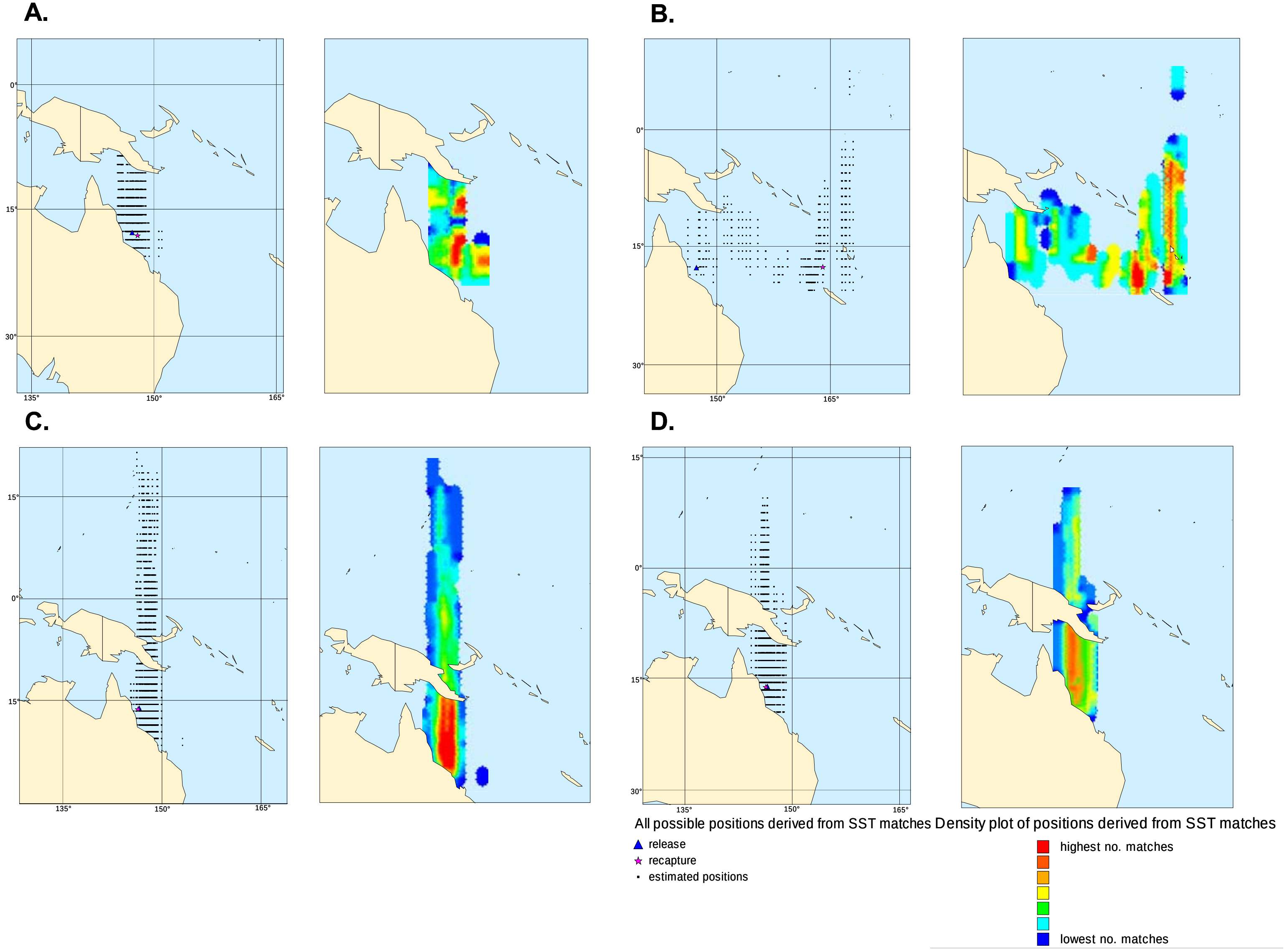


Figure 7.1.10. Position estimates and densities of position estimates for (a) 98-347; (b) 98-353; (c) 99-262; (d) 00-112.

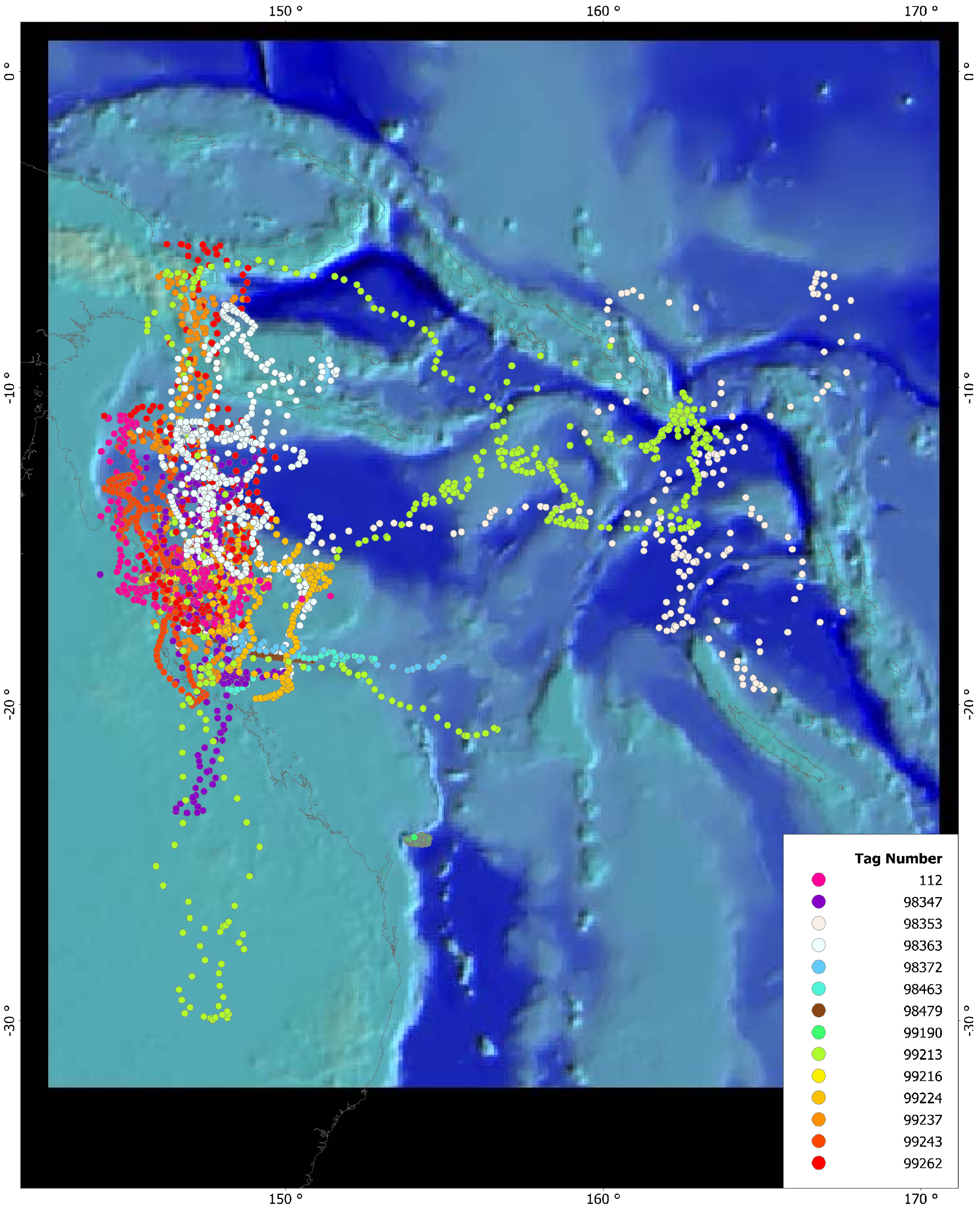


Figure 7.1.11. Estimates of position for bigeye tuna in the western Pacific Ocean as determined by analysis of geolocation data from archival tags using a modified state-space Kalman filter model.

The majority of fish from which AT and CTs were returned appeared to largely be resident within the north-western Coral Sea, with only five (three ATs and two CTs) of the 83 returned able to be confirmed as moving beyond these waters. Further, the recapture of one AT released in the southern part of the fishery in close proximity to its release position and the apparent lack of movement of this fish outside of this area, coupled with a lack of returns of northern released fish in the southern part of the fishery and *vice versa* suggests that there is also substantial residency even within the ET&BF.

However, there is some difficulty in determining the proportion of the bigeye that demonstrated movement outside of the north-west Coral Sea region. At least two ATs (98-372 and 98-479) were observed to initiate movement in an easterly direction; however, calculation of the extent of these movements was prevented by tag failure. If these bigeye did undertake easterly movements similar to that recorded by archival tags 98-353, 98-357 and 99-213, the number of migrating individuals may have numbered five ATs (36 %). Whether this is a true reflection of the proportion of individuals within the population undertaking long-distance movements is difficult to determine without further tagging programs within the region.

The majority of long-distance movements observed in bigeye tagged as part of this study appear to be cyclical, suggesting a return of individuals to populations in the area of the ET&BF and a lack of gene flow outside this area. However, whether the movement patterns of those CTs and ATs caught in areas north of the release areas were also cyclical in nature cannot be confirmed either due to failure of ATs or recapture data being derived from CTs. Without an accurate assessment of the proportion of bigeye in the region undertaking cyclical movement patterns, it is difficult to assess the effects of such movements of individuals into and out of the fishery on catch rates and any temporal variability in these. Genetic studies carried out to date have provided little evidence of genetic differentiation of bigeye tuna throughout the Pacific (Grewe & Hampton 1998; Chow et al. 2000), suggesting some mixing of individuals between populations and therefore the possibility that some of the large-scale movements undertaken by bigeye may not all be cyclical in nature.

Bigeye tagged in other parts of the Pacific largely demonstrate residency to those areas of release (Itano & Holland 2000; Schaefer & Fuller 2002; Sibert et al. 2003), with behaviour involving movement away from the greater release area virtually absent among recaptures. In such areas bigeye have been observed to associate around both artificial and natural features in the ocean such as fish aggregation devices (FADs), weather buoys, seamounts and offshore island features such as reefs (Dagorn et al. 2000; Schaefer & Fuller2002; Musyl et al. 2003; Sibert et al. 2003). While little is known about the fine-scale distribution of bigeye along the AFZ, the distribution of the fleet appears to be associated with topographical features such as the edge of the Great Barrier Reef (GBR) and ocean frontal zones. Topographical features such as seamounts and oceanic features such as ocean frontal zones have been associated with enhanced prey density (Koslow et al. 2000; Fock et al. 2002; Seki et al. 2002) and in areas of low productivity such as the eastern AFZ (Ward & Elscot 2000), serve as important foraging areas for higher order predators such as tuna (Fiedler & Bernard 1987; Seki et al. 2002). It is likely that features such as ocean frontal zones, seamounts and other bathymetric features along the eastern AFZ serve as focal areas for species such as bigeye and if they provide a consistent forage resource, may serve as broad areas of residence.

7.1.4.3. Why migrate?

The trigger for a change in behaviour that results in some fish moving out of the north-west Coral Sea is unclear, but may be related to the end of spawning possibly combined with changes in SST, wind and mixed layer depth. Displacements of adult yellowfin tuna (*Thunnus albacares*) have been associated with seasonal and southerly (meridional) displacement of water temperatures both at the surface and at depth (Zagaglia et al. 2004), thought to create favourable “pathways” for movements.

Ripe female bigeye tuna have been caught in the ET&BF across the period of August to December (Farley et al. 2003) suggesting spawning across these months. All fish that undertook movements out of the broader release area, initiated their movement in the month of December, possibly after the completion of spawning. One hypothesis that may be put forward in explanation of only some animals undertaking large-scale movements is that only the mature portion of the population undertake long distance movements (largely cyclical in nature), with juveniles resident in the ET&BF year round.

Definitions of size at maturity are varied among bigeye tuna, with minimum sizes varying from 64 cm (Hisada 1973) up to 125 cm (McPherson 1992) in the north-west Coral Sea. Fork lengths of bigeye at 50 % maturity during the spawning season in the north western Coral Sea have been reported as 102 cm in females and 87 cm in males with 90 % maturity occurring at 122 cm in females and 120 cm in males (Farley et al. 2003). Of the bigeye recaptured, two individuals with ATs and 16 with CTs were equal to or greater than 87 cm in length and only one with CTs was of 102 cm in length on release. At the time of recapture, all individuals with ATs and 49 with CTs were equal to or greater than 87 cm in length and six (ATs) and 42 (CT) were of 102 cm in length. Although sex allocation of individuals was not made, at the time of recapture at least five individuals with ATs and at least 25 individuals with CTs would have been sexually mature if all individuals were male. If we assume that all were female, at least three with ATs and 21 with CTs would have been sexually mature, substantially more individuals in either case than those with CTs documented to undertake large-scale migrations and comparable to the number of individuals with ATs documented to undertake large-scale migrations. However, if large-scale movements are cyclical in nature, only those individuals with CTs caught on their outward or inward journey would be positively identified as undertaking movements to areas outside the greater release area. As a result, it is highly likely that the number of individuals documented as undertaking such movements is underestimated. All individuals for which large-scale migrations were positively identified ranged 84-89 cm in length on release and all are likely to have been greater than 120 cm on recapture (two were 121 and 129 cm in length, the remainder taking into account time at liberty and average growth rates would have been of a similar length).

The information on movement provided by the analysis of light-based geolocation data presented here suggest bigeye tuna display a range of movement behaviours; residency, cyclical migration and dispersion. Other fish species such as Atlantic cod have been observed to display a similar range of movement behaviours, with the majority of cod resident to particular areas and a smaller number dispersing and undertaking cyclical movements between feeding, overwintering and spawning grounds (Robichaud and Rose 2004). The incidence of migrators and dispersers amongst groups of cod was associated with population size and was dependent on the carrying capacity of the area in which the cod were tagged. Atlantic bluefin tuna (*Thunnus thynnus*) have been observed to demonstrate a range of movement behaviours also, with fish tagged in the waters of North Carolina demonstrating cyclical migration to either spawning areas in the western Atlantic or the

Mediterranean or to non-spawning areas in the western Atlantic and dispersion to the Mediterranean (Block et al. 2001). The reasons behind large scale movements in bigeye are unclear, but may also be associated with movement between spawning and foraging grounds and the proportion of migrators may also be associated with the carrying capacity of the north-west Coral Sea. A need to maximize fitness and reduce competition for resources in a seasonal environment may result in a proportion of the population undertaking such large scale movements. Further collection of data on movements in bigeye via archival tagging coupled with the collection of size and sex information is required to resolve this question.

7.1.4.4. Estimating position using light-based longitudes and filtered SST matched latitudes

Combining light-based estimates of longitude with SST-matched estimates of latitude coupled with a movement filter substantially improved estimates of light-based geolocation positions for bigeye tuna. Additionally, the ability to run movement filters with the inclusion of both release and recapture positions improved position estimates further. However, estimates of position were restricted to broad-scale areas of multiple probable locations rather than point estimates of location at any given time due to the nature of the SST matching process and the relatively low thermal gradient throughout the Coral Sea region, particularly throughout the summer months. This resulted in a spread of latitude estimates along each longitude estimate, inhibiting the ability to estimate any fine-scale movement patterns within the waters encountered by bigeye tuna within the WPO. While the density of position estimates describes areas of high probability of occurrence, the occurrence of individuals across all position estimates cannot be ruled out.

Using SST at low latitudes to derive precise position estimates is problematic. Near the equator, temperatures within the bounds of the errors placed on matching in this study can be present across a wide range of latitudes. The inter-tropical convergence zone (ITCZ), where north-east and south-east trade winds converge at the equatorial area, is situated at about 10°N in July and about 5°S during January when it moves further south over continental land masses such as Australia (Anon 2004). Sea surface temperatures are warmer under the ITCZ because of weak winds and high relative humidity resulting in reduced evaporative cooling of the sea surface (Farrar & Weller 2004). As a result there is a broad warming of the Coral Sea into areas further south than 5°S. This results in a broadening of potential latitude candidates for position estimates and therefore a broadening of the potential area in which a fish may be located. Studies located in higher latitudes do not face as substantial a problem in determining potential locations due to steeper latitudinal gradients in sea surface temperatures which serve to reduce the number of potential candidates for latitude estimates and thereby the variability in SST latitude estimates. In a similar study conducted on Pacific bluefin tuna (*Thunnus orientalis*), unique SST-based latitudes were able to be calculated on 80 % of all days where tuna remained in latitudes higher than 29° N (Itoh et al. 2003). In comparison, unique SST-based latitudes were only able to be calculated on 0.04 % (17 days) of all days bigeye recaptured in this study were at liberty.

The accuracy of light-based longitudes and filtered SST matched latitudes was examined by comparing the known release positions (from the on-board GPS of each tagging vessel) with those estimates for the first ten days of release. Estimates of error for the first day of release were comparable to those calculated using similar comparisons to known locations in other geolocation studies. Comparisons between light-based geolocation estimates and known recapture positions of bigeye tagged in the waters of Hawai'i were calculated as 0.2° and 0.3° for latitude and 0.2° and

0.1° for longitude (Schaefer & Fuller 2002). Direct comparisons between position estimates derived from light-based longitude estimates and SST-matched latitude estimates and Argos-based satellite positions in a double tagging experiment on two species of shark resulted in the calculation of root mean square errors of 0.9° and 0.6° for longitude and 1.5° and 1.2° for latitude (Teo et al. 2004). In the same study, light-based longitude estimates and SST-matched latitude estimates derived from both pop-up satellite tags (PSATs) and ATs deployed on Atlantic bluefin tuna were compared with Argos-based PSAT end points and GPS recapture locations, resulting in root mean square errors of 0.8° and 1.3° for light-based longitudes and 0.9° and 1.9° for SST latitudes derived from ATs and PSAT tags respectively.

The accuracy of position estimates using geolocation has been tested using several other methods such as mooring experiments and deployment of tags on fish in captivity, resulting in similar or worse error estimates than those presented in this study. Welch & Eveson (2001) placed tags on a fixed subsurface mooring at high latitudes, calculating average position errors of 30 km longitude and 44 km in latitude. In a similar mooring experiment at mid-latitudes, position errors calculated were of 0.1° to 0.3° in longitude and 0.8° to 3.5° (Musyl et al. 2003). Gunn et al. (1994) estimated errors of 0.5 ± 0.1° for longitude and 1.5 ± 0.2° for latitude around position estimates derived from tags deployed on SBT in a towed cage. Errors of 2.4 ± 0.4° and 0.5 ± 2.5°for longitude and 1.8 ± 2.0° and 1.3 ± 5.3° for latitude were determined from light data collected from two tagged Pacific bluefin tuna placed in stationary pens (Itoh et al. 2003).

Unlike other studies (e.g. Teo et al. 2004), we allowed the parameters of filtering process to run unconstrained, i.e. latitudes along the longitude strip across both hemispheres could be considered as candidates for SST matches. Unlike temperate species of tuna which are unlikely to cross the equator, constraint on the basis of hemisphere could not be considered for the movement patterns of sub-tropical species such as bigeye tuna, which has been observed to cross the equator in previous tagging studies (Hampton & Gunn 1998; Schaefer & Fuller 2002).

When the movement of those fish that made large-scale east-west movements is partitioned into areas of "residency" and "transit" (See Chapter 7.2 for a detailed description of this), the maximum longitude shift per day during transit (including incorporation of errors associated with light-based geolocation) and therefore that period of greatest movement, was estimated to be a maximum of 0.7° (approximately 75 km). This shift was similar to that calculated elsewhere [117 km/day (Schaefer & Fuller 2002) and 76 km/day (Dagorn et al. 2000), suggesting the maximum daily swimming distance limit incorporated into the movement filter used in this study was realistic.

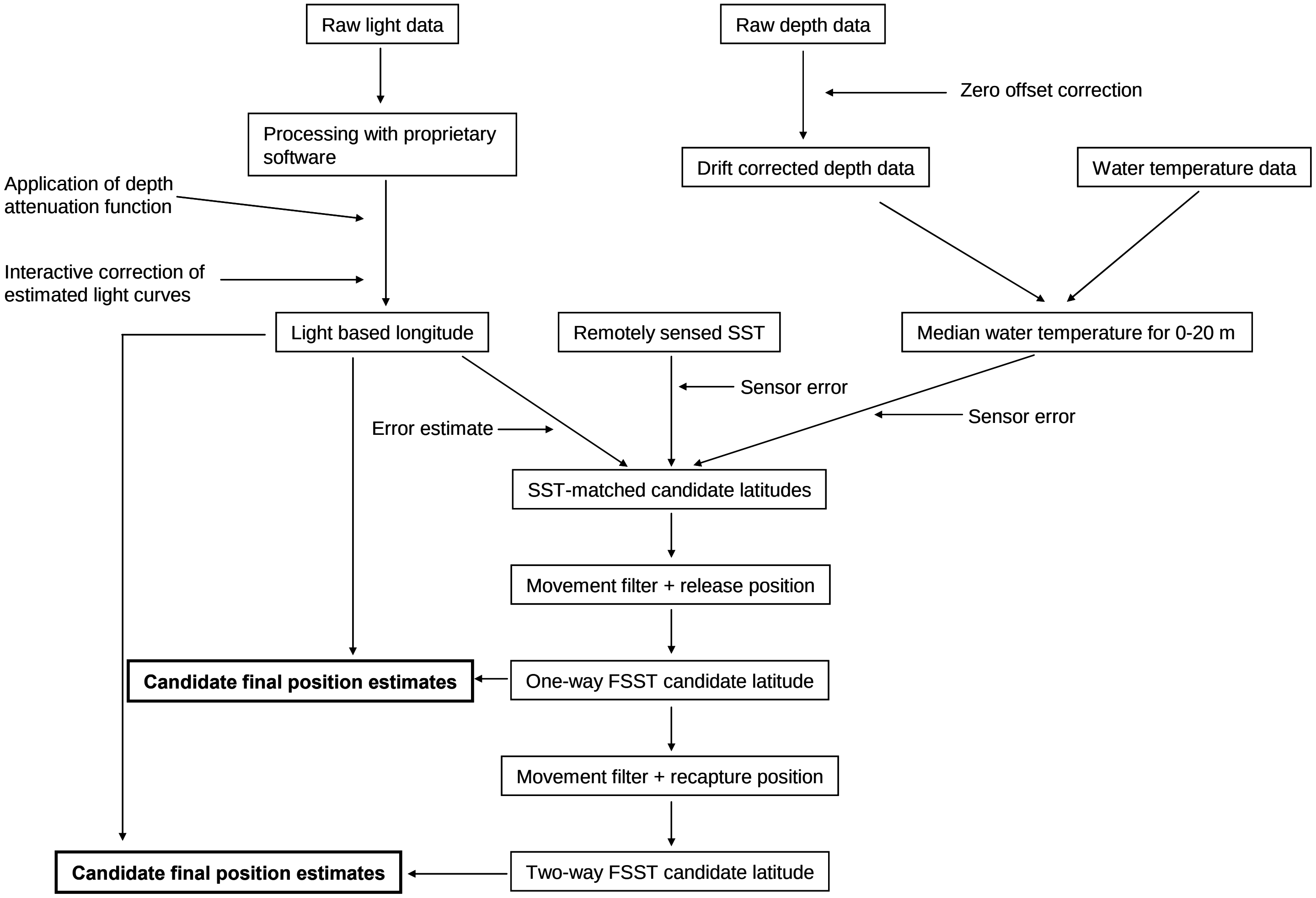
Differences between the SSTs measured by the external sensor of the tag and those remotely sensed via satellite have been identified as an important source of error when calculating SST-matched latitudes, with this effect strongest where latitudinal SST gradients are shallowest (Teo et al. 2004). These differences may be compounded by response times of the thermistor on the tag, drift in depths recorded by the tag and the effects of atmospheric and oceanographic conditions on the accuracy of remotely sensed SSTs. The tags used on bigeye in this study incorporated a temperature sensor located on the end of a stalk located external to the fishes' body. Response times reported by the manufacturer were relatively fast and in the order of 6 s. Drift in pressure sensors was recorded in almost all tags recaptured and ranged from 5-10 m up to a maximum of 15-20 m. In an effort to reduce the error caused by drift in the pressure sensors of the tag, we used the median temperature calculated across temperatures recorded between 0-20 m. Due to the well mixed nature of the top 20 m of the water column with the Coral Sea differences between water temperatures recorded between 0-1 m and the median of the top 20 m were less than 0.2°C and generally less than the error associated with the tags temperature sensor. The product we used, optimum interpolation SST v2 (OI SST v2), is an interpolated weekly SST product, which, although through interpolation on such a time scale, reduced the effect of cloud cover on estimated SSTs, combined both day and night passes thereby including heating/cooling effects at the surface related to day and night (Robinson et al. 1984; McClain et al. 1985). In an effort to overcome these errors, the OI SST v2 incorporates in-situ temperature data from observations from ships and buoys, converting the temperature of the "skin" (about a micron in depth) to a "bulk" (0.5-1 m in depth) SST, thereby correcting for day/night differences (Reynolds et al. 2002). Corrections are also incorporated into OI SST v2 for the negative temperature bias in SSTs when clouds are present.

7.1.4.5. Verification and further development of the position estimation method

Position estimates calculated after application of a modified state-space Kalman filter model on light-based latitudes and longitudes supported the findings resulting from our analysis of light-based longitudes and filtered SST-matched latitudes. One advantage of analysing position estimates with a state-space model is that it not only provides a "most likely track", it also calculates an estimate of error associated with each position estimate (Jonsen et al. 2003; Sibert et al. 2003). However, estimating latitudes at equinoxes still poses a problem and a limitation of the Kalman filter model is that it depends on the model estimates rather than the observed estimates at these times. While we were unable to determine the extent of any north-south movement of bigeye, particularly on smaller scales within the north-west Coral Sea, the Kalman filter appeared to record such movements among a number of tags. However, it is difficult to determine whether this apparent movement was related to serial correlation in the geolocation derived position estimates (each position is dependent on the calculated position from the previous day), rather than true movement. One possible way of reducing these biases and reduce the effect of the equinoxes may be to extend a similar state-space model to include SST matching. Further work investigating the sensitivity and validity of the results of differing state-space models (e.g. Kalman filter, Markov chain Monte Carlo, advection-diffusion methods) should be encouraged.

Rather than providing a point estimate of position for each day a tag was at liberty, the imprecision in the SST-matching process for geolocation in equatorial waters resulted in "clouds" of possible latitudes from which a most likely region of occupancy could be determined. This, as a result, prevents the ability to estimate the position of individual on a fine scale, and subsequently limits any fine-scale investigations examining the relationship between individuals and their environment. As tag manufacturers continue to improve light based geolocation methodology, estimates of longitude and latitude at times other than the equinoxes will also continue to improve, reducing the spatial scale at which inferences on movement can be made. However, estimating latitude at times around the equinoxes will continue to be a problem. As remote sensing and modeling of temperature-at-depth improves the ability to use temperatures other than surface temperatures, possible means of reducing the number of candidate latitudes may include matching of temperatures across a range of depths. Advances in tag technology involving a reduction in pressure sensor depth drift, faster response times in thermistors and enhanced accuracy in temperatures and depths recorded will serve to improve the accuracy in determining temperatures for matching. Similarly, advances in remotely sensing SSTs will reduce spatial scales at which matching can be made and improve accuracy in temperature matching. Where appropriate, incorporation of other environmental data such as bathymetry (Beck et al. 2002) and tidal data (Hunter et al. 2003) can also serve to further refine position estimates.

While determining the best estimate of position using ATs, particularly in equatorial waters is not a simple process (Figure 7.1.12.), this study has demonstrated that combining both SST matching and movement filters can substantially improve our ability to estimate broad-scale movements of bigeye tuna. While movements between the north-western Coral Sea and the greater WPO were evident among some bigeye tagged as part of this study, our ability to determine that proportion of the population that undertake large-scale movements is restricted. However, our results suggest a broad-scale residency of bigeye within the Coral Sea. Further, the lack of returns of northern released fish in the southern part of the fishery and *vice versa* suggests that there is also substantial residency of individuals within populations throughout the ET&BF. Further tagging studies involving deployment of tags throughout the entire ET&BF would serve to provide greater insight into the possibility of resident sub-populations throughout the ET&BF and provide information essential for the effective and sustainable management of this species.



SST: sea surface temperature

FSST: filtered sea surface temperature matched

Figure 7.1.12. Schematic diagram of methodology used to calculate position estimates.

7.2. Behaviour and habitat preferences of bigeye tuna (*Thunnus obesus*) tagged in the western Coral Sea.

K. Evans, N. P. Clear, T. Patterson and J. S. Gunn.

7.2.1. Introduction

In order to effectively manage a fisheries resource, an understanding of the dynamics and interactions of a species with the marine environment is required. Information on these dynamics and interactions are also required in understanding and predicting how changes in the marine environment on varying scales may affect particular fisheries resources (Cury 2004) and this information is essential for any broader form of fisheries resource management (Jennings 2004).

Before the advent of miniaturised tracking and data collection systems (such as ultrasonic telemetry, archival tags and pop-up satellite tags), distributions, movements and habitat preferences of pelagic species were inferred from catch data and conventional tagging programs (Brill 1994; Hampton & Gunn 1998). Although both data collection systems provided information on the habitats species were captured in, they did not provide validation of relationships with particular environmental conditions, information on distributions or movements outside the fishery area or season (if investigating a seasonal fishery), or detailed information on fine-scale interactions of individuals with their immediate environment. Advances in telemetry have facilitated such comprehensive investigations into the movement patterns and habitat preferences of pelagic predators.

Bigeye tuna are one of the most valuable components of the east coast tuna and billfish fishery (ET&BF) in Australian waters. These fish are targeted throughout the year, with between 800 and 1,000 tonnes caught across an area from Cairns to southern New South Wales in recent years (Ward & Bromhead 2004). The expansion of the fishery both spatially and temporally, rapid increases in catch rates and recent debate over potential declines in bigeye stocks (Hampton et al. 1998) have prompted questions regarding the links between bigeye throughout the Pacific Ocean, and in particular, between those fish in the western and central Pacific Ocean.

Tagging studies on bigeye tuna in the western Pacific Ocean (WPO) to date have been restricted to conventional tagging methods (Hampton & Gunn 1998). Rather than resolving questions concerning the relationships between bigeye stocks both within the ET&BF and with those in the broader WPO, the results of these conventional tagging programs suggested that high rates of tag returns in close proximity to release points and a highly seasonal nature of both catch rates within the fishery and recaptures of tags within the tagging program were the result of either: (1) long residence times for the majority of fish with fish demonstrating seasonal changes in behaviour resulting in seasonal changes in their availability to the fishery; or (2) possible cyclic migration pattern with fish returning to the Coral Sea each year (Hampton & Gunn 1998).

While significant insights into the behaviour and habitat utilisation of bigeye tuna within the Pacific Ocean have been attained with the use of both ultrasonic/acoustic tracking and archival tags (ATs; Holland et al. 1990; Josse et al. 1998; Dagorn et al. 2000; Schaefer & Fuller 2002; Musyl et al. 2003), there are a number of limitations to those data collected to date in resolving the possibility of seasonal changes in the behaviour of bigeye. By its very nature, ultrasonic/acoustic tracking can only ever collect distribution and behavioural information across limited temporal and spatial periods and environmental conditions. Individuals must be followed continuously, requiring intensive effort by investigators and substantial logistical inputs (Gunn & Block 2001), therefore limiting interpretations of those data collected. Archival tags allow collection of behavioural and environmental data over longer time periods, however most studies utilising this technology have limited releases of tagged fish to those aggregated around fish attracting devices (FADs). Small sample sizes of bigeye that have either moved away from FADs or were tagged in pelagic waters away from FADs have demonstrated quite different behaviours when compared to those fish associated with FADs (Schaefer & Fuller 2002; Musyl et al. 2003). This thereby limits the interpretation of those data collected on FAD-associated fish to that of the broader population.

In response to these gaps in the knowledge of the vertical distribution of bigeye tuna, variability in this distribution in response to changing environmental conditions and the relationship of the vertical distribution of bigeye to that of the longline fishery in the WPO, a project was initiated in 1999 investigating the habitat preferences of bigeye tuna. This chapter presents the first definitive investigation into the habitat preferences of this species within the WPO, providing important insights not only into the ecology of this species, but also important information on the distribution and therefore availability of this species to the fishery, information which is essential for better estimating catch per unit effort (CPUE) of the fishery throughout this region.

7.2.2. Methods

7.2.2.1. Archival tags and tagging operations

Full details of ATs deployed, tagging operations, location of release, recapture and downloading of ATs are detailed in Chapter 6.

7.2.2.2. Data and analyses

In-house purpose software (Arctag, CSIRO Marine Research) was used to determine day and night from light data collected by each tag. Light curves were generated for each date within the light dataset. Consecutive light level data within that date were then compared with the minimum light level of each curve and with light levels previously defined as daylight levels and then assigned a day or a night flag. A day-or-night flag was assigned to the data where day or night could not be determined (e.g. in situations of sensor malfunction or when an individual's diving behaviour made it impossible to determine when dawn and dusk occurred). Only those data able to be assigned to a day or a night were included in analyses. The illuminated fraction of the disc of the moon for a given day was calculated using algorithms presented in Meeus (1988) and incorporated into the in-house software utilised.

Depth and water temperature preferences were investigated by aggregating depth and water temperature data into 16 m and 0.5°C bins (determined by the maximum resolution data were saved to the tag) and then calculating the proportion of time spent within each bin. These distributions were then compared on a diurnal and seasonal scale and their relationship with changes in the position and strength of the thermocline (as derived from temperature and depth data collected by each AT) was assessed. Depth distributions per night in the days leading up to and past the full and new moons for each lunar cycle an individual was at liberty were compared to determine the effects of lunar phase on the distribution of night-time depth preferences.

Estimates of the location of individuals were determined using geolocation techniques as described in Chapter 7.1. Position estimates were then integrated with depth and water temperature preferences to determine any spatial variability in the behaviour of individuals. Longitudinal movement patterns of individuals were visualised and qualitatively assessed for periods of "residency" and "transit" (Appendix D). An area of residency was defined as that where there was a high density or clustering of light-based longitude estimates within a small geographic region. An area of transit was defined as that of low density of light-based longitude estimates reflecting rapid movement through that area. The distribution of depths and water temperatures experienced within these defined areas of residency and transit were then calculated and compared between regions.

Data on dissolved oxygen levels were obtained using the CSIRO Atlas of Regional Seas (CARS). CARS consists of a set of seasonal maps generated using Loess mapping from data obtained from the National Oceanographic Data Centre (NODC) World Ocean Atlas 98, CSIRO Marine Laboratory's conductivity-temperature-depth (CTD) and hydrology archives, the National Institute of Water and Atmospheric research's (NIWA) hydrographic data and the Antarctic and Southern Oceans Co-operative Research Centre's (CRC) hydrographic data (Dunn & Ridgway 2002; Ridgway et al. 2002).

Possible ontogenetic changes to the physiological thermoregulatory capabilities of individuals were investigated through an assessment of the amount of time spent below 250 m for each day. If the ability to physiologically respond to the cooler water temperatures experienced at depth by bigeye during the day changes with body size, it is likely that both the amount of time spent by individuals between re-heating episodes after cooling at depth and the number of times an individual would need to reheat would vary in association (Holland & Sibert 1994) and in return the amount of time spent at depth would vary. The amount of time spent below 250 m for each day was calculated and compared through time.

7.2.3. Results

Details of archival tag returns can be referred to in Appendix B. Usable data were successfully retrieved from 14 ATs, representing an average of 242.2 ± 127.3 (range: 46-522) days of data per fish.

7.2.3.1. Depth distributions

Bigeye tuna demonstrated a distinct diurnal behaviour in the depths they frequented throughout time. Although there was considerable individual variability, individuals largely spent their time during the day at depths between 250 and 500 m (Table 7.2.1., Figure 7.2.1.) with mean depths throughout the day ranging from 201.8 ± 183.1 to 389.5 ± 101.0 m. Regular excursions were made into waters 0-250 m during the day, although the time spent at these depths comprised far less time than that spent deeper than 250 m. Depths deeper than 500 m and up to the limits of the pressure sensors of the archival tags (985 m) were attained, however these depths comprised, in general, less than 10 % of an individuals time during the day. Much shallower depths were frequented during the night, with over 90 % of all individuals inhabiting waters shallower than 250 m (Table 7.2.1., Figure 7.2.1.). Occasional excursions into waters deeper than 500 m were made by individuals during the night; however these depths largely comprised less than 1 % of an individual's time. Mean depths at night ranged from 53.0 ± 48.3 to 94.2 ± 93.7 m.

7.2.3.2. Water temperature distributions

The water temperature preferences of individuals followed a similar pattern to that of the distribution at depth. During the day the greatest amount of time was spent in waters between 11 and 22°C with regular excursions into colder waters associated with depth and warmer waters associated with regular excursions into shallower waters. Mean water temperatures experienced during the day demonstrated a high level of individual variability ranging from 13.9 ± 3.3 to 20.5 ± 6.1°C (Table 7.2.2., Figure 7.2.2.) with minimum temperatures frequented ranging between 2.5-6.7°C. Warmer temperatures associated with shallower depths were frequented at night, with most individuals spending greater than 80 % of their time in waters warmer than 22°C (Table 7.2.2., Figure 7.2.2.). Mean water temperatures experienced during the night were less variable than those inhabited during the day and ranged from 24.2 ± 3.0 to 26.6 ± 2.2°C, although temperatures experienced ranged almost as much as those experienced during the day.

7.2.3.3. Seasonal variability in depth and water temperature distributions

Time spent at depth by bigeye during the day demonstrated distinct seasonal variability; however these distributions were marked by considerable individual variability. Daytime depth distributions across all years at liberty tended to be bimodal in appearance during the spring months, demonstrating clear partitioning of time between deeper, cooler waters at about 300-500 m and shallower, warmer waters at about 50-100 m (Figure 7.2.3., Appendix E) associated with an increase in time spent in shallower waters. This bimodal distribution in the depths frequented tended to become more uniform over the summer months until it was virtually indistinct during autumn, reflecting a reduction in time spent in surface waters. Distributions demonstrated a return to a more bimodal distribution during the winter months associated with an increase in the time spent in surface waters.

Seasonality in depth distributions at night was not as clear as that demonstrated during the daytime. Depth distributions of a number of bigeye at liberty during spring and summer 1999/2000 and spring and summer 2001/2002 appeared to be distributed across a wide range of depths down to 400-600 m with most time spent above 200 m (Figure 7.2.3., Appendix E). These distributions became more confined during the autumn and winter with depths greater than 200 m rarely frequented. Distributions during autumn and winter appeared to take on a bimodal appearance with the majority of time distributed at the surface and at around 100 m, depths which appeared to be associated with the top and the bottom of the thermocline. Depth distributions of fish at liberty during 2000/01 did not demonstrate the patterns observed in 1999/2000 and 2001/2002, with little change in depth distributions across spring, summer and autumn.

Table 7.2.1. Summary of depth data (m) collected from archival tags deployed 1999-2001 in the Coral Sea.

Tag Number	Daytime				Night-time			
	% time spent 0-250m	% time spent 250-500m	% time spent >500m	Mean±SD (Range)	% time spent 0-250m	% time spent 250-500m	% time spent >500m	Mean±SD (Range)
98-347	34.1	60.3	5.6	310.4±166.2 (0-985[1])	94.5	4.5	1.0	86.3±94.3 (0-882)
98-353	10.2	89.5	0.3	364.8±94.0 (4-985[1])	99.6	0.4	0.0	53.1±41.8 (0-773)
98-363	13.9	85.2	0.9	355.1±95.5 (0-985[1])	97.8	2.1	0.1	54.4±52.0 (0-985[1])
98-372	14.5	84.8	0.7	336.4±105.4 (5-713)	99.4	0.5	0.1	53.0±48.3 (3-761)
98-463	40.8	48.0	11.2	305.2±196.6 (1-985[1])	93.0	6.8	0.2	94.2±93.7 (1-985[1])
98-479	66.4	28.0	5.6	201.8±183.1 (1-705)	97.6	2.2	0.2	80.5±73.3 (1-633)
99-190	7.9	87.4	4.7	389.5±101.0 (0-978)	99.6	0.4	0.0	53.1±43.3 (0-985[1])
99-213	25.5	73.4	1.1	311.2±128.6 (0-985[1])	99.1	0.9	0.0	68.9±49.7 (0-985[1])
99-216	29.3	64.9	5.8	324.9±152.4 (0-9851)	96.4	2.6	1.0	83.2±83.5 (0-713)
99-224	38.7	56.2	5.1	301.6±171.5 (0-985[1])	97.7	2.2	0.1	83.3±61.9 (0-985[1])
99-237	21.3	75.5	3.0	335.7±135.6 (2-985[1])	95.2	4.5	0.3	78.7±78.0 (1-825)
99-243	30.6	64.9	4.5	318.7±148.3 (0-980)	95.6	3.2	1.2	86.0±90.0 (0-884)
99-262	17.4	81.8	0.8	344.3±116.7 (0-980)	98.8	1.0	0.2	64.7±57.7 (0-969)
00-112	19.0	80.5	0.5	325.9±106.1 (0-981)	99.4	0.5	0.1	59.2±44.8 (0-744)

[1] Limit of depth sensor

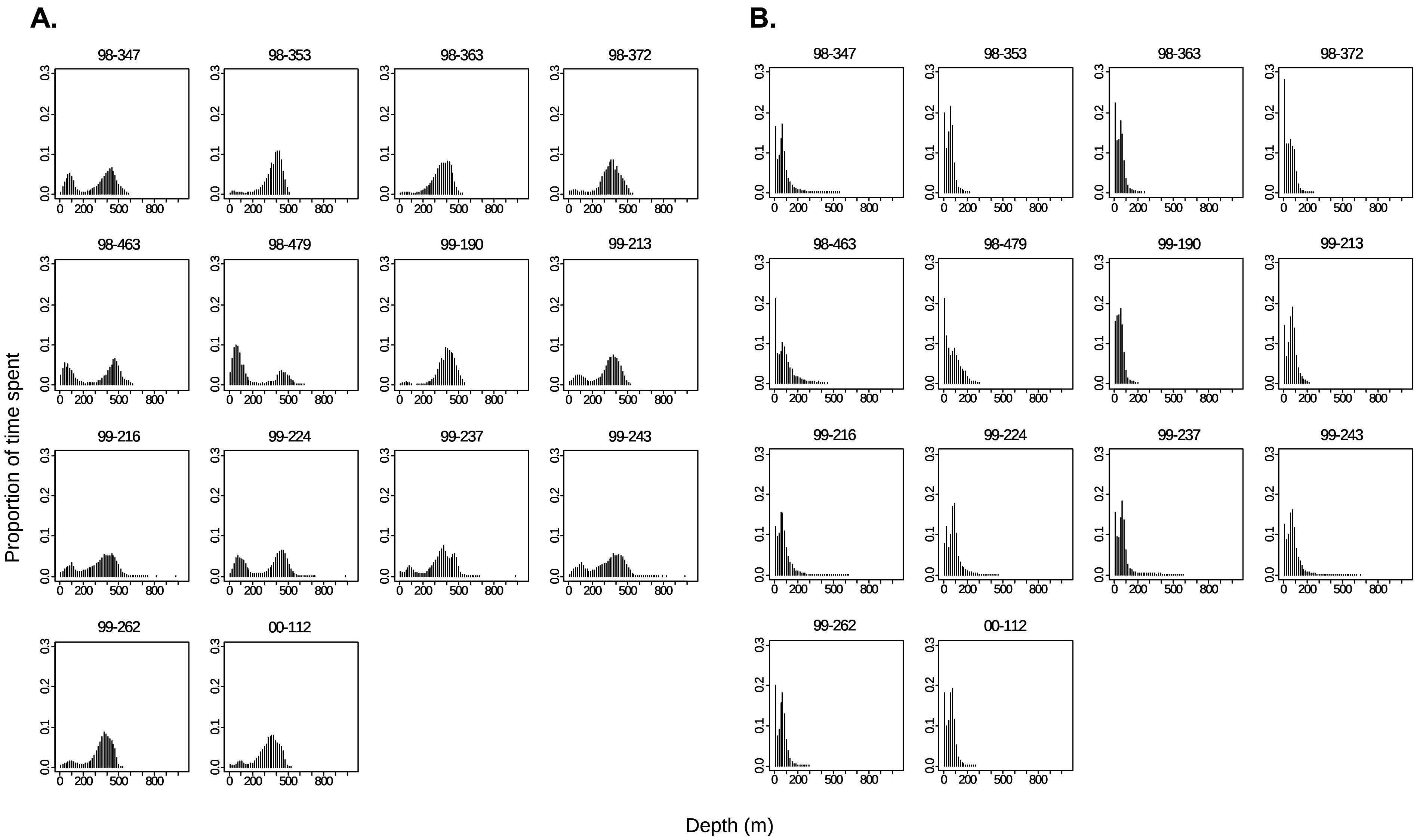


Figure 7.2.1. Distribution of depths frequented by bigeye tuna at liberty 1999-2002 in the western Pacific Ocean (a) day; (b) night (n=14).

Table 7.2.2. Summary of temperature data (°C) collected from archival tags deployed 1999-2001 in the western Pacific Ocean.

Tag Number	External temperature								Internal temperature								Temperature difference
	Daytime				Night-time				Daytime				Night-time				
	% time spent								% time spent								
	0-11°C	11-22°C	>22°C	Mean±SD (range)	0-11°C	11-22°C	>22°C	Mean±SD (range)	0-11°C	11-22°C	>22°C	Mean±SD (range)	0-11°C	11-22°C	>22°C	Mean±SD (range)	Mean±SD (range)
98-347	24.1	47.5	28.4	16.6±6.0 (4.9-28.9)	2.1	10.7	87.2	24.8±3.5 (4.9-29.3)	0.2	63.3	36.5	20.6±4.7 (10.9-29.5)	0.0	5.2	94.8	26.5±2.4 (11.1-30.5)	3.2±2.8 (0-19.6)
98-353	34.1	60.3	5.6	14.5±3.4 (3.3-29.1)	94.5	4.5	1.0	26.2±1.8 (5.3-30.1)	0.0	90.3	9.7	17.4±3.4 (11.7-29.9)	0.0	3.1	96.1	27.1±1.7 (14.5-30.5)	2.4±1.9 (0-18.2)
98-363	21.4	74.8	3.8	14.4±3.6 (4.5-30.5)	0.2	4.3	95.5	26.1±2.1 (4.1-30.7)	0.0	85.8	14.2	19.0±3.2 (11.3-30.3)	0.0	3.6	96.4	27.1±1.9 (8.5-30.7)	3.3±2.8 (0-22.2)
98-372	13.8	78.3	7.9	15.2±4.0 (5.7-27.9)	0.1	3.1	96.8	26.0±1.8 (5.9-29.1)	0.0	88.9	11.1	17.9±3.6 (11.7-28.9)	0.0	3.5	96.5	26.7±1.8 (15.1-29.7)	2.3±1.9 (0-19.8)
98-463	26.0	38.0	36.0	17.2±6.5 (3.3-30.9)	0.5	16.1	83.4	24.2±3.0 (4.9-27.5)	0.4	59.2	40.4	20.2±5.2 (10.1-28.9)	0.0	5.5	94.5	25.7±2.2 (11.9-28.9)	2.7±2.4 (0-20.8)
98-479	12.7	26.5	60.8	20.5±6.1 (6.7-28.7)	0.3	15.0	84.7	24.4±2.3 (7.3-27.5)	0.1	32.0	67.9	23.1±4.8 (10.7-28.3)	0.0	2.8	97.2	25.7±1.6 (13.7-28.5)	2.3±2.3 (0-19.4)
99-190	20.9	70.5	4.1	13.9±3.3 (5.3-27.9)	0.1	29.9	70.0	24.3±2.1 (4.5-28.9)	0.0	89.7	10.3	17.6±3.4 (11.3-28.9)	0.0	6.7	93.3	25.2±2.1 (11.3-28.9)	2.6±2.4 (0-20.0)
99-213	29.3	52.5	18.2	15.3±5.6 (2.5-30.5)	0.1	4.1	95.8	26.6±2.2 (2.7-30.5)	0.1	69.4	30.5	19.3±4.4 (8.7-30.3)	0.0	0.8	99.2	27.7±1.7 (10.9-31.3)	3.6±3.1 (0-21.8)
99-216	26.5	53.8	19.7	15.8±5.6 (2.9-30.1)	1.6	8.0	90.4	25.8±3.3 (6.3-30.7)	0.4	68.9	30.7	19.9±4.6 (9.3-30.5)	0.2	4.8	95.0	27.2±2.6 (10.1-30.9)	3.3±2.7 (0-22.0)
99-224	18.2	48.1	33.7	17.6±6.3 (3.3-30.1)	0.2	7.4	92.4	25.6±2.3 (4.1-30.3)	0.0	58.9	41.1	21.1±4.9 (9.9-29.5)	0.0	1.2	98.8	26.9±1.4 (8.3-30.3)	3.0±2.6 (0-21.0)
99-237	17.4	66.7	15.9	16.2±5.0 (3.1-30.9)	0.5	7.7	91.8	26.2±3.1 (5.7-31.1)	0.3	77.8	21.8	19.3±4.2 (8.1-29.7)	0.1	7.4	92.5	26.7±2.8 (10.5-30.1)	2.5±2.2 (0-19.6)
99-243	4.9	72.4	22.7	18.0±5.0 (5.1-31.7)	1.2	6.0	92.8	26.6±3.4 (6.5-31.9)	0.4	64.8	34.8	20.3±4.4 (7.1-29.9)	0.2	4.9	94.9	26.9±2.6 (9.3-30.3)	2.2±2.2 (0-20.8)
99-262	8.3	82.9	8.8	15.1±4.0 (2.9-30.3)	0.2	1.9	97.9	26.6±2.0 (4.1-30.9)	0.0	79.0	21.0	19.2±3.8 (12.1-30.3)	0.1	1.4	98.5	27.5±1.6 (8.9-30.5)	3.0±2.5 (0-23.4)
00-112	15.6	75.2	9.2	15.2±4.2 (3.1-31.1)	0.1	2.6	97.3	26.3±1.8 (6.1-30.3)	0.0	81.5	18.5	19.4±3.4 (10.1-29.7)	0.0	1.6	98.4	27.4±1.5 (13.1-30.5)	3.1±2.5 (0-20.4)

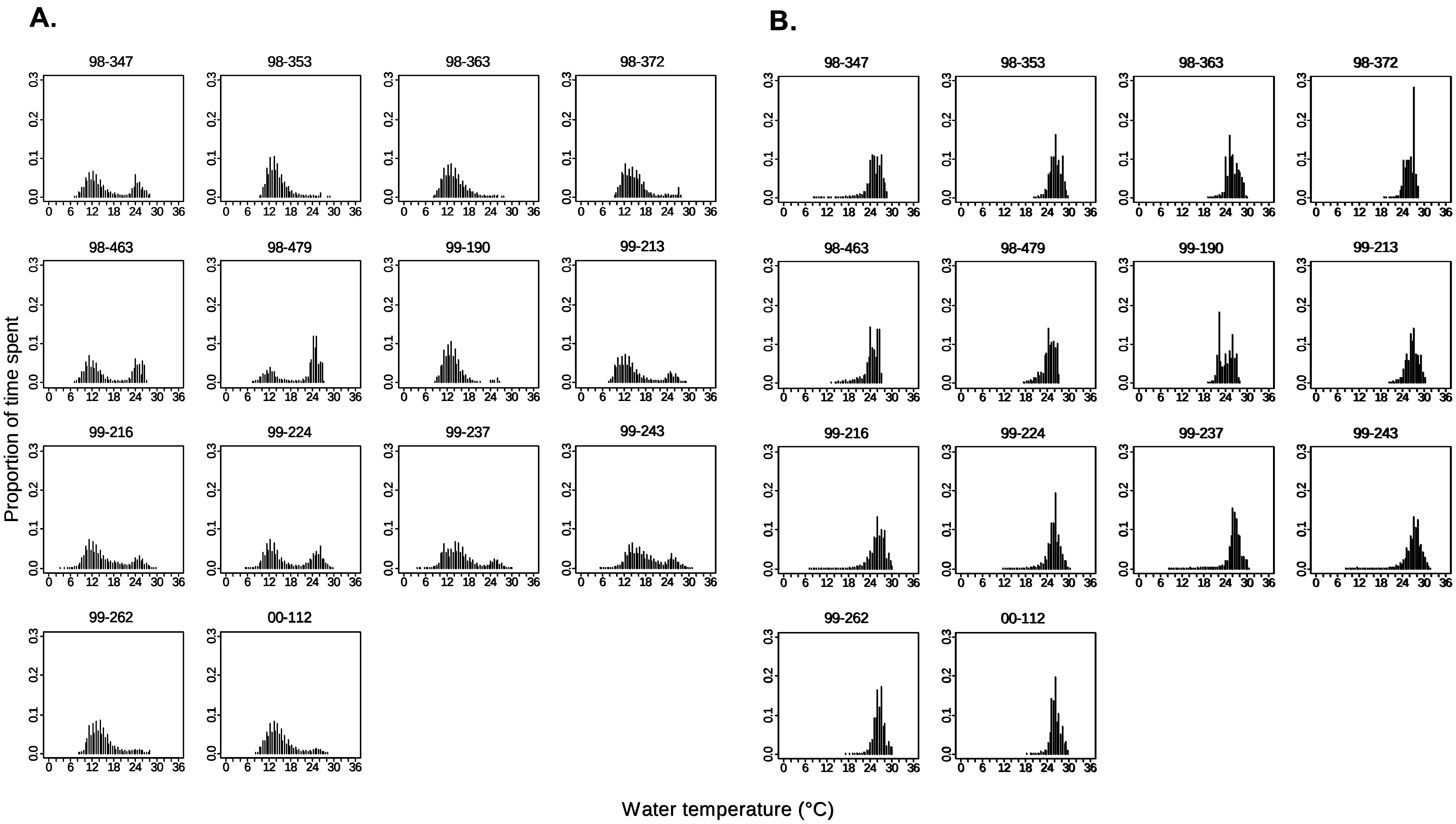


Figure 7.2.2. Distribution of water temperatures frequented by bigeye tuna at liberty 1999-2002 in the western Pacific Ocean (a) day; (b) night (n=14).

Water temperature distributions during the day followed those of daytime depth distributions across seasons, demonstrating a strong bimodal distribution during spring centred at around 12°C and 25°C. Again, this distribution appeared to smooth during the summer and autumn months taking on a more uniform appearance, following a decrease in time spent in surface waters (Figure 7.2.4., Appendix E). Distributions became more bimodal in appearance during the winter months, particularly in tags 98-347 and 99-213, in association with a cooling of surface waters and an increase in surface water habitation. Water temperature preferences at night again followed that of depth distributions with more time spent across all temperatures during spring and summer in comparison to autumn and winter in 1999/2000 and 2001/2002. However, water temperature preferences across autumn and winter did not demonstrate the bimodal distribution depth preferences did. Distributions instead appeared to become more sharply confined, centering around 25 to 27°C (except in tag 99-190 where water temperature distributions were centered around 23°C) and with the bottom of the thermocline.

7.2.3.4. Spatial variability in depth and water temperature preferences

Geolocation estimates derived from light data collected by archival tags suggest that bigeye tagged as part of this study were largely resident within the western Coral Sea region (Chapter 7.1, Appendix C). As a result, spatial assessment of depth and water temperature preferences were confined to three archival tags, two of which demonstrated distinct east-west movements (98-353 and 99-213) and one tagged and largely resident in the southern part of the fishery (99-190).

Both the archival tags 98-353 and 99-213 demonstrated similar depth and water temperature distributions (Figure 7.2.5., 7.2.6., Appendix F). Daytime depth and water temperature preferences were primarily bimodal in distribution whilst fish were located in the western Coral Sea and broke down, becoming more uniform in distribution as movements were made to the east and into the greater Coral Sea. Depth and water temperature distributions demonstrated by tag 99-213, became more bimodal in appearance indicating a greater use of surface waters and coinciding with a return to the western Coral Sea again. This distribution then became more uniform, indicating less use of surface waters as the fish moved eastward for the second time. At night the majority of time was spent at the surface in the western Coral Sea with distributions moving towards a preference for waters around 100 m as fish moved towards the east. Water temperature preferences at night did not appear to be consistent between the two fish as movement was made from west to east, although both fish utilised warmer waters more frequently as they moved to the east.

While the distribution of depths and daytime water temperatures frequented by 99-190 varied on similar scales to the distributions of depth and water temperature of individuals largely resident in the northern ETBF, water temperatures at night, were consistently cooler (Appendix E), reflecting the cooler surface waters inhabited by this fish.

7.2.3.5. Depth distributions in relation to dissolved oxygen levels

Dissolved oxygen profiles provided by CARS suggest that across the Coral Sea oxygen levels vary both spatially and temporally on the order of 2 ml/L^{-1} (Figure 7.2.7.), ranging from approximately 5 ml/L^{-1} in surface waters of the northern Coral Sea to approximately 4 ml/L^{-1} in the southern Coral Sea and approximately 4 ml/L^{-1} at 1000 m in the north-eastern Coral Sea to approximately 2 ml/L^{-1} in the south-western Coral Sea. Seasonal variability is minimal at depth, with waters less than 100 m demonstrating a slight decline in dissolved oxygen levels over the summer and autumn months and a slight increase over the winter and spring months (*ca.* <0.5 ml/L^{-1}). Oxygen minima appeared to occur at approximately 500 m, with dissolved oxygen levels of 1.5 ml/L^{-1} occurring in the eastern Coral Sea. Daytime depth distributions of individuals tagged suggest that bigeye spend the majority of their time in waters with dissolved oxygen levels of 2-4 ml/L^{-1} and make regular excursions into waters with dissolved oxygen levels of 3-5 ml/L^{-1}. Time spent at night appears to be largely spent in waters with dissolved oxygen levels of 3-5 ml/L^{-1}.

7.2.3.6. Physiological responses to water temperatures

Body temperatures of bigeye closely followed that of ambient water temperatures (Figure 7.2.8.), with differences between the two varying on average in the order of 2-3°C (Table 7.2.2.). As with distributions of water temperature during the day, internal temperatures demonstrated a mostly bimodal distribution. This bimodal distribution reflected cooler internal temperatures of 14-16°C associated with cooler waters frequented at depth and warm internal temperatures centred around 26-28°C associated with time spent in warmer, shallower waters (Figure 7.2.8.). Mean internal temperatures experienced during the day demonstrated a high level of individual variability ranging from 17.4 ± 3.4 to 23.1 ± 4.8°C (Table 7.2.2.), with minimum internal temperatures experienced ranging between 8.1-12.1°C. Warmer internal temperatures were experienced at night with all individuals experiencing internal temperatures greater than 22°C over 90 % of the time (Table 7.2.3.; Figure 7.2.8.). As with water temperatures experienced, internal temperatures were less variable at night, with mean temperatures ranging 25.2 ± 2.1 to 27.7 ± 1.7°C.

7.2.3.7. Ontogenetic variability in physiological responses to water temperature and behavioural classification

The amount of time spent in waters deeper than 250 m during the day varied substantially throughout time (Figure 7.3.9.). Nearly all individuals (92.6 % of all fish tagged) demonstrated days in which no excursions into waters deeper than 250 m and the percent time spent below 250 m during the day ranged from 0-100 %. For those bigeye for which data were available for greater than 90 days there appeared to be little evidence of a distinct trend or change in the amount of time spent below 250 m that could be attributed to possible ontogenetic change in the physiological capabilities of individuals. Periods in which lower amounts of time were spent below 250 m during the day appeared to be concentrated during spring and summer months, reflecting overall greater periods of time spent in surface waters during these months as detailed in section 7.2.3.3.

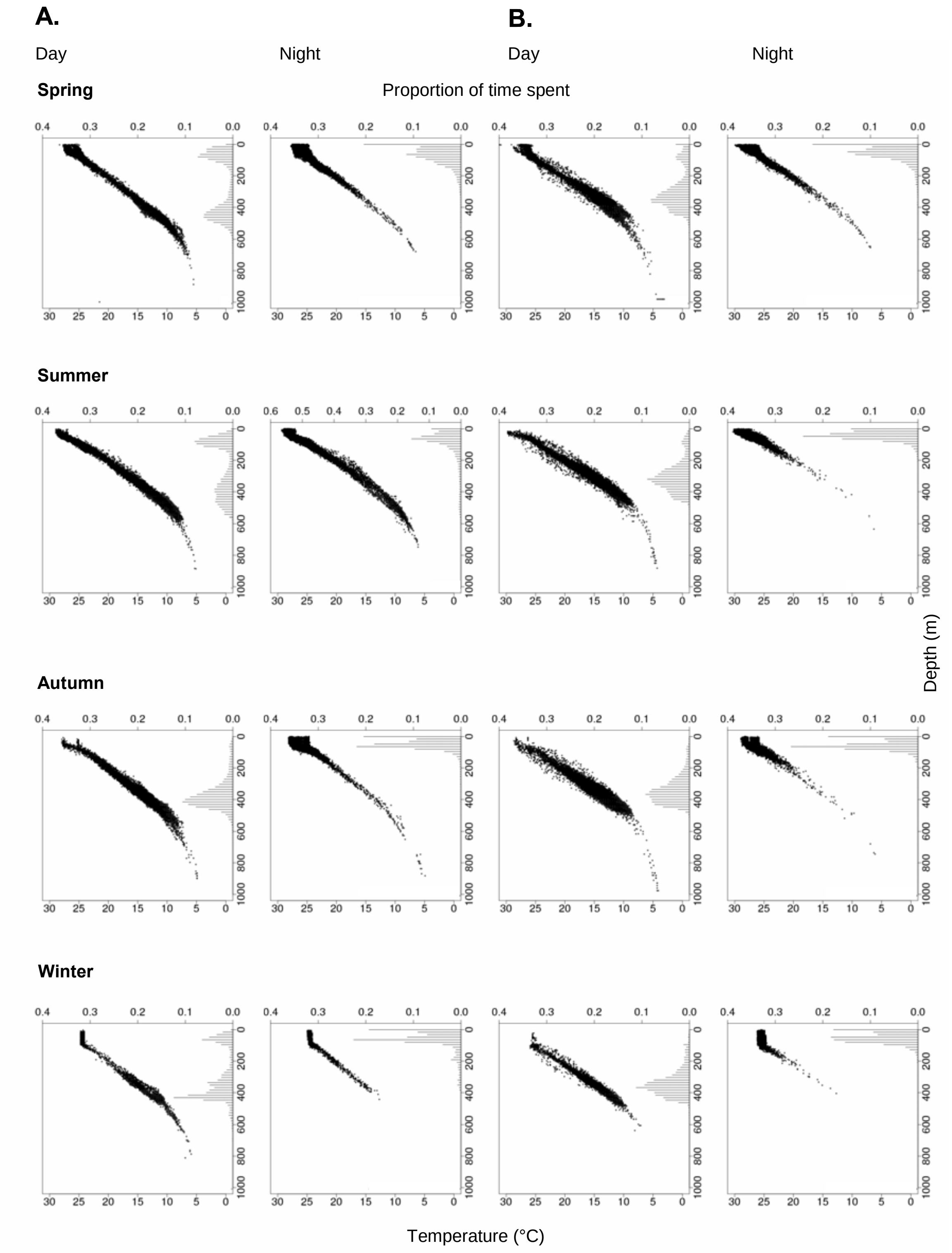


Figure 7.2.3. Distribution of depths frequented by bigeye tuna with the archival tags (a) 98-347 (at liberty 1999-2000) and (b) 00-112 (at liberty 2001-2002) in relation to water temperature profiles during Spring, Summer, Autumn and Winter.

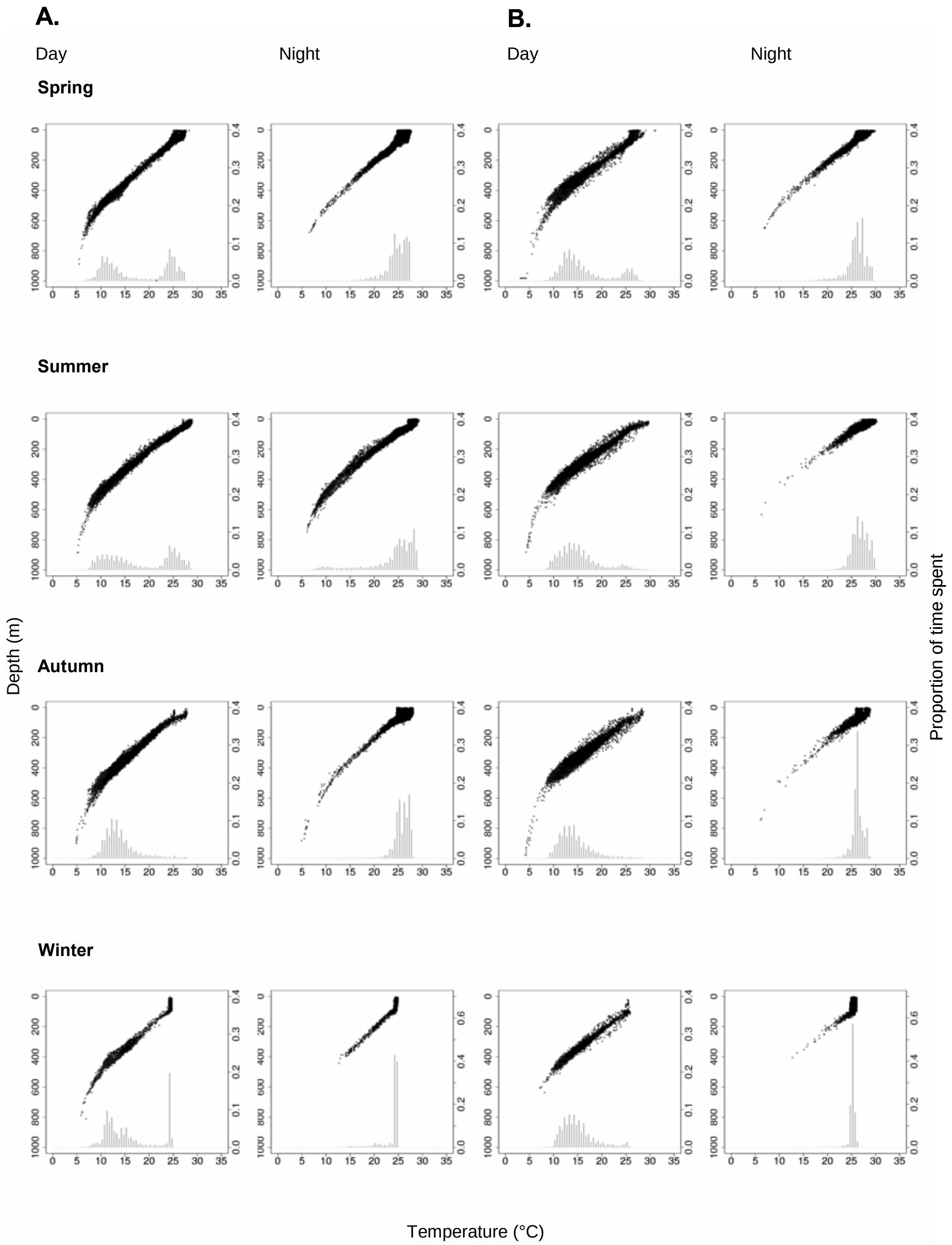


Figure 7.2.4. Distribution of water temperatures frequented by bigeye tuna with the archival tags (a) 98-347 (at liberty 1999-2000) and (b) 00-112 (at liberty 2001-2002) in relation to water temperature profiles during Spring, Summer, Autumn and Winter.

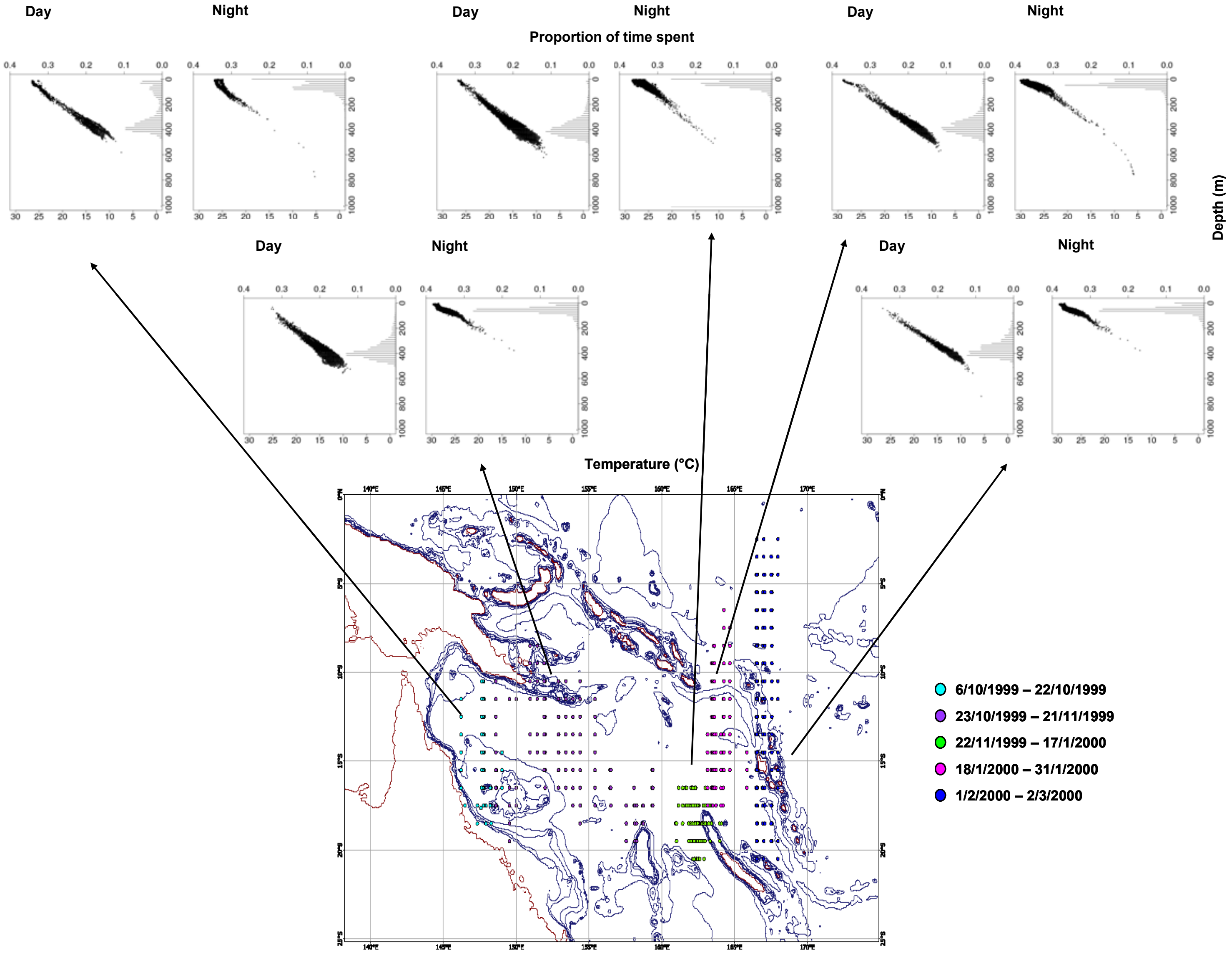


Figure 7.2.5. Spatial variability in the time spent at depth by the archival tag 98-353 during the period 6/10/1999-2/3/2000.

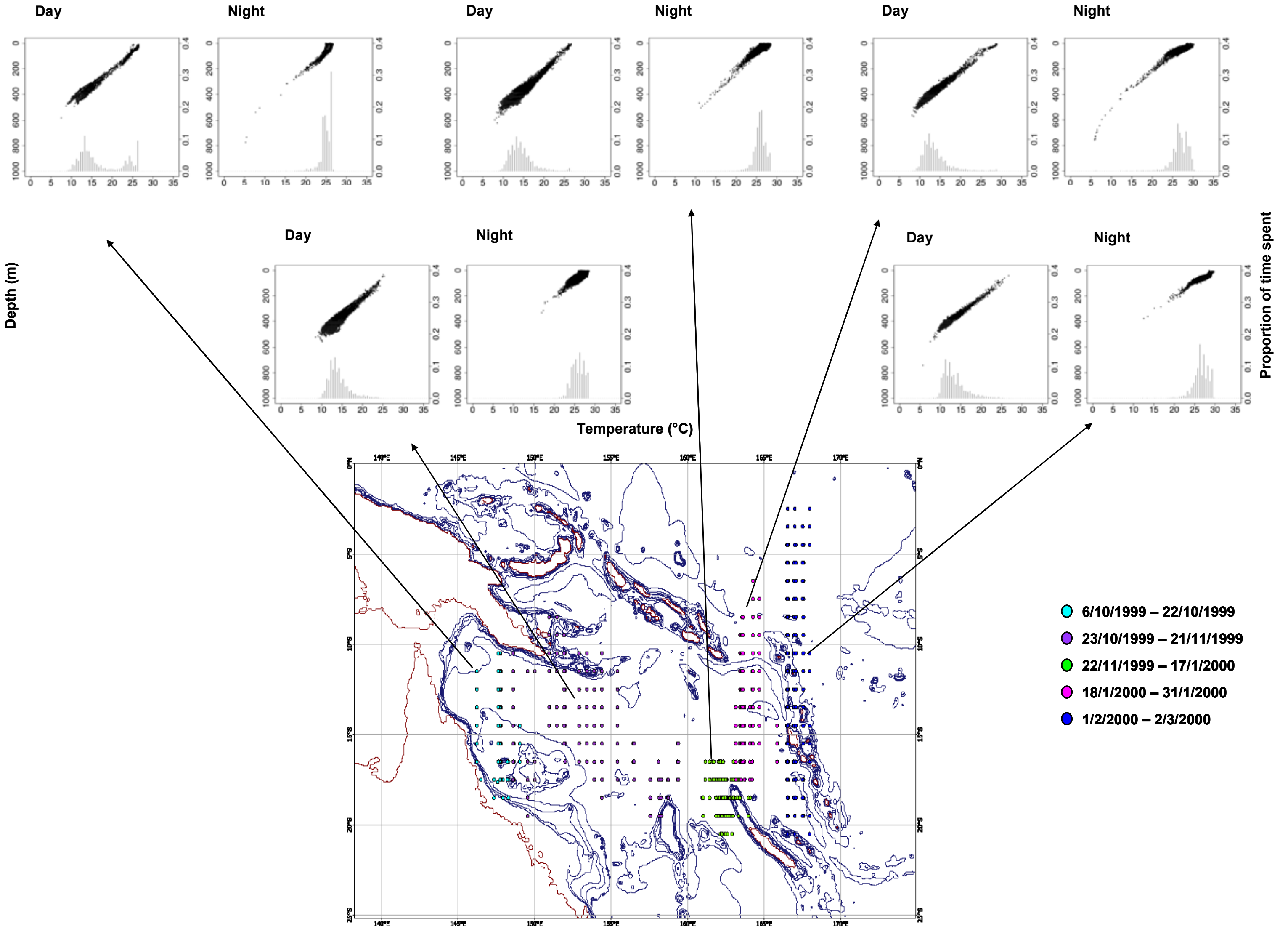


Figure 7.2.6. Spatial variability in the time spent at water temperature by the archival tag 98-353 during the period 6/10/1999-2/3/2000.

We found that the amount of time spent in waters greater than 250 m during the day was additionally a reasonable reflector of diving behaviour in bigeye and could be used to distinguish between days of “classic” behaviour and days of other behaviour that could not be classified as “classic” in nature (or a combination of classic or otherwise). We defined “classic” behaviour as that defined by a descent to depths of between 300 and 500 m during the daytime punctuated by rapid regular excursions into waters less than 200 m and resembling that of “typical bigeye distribution and behaviour” as defined by Holland et al. (1992), the “non-associated type 1 behaviour” defined by Schaefer and Fuller (2002) and the “W-shaped daytime vertical movement pattern” defined by Musyl et al. (2003; see Appendix D for an example of this diving behaviour). When we defined classic behaviour as that where 75 % or more of the total time during the day was spent below 250 m (Figure 7.3.9.), we observed 95.2-100 % (mean ± SD: 98.2 ± 1.5) of all days correctly classified.

7.2.3.8. Distribution of depths in relation to lunar phase

Most individuals during part of their time at liberty demonstrated a marked movement from surface waters (0-50 m) into deeper waters (50-100 m) around the full moon, with a movement back into shallower waters centred around the new moon (Figure 7.2.10., Appendix G). This shift between shallower and deeper waters was reflected to a lesser extent in waters 100-150 m, with individuals frequenting these deeper waters to a slightly higher extent around the full moon and to a lesser extent around the new moon. However, individuals at liberty across the same temporal period did not always demonstrate similar shifts in depths frequented, nor did individuals demonstrate a consistent shift in depth distribution with lunar phase across the entire time at liberty.

7.2.4. Discussion

7.2.4.1. Time spent at depth and water temperature

The data collected from the ATs deployed on bigeye tuna as part of this project represent the most continuous recording of the behaviour and habitat preferences of this species to date. Bigeye tuna in the Coral Sea, similarly to bigeye tagged away from seamounts and FADs in other areas of the Pacific Ocean, displayed a distinct diurnal shift in diving behaviour, generally diving at dawn to spend the large proportion of the day at around 300-500 m and returning to shallower waters at dusk to spend the majority of time at night in waters less than 200 m. However, considerable individual variation was evident both in depth and water temperature preferences, suggesting a flexibility in the foraging strategies and physiology of individuals.

The distribution of an animal at a given time will be determined by a number of factors both physical and biotic in nature. Choice of habitat will largely be the result of matching environmental preferences with food availability and finding a means of suitably balancing energetic expenditure with that of energy gain (Sogard & Olla 1993; Ydenberg et al. 1994). Matching these factors in a variable environment such as the ocean can often result in a number of responses, the extremes of which are determined by the physiological capabilities and behavioural flexibility of that species (Ydenberg et al. 1994; Staniland et al. 2004).

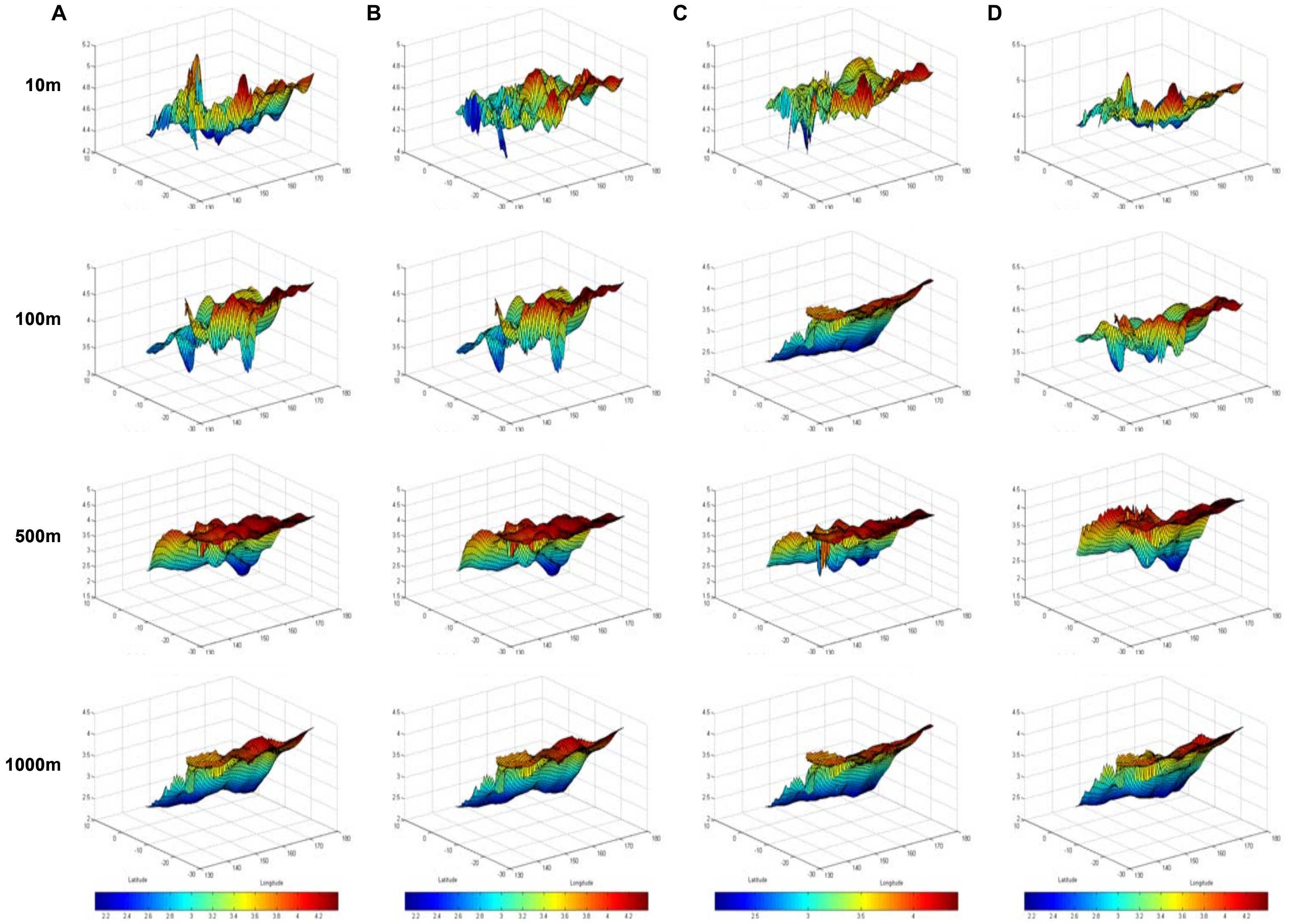


Figure 7.2.7. Dissolved oxygen levels (ml/L^{-1}) at depth across the Coral Sea in (a) Spring; (b) Summer; (c) Autumn and (d) Winter.

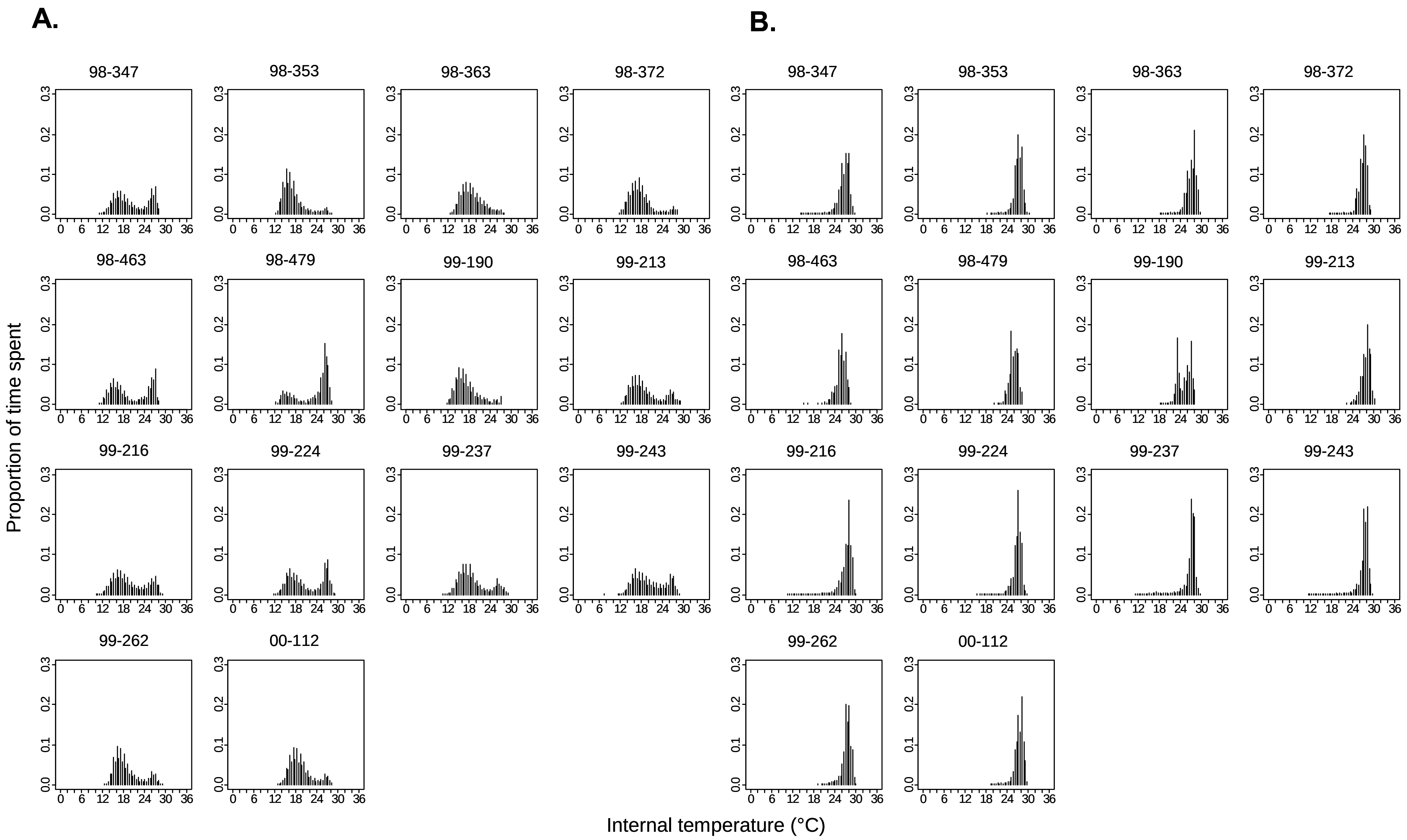


Figure 7.2.8. Distribution of internal temperatures of bigeye tuna at liberty 1999-2002 in the Coral Sea (a) day; (b) night (n=14).

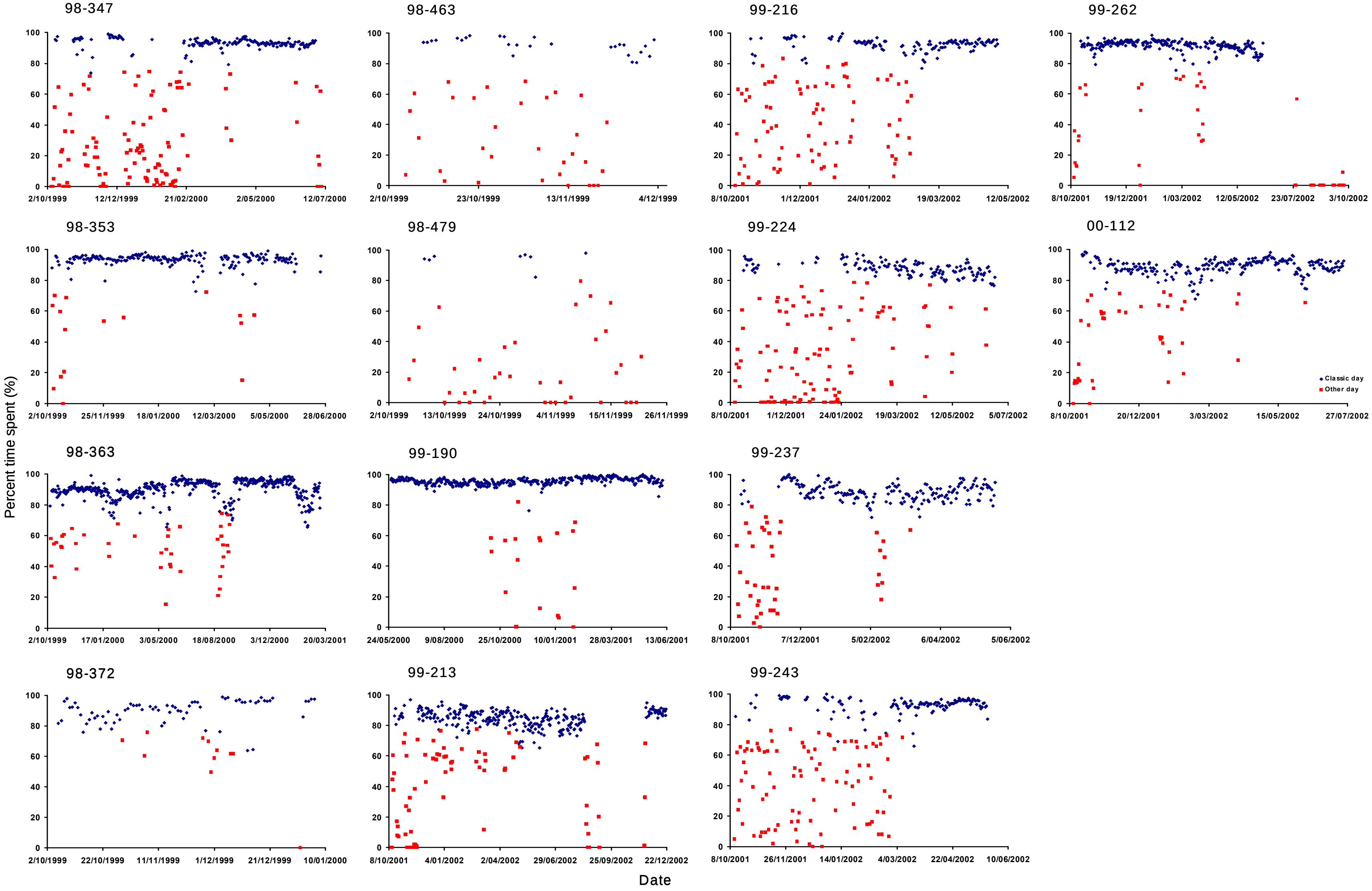


Figure 7.2.9. The percentage of time spent in waters deeper than 250 m during the day by bigeye tuna at liberty (a) 1999/2000; (b) 2000/2001and (c) 2001/2002.

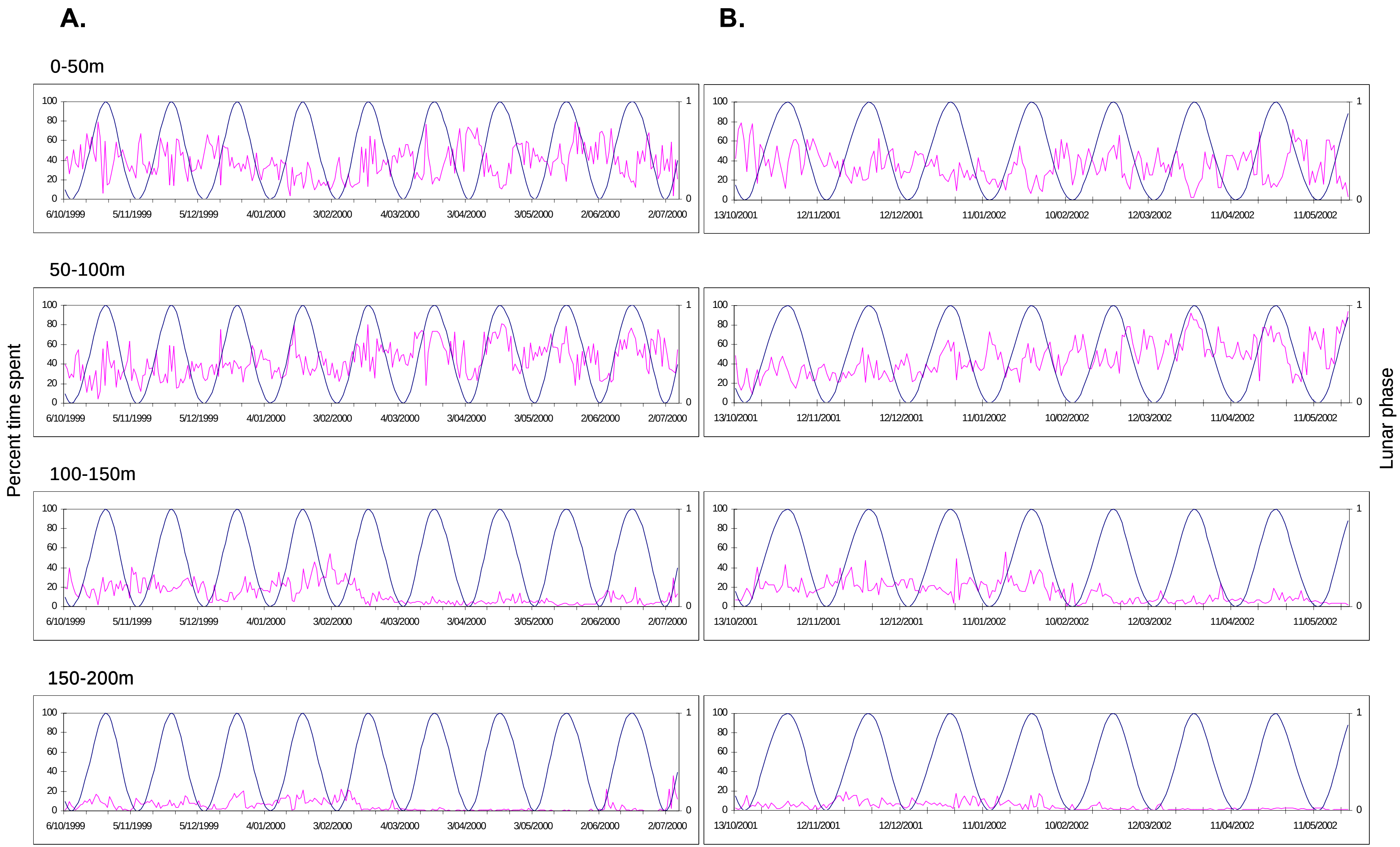


Figure 7.2.10. Time spent across 0-200m at night (in pink) by the archival tags (a) 98-347 and (b) 99-243 in relation to lunar phase (in blue; 0: new moon, 1: full moon).

Many authors have suggested the diurnal variability observed in the diving behaviour of bigeye tuna is associated with similar diurnal vertical movements of their prey (Dagorn et al. 2000; Marcinek et al. 2001; Schaefer & Fuller 2002; Musyl et al. 2003). A number of species reported from the stomachs of bigeye tuna are known to diurnally migrate (Miyabe & Bayliff 1998; Holland et al. 2003; Luo et al. 2000) and bigeye tuna have been observed to associate closely with the movements of the sound scattering layer (SSL) both during the day and at night (Josse et al. 1998). Information on the diet, predator-prey relationships and interactions between predator-prey relationships and the environment of bigeye tuna in the WPO is sparse. Investigations into these would provide greater insights into the foraging behaviour and the influence of environmental determinants on the foraging behaviour of bigeye tuna.

The wide temperature tolerance and regular excursions of bigeye tuna from deeper, cooler waters to shallower, warmer waters during the day as a means of behavioural thermoregulation, coupled with a physiology allowing short-latency physiological thermoregulation (Holland et al. 1992), allow bigeye tuna to exploit a larger component of their environment than other tropical and subtropical tunas such as yellowfin (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*) tuna, species that are largely confined to waters above the thermocline (Grudinin 1989). These capabilities allow bigeye to increase foraging time spent below the thermocline, thereby enabling almost continual exploitation of the SSL and maximising the ability to successfully forage in a patchy environment. This also serves to maximise the number of prey species available to bigeye and minimises competition with other tropical and subtropical tuna species for prey resources.

The depth preferences of bigeye in the Coral Sea appear to be quite different to those recorded from bigeye tuna elsewhere in the Pacific Ocean. Bigeye tagged in the eastern Pacific Ocean (EPO) away from structures known to influence diving behaviour (e.g. FADs, seamounts), were observed to prefer much shallower depths both during the day (200-350 m in comparison to 300-450 m) and at night (10-50 m in comparison to 50-100 m) than those recorded in this study (Schaefer & Fuller 2002). Water temperature preferences between the two regions however, appeared to be similar during the day (13-14°C in the EPO and 12-13°C in the WPO) and at night (22-26°C in the EPO and 24-26°C in the WPO). It is possible that the thermal structure of the ocean and the relation of the SSL to this determine the vertical distribution of bigeye and the differences observed between the two regional populations are the result of differing oceanographic conditions. Hanamoto (1987) reported that the optimum temperature for bigeye (10-15°C) was shallower in the EPO at 100-400 m than in the WPO where it was 400-600 m. However, it is difficult to compare the depth and water temperature preferences of the two regional populations of bigeye in the Pacific Ocean due to differences in the presentation and analyses of the AT data. The assessment of depth and water temperature preferences presented here for each fish are pooled across the entire time at liberty, whereas those presented for the EPO were presented divided on the basis of a behavioural classification and were pooled across all fish within the behavioural classification. Water temperature preferences were further divided on a monthly basis. One bigeye tagged in the same region in the EPO in a subsequent study demonstrated similar depth and water temperature preferences to those presented here (Musyl et al. 2003). However, again comparisons between the two studies are limited and larger sample sizes are required to quantitatively compare the depth and water temperature preferences of the regional populations.

7.2.4.2. Temporal and spatial variability in depth and water temperature preferences

Shifts in the depth and water temperature preferences of bigeye tuna in the WPO appear to be closely related to seasonal shifts in the thermal structure of their oceanic environment. Seasonal shifts in diving behaviour have been documented for a number of marine animals and have been linked to variability in prey distributions associated with changes in the thermal structure of the ocean and with breeding events (Georges et al. 2000; Kitagawa et al. 2000; Stockin et al. 2001; Charrassin et al. 2002; Kitagawa et al. 2004).

Water temperatures collected by the archival tags in this study demonstrate a seasonal shift in the thermal structure of the marine environment, with warming of waters at the surface and at depth during the summer months, followed by cooling through autumn and winter and the production of a more distinct thermocline, which persisted into the spring months. The distribution of the SSL at night has been observed to be closely associated with the thermal gradient maxima and maximum trophic accumulation (Marchal et al. 1993). The slight shifts in the depth and water temperature preferences of bigeye tuna at night across seasons traces the movement of the thermocline and may be associated with shifts in the SSL in response to changing ocean thermal properties.

A higher proportion of time was spent in surface waters during the day and across deeper waters at night across the spring months than in other seasons by nearly all bigeye tuna tagged. Bigeye tuna have been reported to aggregate in surface waters of the north-western Coral Sea in association with large spawning aggregations of the lantern fish *Diaphus* sp. during the spring months (McPherson 1988). Prey species of tuna elsewhere have been observed to alter normal diel migrations at particular times of the year aggregating in large surface schools during the day (Marchal & Lebourges 1996). The higher incidence of surface behaviour during the day may be associated with the incidence of such prey aggregations, however it is difficult to postulate on the occurrence of a higher proportion of deep diving (>200 m) behaviour at night during this period. Ripe female bigeye tuna have been caught in the ET&BF across the period of August to December (Farley et al. 2003) and the shifts in diving behaviour observed both during the day and at night may be associated with spawning activity. Variability in the thermal structure and productivity of the ocean may also have influences on the diving behaviour of individuals perhaps causing prey to distribute at lower depths than at other times of the year.

During summer and into autumn both the depth and water temperature preferences of bigeye tended to become more uniform in distribution and may be the result of a deepening of the warm water mixed layer. With a deepening of this warm layer of water, bigeye at depth during the day may be able to stay at depth for longer due to a reduced rate of cooling and when returning to shallower waters to re-heat, may not need to make as extensive an upward excursion to reach these warmer waters than they would during winter and spring. A consistent decrease in the number of upward excursions made by bigeye tagged in this study was not evident, however while we did count the number of excursions made above 200 m each day by individuals we did not assess the depth to which excursions were made and whether this was consistent through time.

Seasonal changes have been observed in the depth distributions of bigeye tuna tagged in the EPO. However, interpretation of these data is confounded by the pooling of data from multiple tags. It is subsequently impossible to assess individual variability in depth distributions and the biases such variability may have on the observed variability associated with seasonal change.

While shifts in the depth and water temperature preferences were observed in those bigeye tuna that moved eastward out of the ET&BF, it is difficult to determine if these were directly associated with the movements or a factor of seasonal shifts in preferences. The higher incidence of surface behaviour observed in the western Coral Sea in both of these fish occurred during the months of spring, similar to that observed in ET&BF residents. Similarly, the shift to more uniform temperature and depth distributions coincided with those months during summer and autumn, suggesting depth and water temperature preferences may vary to a larger degree on temporal rather than spatial scales. Surface water temperatures in general, increase from east to west across the Coral Sea (Stephens et al. 2002) and it is likely the slight increase in the utilisation of warmer waters at night as the two bigeye moved eastward is a factor of broad-scale oceanographic features of the region.

The depth and water temperature preferences of the one bigeye tagged in the southern part of the ET&BF did vary to some degree from those of bigeye in the northern part of the fishery. However, the habitat preferences of individuals within the northern part of the fishery varied as much, if not to a larger extent as those of individuals from the two areas. Water temperature preferences of this southern fish at night were however, slightly lower in general than those of bigeye tagged in the northern part of the fishery, reflecting the slightly lower surface temperatures in the south, particularly during the autumn and winter months (ca. 22°C in comparison to ca. 25°C). It is possible that water temperature differences between the two areas are not great enough to elicit major changes in the diving behaviour of bigeye inhabiting this area. Given the degree of individual variability observed between individuals in the northern part of the fishery and the small sample sizes of fish in the southern part of the fishery, it is difficult to assess the presence of spatial differences in the habitat preferences of fish within these two areas.

7.2.4.3. Depth distributions in relation to dissolved oxygen levels

Bigeye tuna have been repeatedly reported to regularly inhabit waters with dissolved oxygen levels down to 1-2 ml/L^{-1} (Hanamoto 1987; Lowe et al. 2000; Musyl et al. 2003). While we have no direct observations of dissolved oxygen concentrations frequented by bigeye tuna in the Coral Sea, depth distributions of individuals coupled with dissolved oxygen profiles of the Coral Sea suggest bigeye tuna inhabiting these waters demonstrate similar dissolved oxygen tolerances. Waters less than 2 ml/L^{-1} occur at 500 m depth within the Coral Sea, particularly during spring months, however these levels appear to only occur in a small part of the eastern equatorial Coral Sea. Bigeye tuna tagged in the EPO demonstrated depth distributions across waters with dissolved oxygen levels of approximately 1.5-4.5 ml/L^{-1} (Musyl et al. 2003), with the majority of time spent in waters with dissolved oxygen levels of > 2 ml/L^{-1}. It is possible that bigeye tuna across the Pacific are largely distributed in waters with dissolved oxygen levels of > 2 ml/L^{-1}, rarely frequenting waters with dissolved oxygen levels lower than this. The dissolved oxygen level tolerance of bigeye tuna has been demonstrated to be distinctly higher than that reported for other tuna species inhabiting sub-tropical/tropical waters [e.g. yellowfin and skipjack tuna; the depth distributions for which are limited by a reduction of dissolved oxygen to 3.5 ml/L^{-1} (Brill 1994)], largely due to a higher blood oxygen affinity in the gills coupled with a reduced blood oxygen affinity in the muscles (Lowe et al. 2000). This allows bigeye to maintain a high metabolic rate enabling rapid growth, assimilation of energy and maintenance of high energetic outputs and in turn, allows bigeye to maximize that area an individual can exploit within an environment in which food is patchily distributed both spatially and temporally (i.e. energy speculate; Brill 1996; Korsmeyer et al. 1996).

The need for bigeye to maintain warm muscles temperatures in order to maximize oxygen offloading within the muscles highlights the importance of the regular excursions demonstrated by individuals during the day from colder, deeper waters into warmer, shallower waters. As postulated by Musyl et al. (2003), it may be that water temperature is the major determinant of that habitat frequented and utilised by bigeye tuna.

7.2.4.4. Distribution of depths in relation to lunar phase

Changes in the depth distributions of bigeye tuna at night in response to the phase of the moon have been documented previously (Schaefer & Fuller 2002; Musyl et al. 2003), however, there has been little discussion over the ecological reasons for such a response. As observed in this study, the responses of bigeye elsewhere in the Pacific Ocean were not consistent across lunar cycles, nor were they consistent between individuals. This may at least in part due to a number of factors: (i) individual variability in the reaction of bigeye to lunar phase; (ii) variability in the response of the prey species to lunar phase causing a subsequent variability in the diving behaviour of bigeye; or (iii) variability in environmental conditions such as cloud cover or ocean conditions masking the response of prey species or bigeye to lunar phase. It is likely that the variability in diving behaviour response to lunar phase is a combination of all three.

Zooplankton have been observed to demonstrate mixed reactions to lunar phase. Hernández-León et al. (2001) reported that during the full moon phase, organisms of the deep scattering layer (DSL) did not migrate to the upper mixed layer at night in response to higher predation as a result of higher illumination levels in surface waters. During the new moon phase however, surface waters were attained at night by the diurnally migrating DSL. Conversely, Marchal et al. (1993) observed little difference in depth of SSL on the new and full moon phases, instead reporting that the night-time depth of the SSL was more closely related to the position of the thermocline than any particular isolume. Differing responses of prey items to irradiance and water temperatures are likely to manifest in varying responses in the diving behaviour of foraging predators.

The time of moon rise and moon set, cloud cover, wind conditions and water turbidity are all likely to influence the amount of downwelling irradiance associated with lunar phase in the ocean environment. Water turbidity has been documented to result in changes in the vertical distribution of zooplankton and micronekton by over 100 m, while at the same time significant changes in water temperature salinity and oxygen resulted in little change in depth distributions (Frank & Widder 2002). If diurnally migrating prey species of bigeye are responding to light conditions, these factors are also likely to result in changes in the depth distributions of these prey species and subsequently, the foraging behaviour of bigeye themselves.

Changes in the diving behaviour of predators in response to changes in the diurnal migrations of their prey in association with lunar phase have been documented previously (Horning & Trillmich 1999). Galapagos fur seals were observed to not only undertake deeper foraging dives around the full moon than at any other time of the lunar cycle, but as a further behavioural response to shifts in prey distribution and higher energy costs associated with foraging, concentrate foraging around the new moon (Trillmich & Mohren 1981; Horning & Trillmich 1999). Further investigations into the diving behaviour of bigeye tuna and ambient irradiance as collected by the archival tags in this study may provide further insights into the variability in response to lunar phase observed.

7.2.4.5. Physiological response to water temperature preferences and possible ontogenetic change

The bigeye tuna tagged as part of this study as in other studies (Musyl et al. 2003), demonstrated a wide tolerance for water temperatures, although minimum temperatures were up to 4°C lower than those documented elsewhere. Differences between the ambient water and internal temperatures were as high as 23.4°C, supporting suggestions that vertical excursions are incredibly rapid and thermal conductivity within individuals can also be altered rapidly (Holland et al. 1992). Ascertaining fine scale changes in the thermal conductivity of individuals is difficult however, given the time scales at which both external temperature and internal temperature were collected in this study (four-minute intervals). Initial investigations into the data revealed that because of the rapid excursions undertaken by individuals, temperature data for large portions of either the descent or ascent or both were missing and in many cases partial data were only available for one side of the excursion. There appeared to be little evidence of change in the physiological response of individuals to water temperature differences in the bigeye tagged as part of this study. This may largely be the result of two factors: (i) that the bigeye in this study had already attained the physiological maturity of adults or (ii) that the amount of time spent below 250 m is not an appropriate measure for assessing physiological development. While the physiology and behavioural thermoregulation of bigeye tuna have been the focus of a number of studies (Holland et al. 1992; Holland & Sibert 1994), little has been done to investigate the development of these physiological capabilities, largely due to the limitations of capturing, handling and electronically tagging smaller individuals. Further studies incorporating finer-scale data may allow investigation into such variables as temporal periods for internal temperature recovery after time spent at depth time and temporal scales for internal cooling across a number of size ranges within this species.

Bigeye tuna tagged as part of this study demonstrated little evidence of the relationship between the size of individuals and average depths attained during the day observed in Musyl et al. (2003). Individuals up to 50 cm smaller than the largest individuals recaptured in this study attained similar or deeper depths on average during the day. However, it is difficult to directly compare the results of the two studies for a number of reasons. Firstly, it is not clear at what time the length measurements of Musyl et al. (2003) were taken, either at deployment or on recapture. Secondly of the ten tags presented in Musyl et al. (2003), 50 % were observed to associate with FADs, demonstrating surface behaviour for most of their time at liberty, and a further four associated with a seamount feature and were noted to demonstrate variable vertical movements restricted to a shallower depth range than the one fish unassociated with structures known to influence diving behaviour. Both factors are likely to confound any analyses conducted.

7.2.4.6. Further investigations into the behaviour and habitat preferences of bigeye tuna in the western Pacific Ocean

Data collected as time-dependent series such as those collected by archival tags comprise of highly correlated observations that are ordered in structure. Within such auto-correlated time series the mean does not have the minimum variance property and is inefficient, resulting in severe underestimation of the variance (Chatfield 2004). These data violate the assumption of serial independence required for many statistical tests (Hurlbert 1984) and if ignored, can compromise any interpretation of those data (Reynolds 1994). Further to this, with time series data such as that derived from archival tags, the individual animal is regarded as the experimental unit, thereby requiring animals to be independent of each other. Pooling of the data from a number of individuals can result in a confounding of between-individual variability with within-individual variability leading to a false interpretation of the data.

Quantitative assessments of the behaviour and habitat preferences of bigeye tuna have been limited to date as a result of the nature of these data and the results presented here are also a reflection of this. However, it must be noted that the data presented here constitute the largest time series of depth, external and internal temperature data for bigeye tuna collected to date. Assumptions such as those described above are capable of being overcome with such a dataset and analyses in a statistical environment are available to quantitatively assess such data. Further analyses of the data collected from individuals tagged in the Coral Sea are planned involving non-parametric assessments of diving behaviour and variability in this behaviour both temporally and spatially and will provide us with new insights into the unique physiological capabilities of this species. These investigations are likely to compliment the quantitative definitions of diving behaviour – we were able to successfully use a simple measure of the amount of time spent at depth in order to define “classic” daytime diving behaviour in this species. Further investigations into the quantitative interpretation of diving behaviour are likely to provide insights into seasonal and spatial changes in diving behaviour.

The data collected as part of this study, while limited in many ways, inspire many further questions of this species. Further tagging studies involving a larger number of individuals from the southern part of the Queensland fishery and from further south in New South Wales should be encouraged and may provide further detail into possible spatial differences in the behaviour and habitat preferences of bigeye throughout the ET&BF. Collaborative investigations into behaviour and habitat preferences of non-FAD and seamount associated bigeye should be encouraged as a means of assessing possible broad scale geographic differences between regional populations. Finally, investigations involving a broader size range of individuals may provide insights into ontogenetic changes in the physiology, behaviour and habitat preferences of this species.

7.3. Availability vs. catchability – integrating bigeye behaviour with fishing fleet behaviour.

A. Langley, P. Williams, J. Hampton

7.3.1. Introduction

The tuna longline fishery off the eastern coast of Australia was developed by the Japanese in the early 1950s (Ward 1996). A domestic fishery commenced in the mid 1980s and operates throughout the Australian Fishing Zone (AFZ) from Cape York to south-eastern Tasmania. Bigeye tuna represent a significant component of the longline catch, particularly within the north-western Coral Sea (Hampton & Gunn 1998). In this area, the domestic longline fishery operates throughout the year, although bigeye catch rates are highest during the months May to July. Historically, the Japanese fleet also targeted localized surface aggregations of bigeye and yellowfin during October-November using the hand-line and pole-and-line methods (Ward 1996).

These surface aggregations are targeted by the domestic longline fleet and the availability of surface orientated fish has also enabled the tagging of significant numbers of bigeye both in this study and in a tagging study conducted in the early 1990's (Hampton & Gunn 1998). A strong seasonal trend in bigeye catch rates and tag returns was observed by Hampton & Gunn (1998), indicating seasonal variability in catchability. Two hypotheses to explain the observations from the fishery resulted: 1) that there was a seasonal movement of bigeye into and out of the main fishing area or 2) that there was a gradual dispersal of fish from the release area with a significant proportion of the fish remaining resident in the area for some time and catchability varying seasonally due to variation in oceanographic conditions influencing the vertical distribution of bigeye.

The purpose of this chapter is to further investigate the observed variation in bigeye catchability by comparing those data collected from archival tags (ATs) with the trends in the catch rates of bigeye from the domestic longline fishery. Catch rates from the longline fishery vary diurnally, seasonally, inter-annually and with respect to the lunar period. These trends were examined in relation to the observed changes in the spatial (Chapter 7.1) and vertical distribution (Chapter 7.2) of bigeye from ATs.

The relative catchability of bigeye to longline fishing gear can be subdivided into four main components:

- Availability, defined as the proportion of the population that is present within the broader area of the fishery.
- Vertical vulnerability, defined as the relative extent of the overlap between the depth distribution of the targeted fish and the depth distribution of the fishing gear.
- Spatial vulnerability, defined as the relative overlap between the spatial distribution of the targeted fish population and the area of operation of the fishery. Spatial vulnerability is likely to increase/decrease with increased aggregation/dispersal of the fished population.
- The propensity for the targeted fish to take a baited longline hook. This may vary with respect to the type of bait used and trends in the foraging behaviour of bigeye.

This study largely concentrates on the first three elements of the catchability of bigeye due to limited information are available concerning the dietary habits of and variation in the foraging behaviour of bigeye. For the purpose of this study, catchability was defined as the cumulative effect of changes in the vertical and spatial vulnerability of bigeye.

7.3.2. Methods

7.3.2.1. *Standardised CPUE analysis*

Catch and effort data were available from individual longline sets conducted by the Australian domestic longline fleet operating off the east coast of Australia from 1994 to 2003. The data set was subdivided into two separate areas for analysis: the northern area (north of 19°S) and the southern area (between 19°S and 35°S and east to 160°E). The former area encompassed the area where most of the ATs in this study were released and subsequently recaptured, while the larger southern area included a high proportion of the total fishing effort by the longline fishery (Figure 7.3.1.). Overall bigeye catch rates were very low south of 35°S; consequently, this area was considered to be beyond the main bigeye fishery and not included in analyses.

Catch per unit effort (CPUE) data included the following variables: unique vessel identifier, fishing date, time of set, location of set, number of hooks set, number of hooks between floats (HBFs), and the catch of bigeye, yellowfin, and swordfish (number of fish caught). The catches of yellowfin and swordfish were included in the model to account for differences in targeting behaviour that may influence the catch rate of bigeye and are not explained by the other model variables. The phase of the moon corresponding to the day of fishing was also determined (calculated as the number of days from the full moon). Range checks were applied to each of the main variables and records containing extreme values were deleted.

Annual trends in the distribution of fishing effort were examined with respect to each of the main variables.

A generalised linear modeling approach was applied to describe the relationship between bigeye catch rates and the potential explanatory variables. The dependent variable was the natural logarithm of the catch rate (number of fish caught per hook) of bigeye. Because the model does not accept zero values, zero catch rates of bigeye were substituted by a small nominal value (0.00001 fish per hook). Initially, a simple linear model including all the potential explanatory variables was applied to model the catch rate of bigeye. The catch of yellowfin and swordfish was included in the model to account for differences in targeting practices that may not be accounted for by the other variables in the model. The model had the form:

> Log(CPUE) ~ as.factor(HBF) + polynomial(moonphase,3) + as.factor(yearquarter) + polynomial(hour,3) + polynomial(no. swordfish,3) + polynomial(no. yellowfin,3) + polynomial(latitude,3) + polynomial(longitude,3) + as.factor(vessel)

For each of the main variables included in the CPUE models, the predicted relationship between bigeye catch rate and the variable was examined.

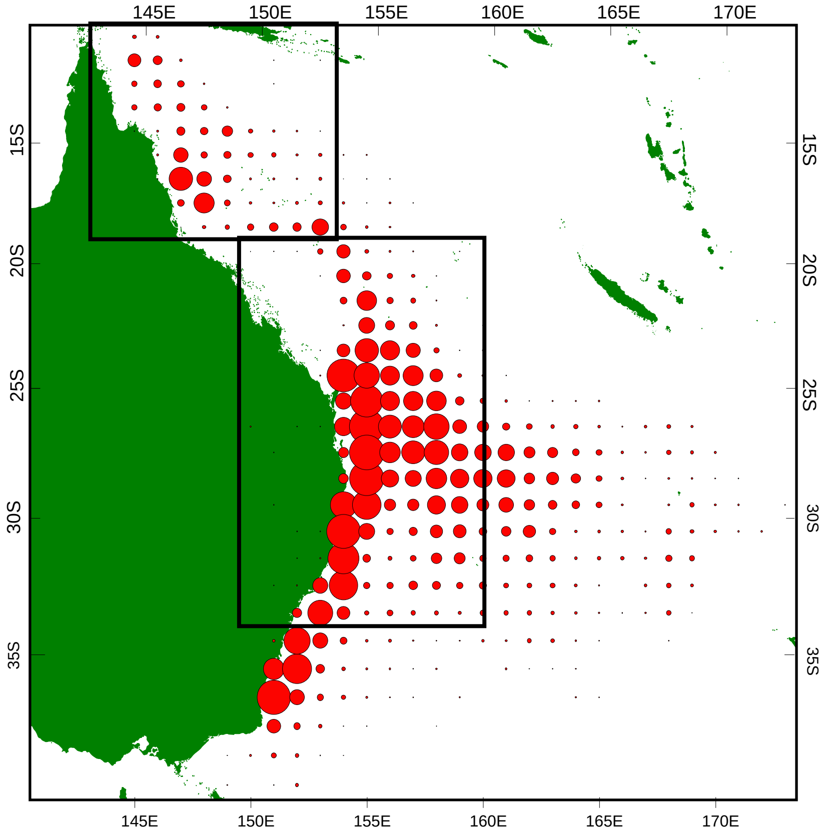


Figure 7.3.1. Distribution of effort by the Australian longline fleet, 1999–2003. The black boxes represent the northern and southern areas included in the standardized CPUE analysis.

Several other model options were investigated to examine the interaction between the main variables that were included in the primary model. These included the factors likely to influence the depth distribution of bigeye relative to the fishing gear (HBFs/moon phase/time of day) and spatio-temporal trends in the catch rate of bigeye (month/latitude). Separate analyses were undertaken for the southern and northern fisheries. For the purpose of this analysis the variables were categorized as follows:

HBFs: three categories: 5-7, 8-9, and 10-20;

time of day: two categories: day-time, < 15:00; night-time, ≥ 15:00;

moon phase: three categories: new moon, half moon, and full moon.

The coefficients derived for the second-order interactions between the categorical variables from the generalized linear model were examined.

7.3.2.2. Longline depth distribution

The depth distribution of individual hooks was calculated using catenary curve geometry (Suzuki et al. 1977) and assuming a floatline length of 10 m, a branchline length of 24 m, and a spacing of 50 m between branchlines. Floatline length, branchline length and branchline spacing were assumed on the basis of recent observations from the fishery (S Beverly[1] personal communication). The predicted depth distribution of the fishing gear was compared for day and night sets and then compared with actual observations from the fishery obtained from time-depth-recorders (TDRs) during recent archival tagging trips (Secretariat of the Pacific Community, unpublished data).

7.3.2.3 Archival tag analysis

Data collected from ATs deployed in the western Coral Sea (see Chapter 6 for details) were used to investigate the perceived effect that light might have on the vertical distribution of bigeye in considering the vertical vulnerability of bigeye to longline gear. For the purpose of this analysis, day was defined as between 20:00 UTC and 07:00 UTC, while night was between 09:00 and 18:00 UTC. The transition periods were excluded from the analysis to avoid the influence of seasonal changes in day length (Figure 7.3.2.).

Trends in the diurnal depth distribution of tagged fish were also examined by month and with respect to moon phase. For the purpose of this analysis, the new/full moon period was defined as the 3.5 days either side of the date of the new/full moon. For the remainder of the lunar phase (half moon), the depth distribution of bigeye was compared for periods when the moon was present and absent in the night sky. At full-moon, the moon rises around dusk and sets around dawn, while at new-moon, the moon rises at dawn and sets around dusk (i.e. similar to the sun). For days after the full-moon, the moon will rise at a progressively later time of the night until the new-moon. Likewise, for days after the new-moon, the moon will set at progressively later times of the night until the next full-moon. This means that, for each day after the full-moon, when the moon is in the night-sky for the entire night, until just before the new-moon (when the moon is not in the night-sky), there will be periods in the night where there is no lunar light (i.e. the moon will not be above the horizon). Time of moon rise and moon set were derived from standard astronomical charts for the Coral Sea region (e.g. http://www.xylem.f2s.com/kepler/js_sunrise_moonrise.html; http://www.roe.ac.uk/info/srss.html).

Archival tag data were analysed to examine the time and depth of capture of individual bigeye. This was undertaken by visual examining the depth profiles of individual fish during several days prior to recapture of the tagged fish. The timing of capture is evident by a lack of strong vertical movement once the fish has been caught on the longline.

Longitude and latitude estimates derived from light data collected by ATs were calculated using ‘Global Position Estimator’ software (Wildlife Computers, Redmond; see Chapter 7.1 for details). Most probable horizontal movements were then estimated from geolocation derived position estimates using Kalman filter analysis (Kftrack *R* Package by J. Sibert and A. Nielsen, http://www.soest.hawaii.edu/PFRP/elec.tagdata/tagdata.html; Sibert et al. 2003). Estimated tracks from individual tags were examined and daily location estimates of tagged fish were calculated relative to the main site of release (approximated as 17°S, 147°E). The monthly direction and total

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[1] Steve Beverly, Secretariat of the Pacific Community.

displacement of individual tagged fish was also determined from the Kalman filter geolocation data.

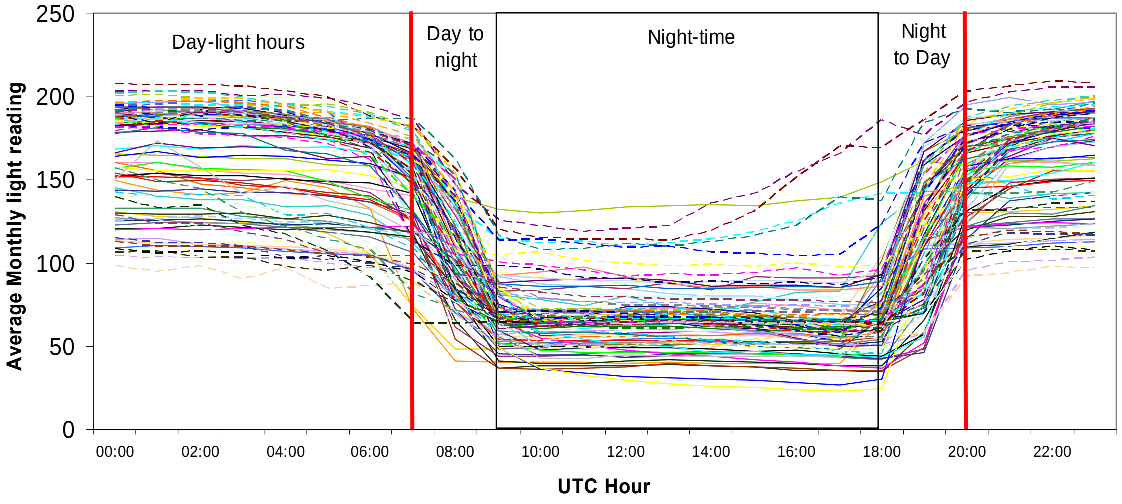


Figure 7.3.2. Average monthly light readings by UTC hour for all tags, showing the day and night UTC hours selected for analyses.

For the northern area of the longline fishery, the monthly spatial distribution of individual tagged fish was compared to the distribution of monthly fishing effort (number of sets) aggregated for the period 1998 to 2003. Fishing effort was aggregated by degree of latitude and longitude and the spatial distribution was defined [contour function, R Development Core Team (2004)]. A qualitative examination of the extent of the overlap between the main area of fishing effort and the monthly distribution of individual tagged fish was then undertaken.

7.3.3. Results

7.3.3.1. CPUE analysis

7.3.3.1.1. Data summary

The southern and northern CPUE data sets included records from 39,748 and 12,154 individual longline sets, respectively.

For the southern fishery (south of 19°S), there were strong trends in the operation of the fishery over the study period with a shift in the distribution of fishing effort to concentrate in the period around the full moon (+/- 1 week) and from predominantly morning sets to mainly night-time sets (Figure 7.3.3.). The fishery also expanded to encompass a broader latitudinal and longitudinal range over the study period (Figure 7.3.3.) as previously described in detail by Campbell & Hobday (2003). There was also an increase in the number of hooks deployed during each set, while the configuration of the fishing gear remained relatively constant (around 8-10 HBFs). The catch composition also shifted from predominantly yellowfin to swordfish and bigeye, although the relative catch rate of each species varied between years (Figure 7.3.3.).

Prior to 1997, the southern fishery principally operated during the second half of the year, while in subsequent years fishing effort was distributed throughout the whole year (Figure 7.3.3.).

Similar trends in the operation of the fishery were less evident in the northern area. However, there was a shift from exclusively morning longline sets to fishing throughout the day and an expansion of the fishery into more northern waters. Catches of yellowfin declined across the period investigated (Figure 7.3.4.). Most vessel fishing days comprised a single longline set, although from 1996 approximately 10-15 % of days fished comprised two sets. This may correspond to the introduction of a regulation that limited individual sets to 500 hooks, thereby, encouraging some vessels to undertake more than one set per day. In contrast, for the southern fishery, the fishing operation almost exclusively involved the deployment of a single longline set during a day of fishing.

In general, catch rates from the northern fishery increased during April-May, reached a peak in May-July, and declined in the following two months (Figure 7.3.5.). A second, shorter peak in catch rates occurred intermittently during August-November. However, there was considerable inter-annual variability in the timing and duration of the main bigeye fishing season and considerable variation in the relative magnitude of the catch rates achieved between the two season peaks. The secondary peak was strongest in 1998 and 1999, with very high catch rates achieved in September and August, respectively. In other years, there was no indication of a strong peak in CPUE during this period (1996, 2000, 2002, and 2003). Catch rates were generally low from December to March (Figure 7.3.5.).

Overall catch rates in the southern fishery were lower than for the northern fishery (Figure 7.3.5.). A general seasonal trend in catches was evident with higher catch rates during the months May-July and low catch rates from November to March. There was no secondary peak in catch rates as observed in the northern fishery during August-November. Catch rates of bigeye varied considerably between years, with high catch rates in 1997 and very low catch rates in 1998 (Figure 7.3.5.). Limited targeting of bigeye occurred in the southern fishery in 1994 and 1995 and, consequently, catch rates were very low. Fishing effort in the southern fishery has been highly cyclical from 1997, due to a synchronicity with lunar phase, with effort peaking about the full moon and negligible during the new moon (Figure 7.3.5.).

7.3.3.1.2. The southern fishery

For the southern fishery, bigeye catch rates generally increased with increasing number of HBFs, although limited data were available from sets with more than 13 HBFs and the coefficients are poorly determined (Figure 7.3.6.).

Catch rates were highest during the full moon period and lowest during the new moon (Figure 7.3.6.). There was a strong diurnal trend in bigeye catch rates with sets deployed during late afternoon and evening having the highest catches, while catch rates were lowest from sets deployed during the morning (Figure 7.3.6.).

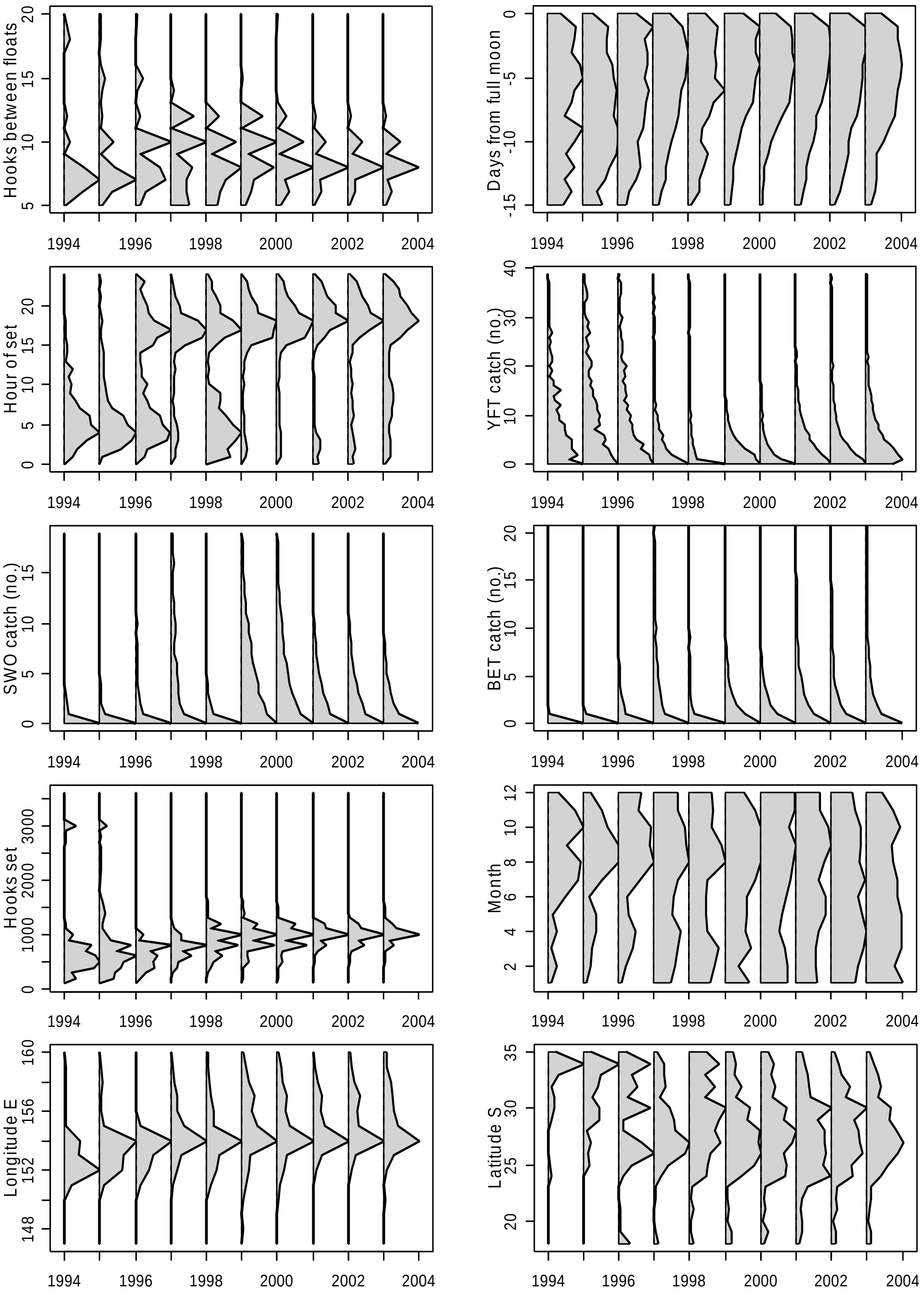


Figure 7.3.3. Annual distribution of the data records with respect to the main variables included in the catch and effort data set for the southern fishery (south of latitude 19°S).

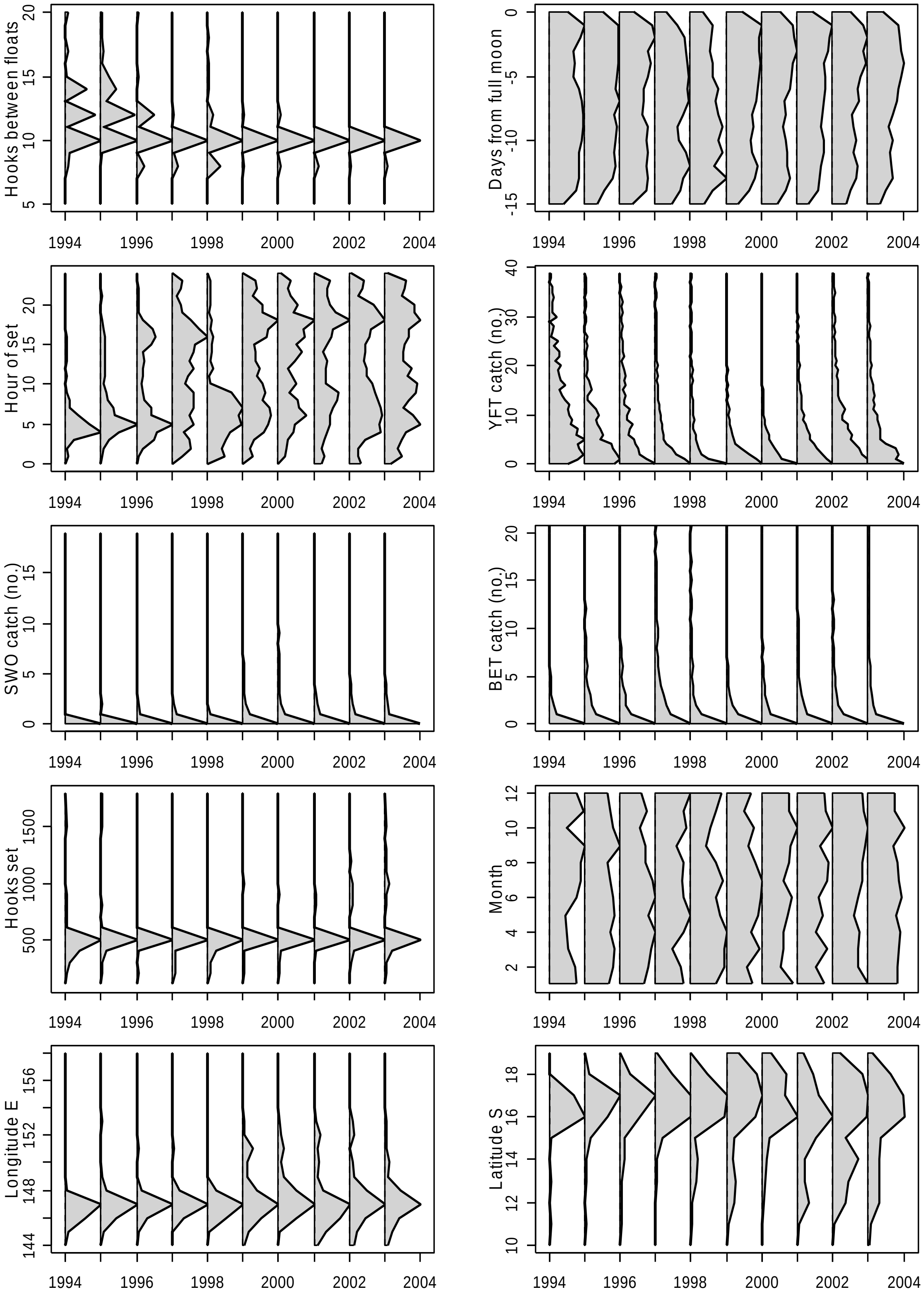


Figure 7.3.4. Annual distribution of the data records with respect to the main variables included in the catch and effort data set for the northern fishery (north of latitude 19°S).

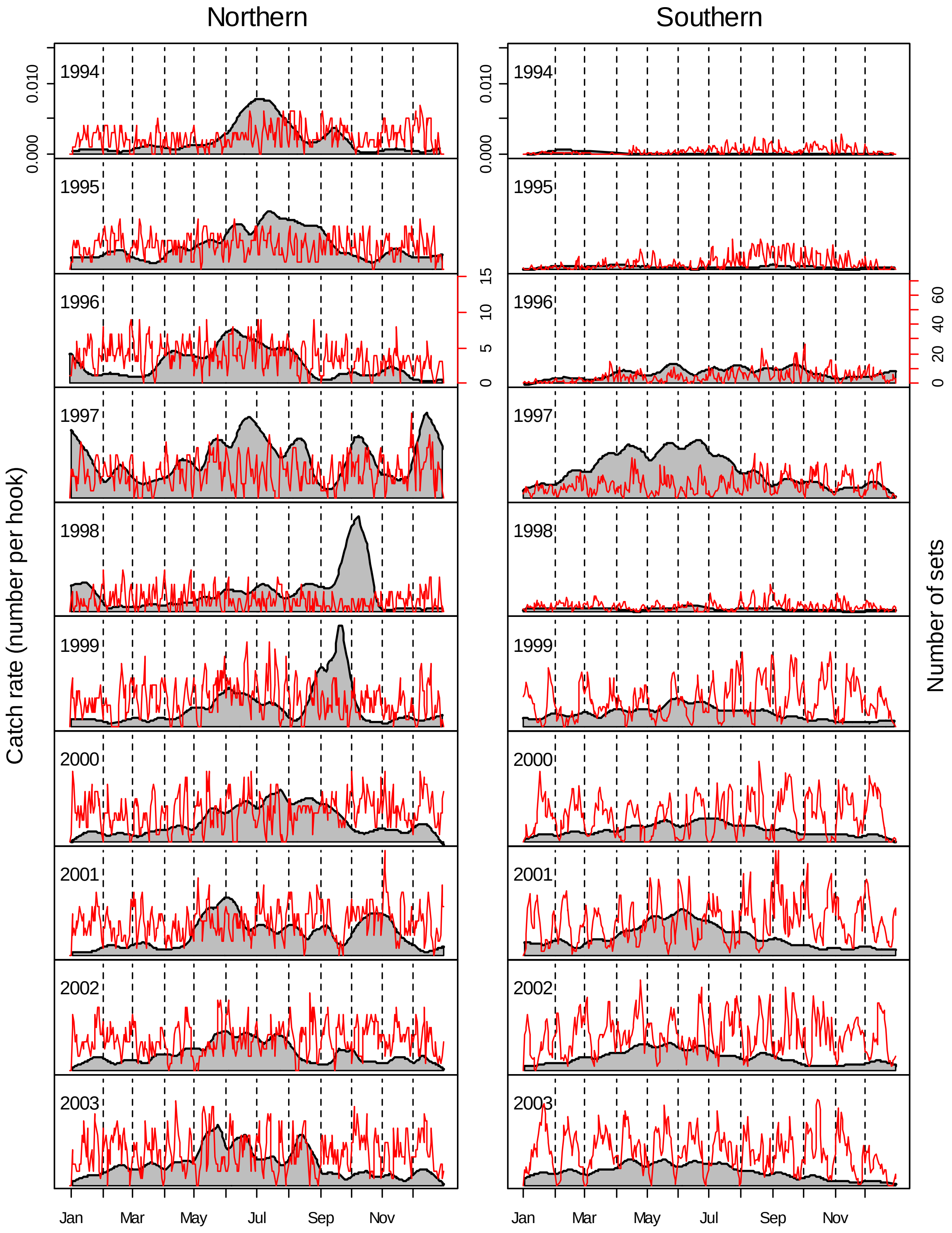


Figure 7.3.5. Seasonal trends in the catch rate (number of fish per hook) of bigeye (grey) and the daily number of sets (red line) from the northern (left) and southern (right) longline fishery for the period 1994 to 2003. The catch rate is presented as a 30-day running average. Note the scales for the daily number of sets is different between the two areas (y-axis, third row).

The latitude and longitude variables accounted for spatial differences in bigeye catch rates, confirming a higher CPUE of bigeye in the northern area of the Coral Sea within the Australian Exclusive Economic Zone (EEZ; Figure 7.3.8.).

A strong seasonal trend in catch rates of bigeye was evident, with highest catch rates occurring during the second quarter of the year (April-June) and lowest catch rates occurring in October-December (Figure 7.3.6.). Considerable inter-annual variability in the relative catch rate of bigeye was also evident. High catch rates occurred in 1997 and 2001, while catch rates were low in 1994-1996 and 1998 (Figure 7.3.6.).

7.3.3.1.3. The northern fishery

For the northern fishery, catch rates were highest for shallow gear configurations (less than 8 HBFs), although the coefficients were poorly determined due to the small number of records for these gear categories. Similarly, higher catch rates were also predicted for the deepest gear (greater than 16 HBFs), but these coefficients also have low precision (Figure 7.3.7.).

The relationship between bigeye catch rate and both moon phase and time of the day of the set were similar to those relationships described for the southern fishery, i.e. highest catch rates during the full moon and from evening-night sets (Figure 7.3.7.).

Catch rates were highest in the southern area of the northern fishery (south of latitude 16°S) (Figure 7.3.7.).

Similar to the southern fishery a strong seasonal trend in bigeye catch rates was evident, with catch rates highest during the second and third quarters of the year and low during the remaining period. The duration and magnitude of the seasonal peak in catch rates varied inter-annually, with high catch rates in 1997 (Figure 7.3.7.).

7.3.3.1.4. Fishery comparison

The parameterisation of the diurnal and lunar trends in the catch rates of bigeye were very similar in the CPUE models for the two fisheries. This indicates that bigeye demonstrate a behavioural response to these two variables (time of day and lunar phase) that directly influences the longline catch rate of the species. The fishery has evolved in response to this behaviour, targeting the species by increasing fishing activity during the evening and around the full moon period (Figure 7.3.3. and Figure 7.3.4.).

Both fisheries exhibit considerable inter-annual variation in bigeye catch rates. Catch rates in the two fisheries in the second quarter demonstrated a significant correlation in the two models (correlation coefficient: 0.7, $p = 0.03$) with catch rates in the forth quarter demonstrating a high degree of correlation, although this was not statistically significant (correlation coefficient: 0.6, $p = 0.09$).

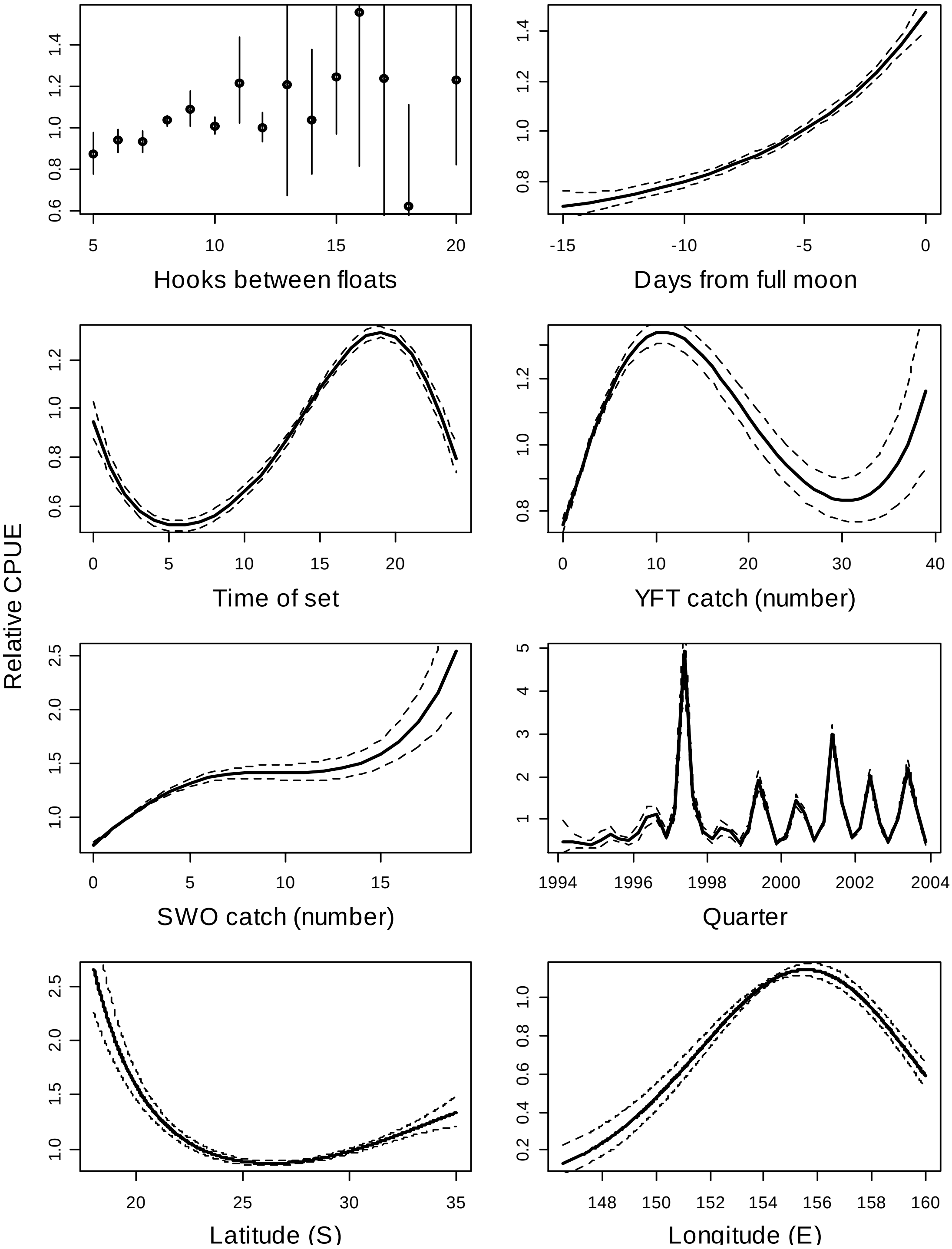


Figure 7.3.6. Predicted relationship between bigeye catch rate for the southern fishery and each of the main variables included in the generalized linear model. The dashed lines represent the confidence interval (+/- 2 standard errors).

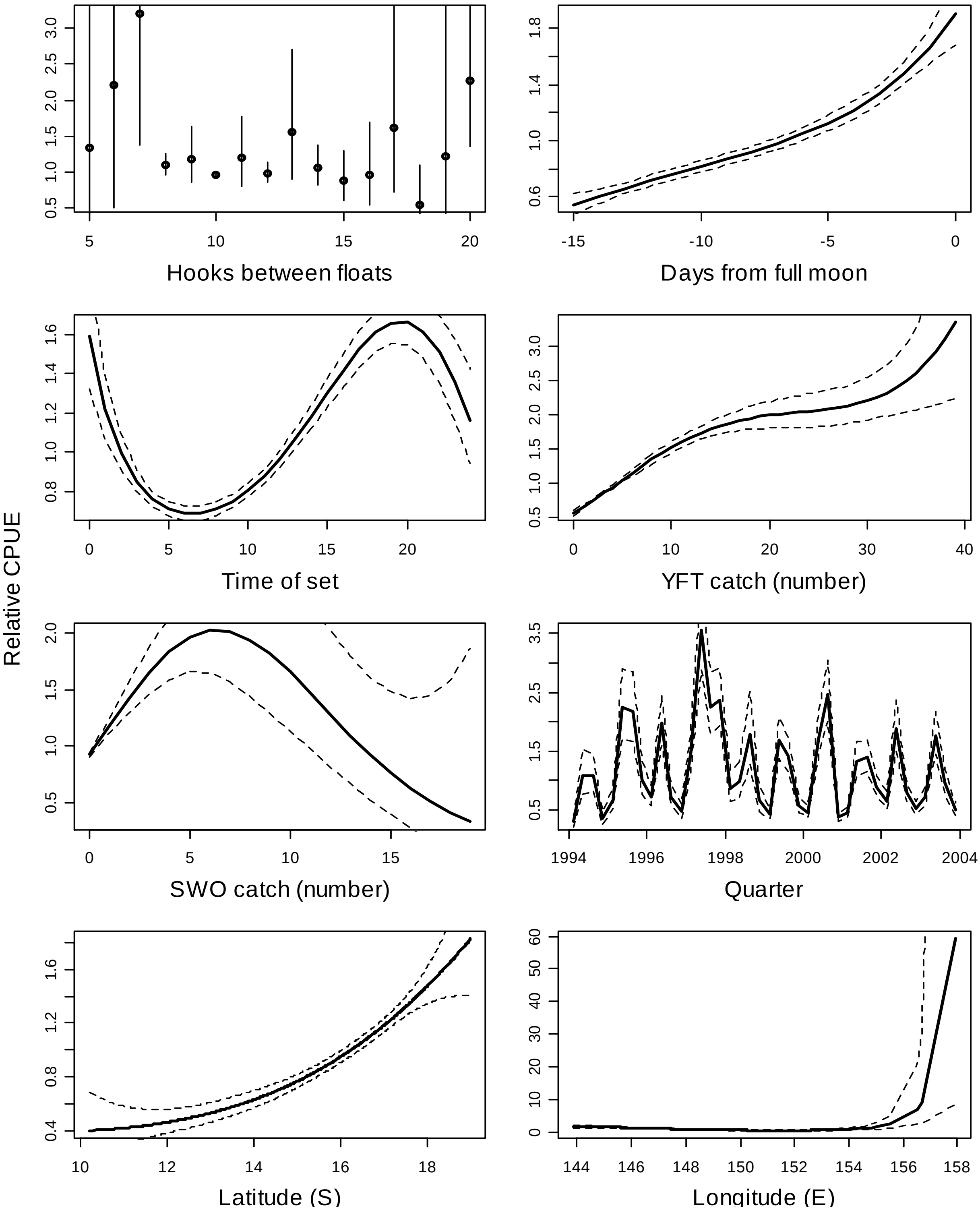


Figure 7.3.7. Predicted relationship between bigeye catch rate for the northern fishery and each of the main variables included in the generalized linear model. The dashed lines represent the confidence interval (+/- 2 standard errors).

There was no comparable trend in the bigeye catch rates with respect to the HBF configuration between the two fisheries. However, the coefficients for the individual categories were poorly determined at the extremes of the range, reducing the power of any comparison between the two CPUE models.

The two models revealed comparable trends in the catch rate of bigeye relative to the catch of the two other associated species (yellowfin and swordfish). For both CPUE models, catch rates of bigeye increased with increasing catch of yellowfin and swordfish, up to a catch of about 5 swordfish per set and 10 yellowfin per set. The relationship was less well determined for the larger catches of the two associated species, partly due to the lower incidence of larger catches. Nevertheless, the two models do indicate some degree of association between these three species.

7.3.3.1.5. Interaction models

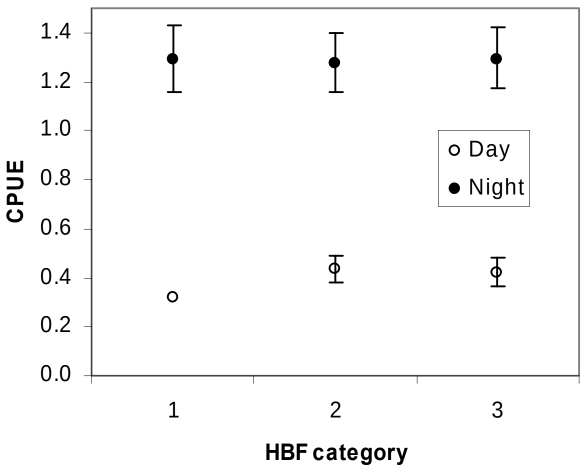
Interactions between the three main variables likely to influence the depth distribution of bigeye (time of day and moon phase) and the depth distribution of longline gear (HBF) were investigated in a simple GLM model. For the southern fishery, the model explained 11 % of the observed variation in the natural logarithm of bigeye tuna catch rate (numbers per hook).

Catch rates were highest during night-time/full moon for all gear configurations and lowest during the day, particularly during the new moon (Figure 7.3.8.). Overall, night-time catch rates were correlated with lunar intensity, with catch rates increasing from new moon to full moon. During the night, there was no difference in catch rates between gear configurations, with the exception of lower CPUE for the deeper gear (≥ 10 HBFs) during the night-time/half moon. Day-time catch rates were comparable during full moon and half moon, but lower during the new moon. For all lunar periods, day-time catch rates were lowest for the shallowest gear configurations (5-7 HBFs; Figure 7.3.8.).

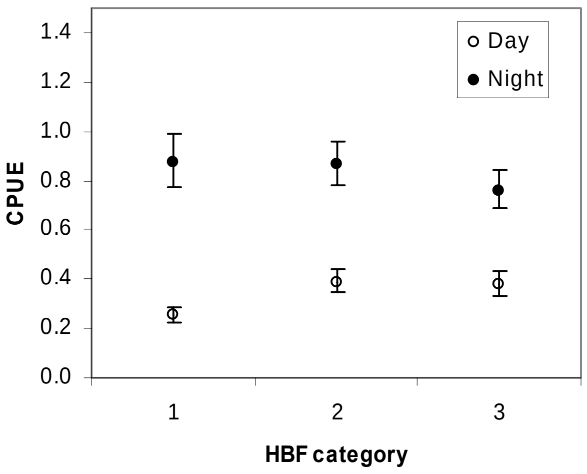
The analysis was repeated for the northern fishery area. However, the coefficients were determined with very large confidence intervals and, consequently, were not sufficiently precise to investigate trends between the three variables.

Inclusion of latitude and month as interaction terms in GLMs revealed distinct spatio-temporal trends in the catch rates of bigeye from the two fishery areas. For the southern fishery, catch rates were low in March, particularly south of 23°S (Figure 7.3.9.). An initial seasonal increase in catch rates occurred in April, with catch rates increasing south of 23°S, while remaining relatively low further north. As the season progressed, most of the increase in catch rates occurred in the more northern area of the fishery (between 23°S and 19°S) and this area yielded the highest catch rates in May-June (Figure 7.3.9.).

Full moon



Half moon



New moon

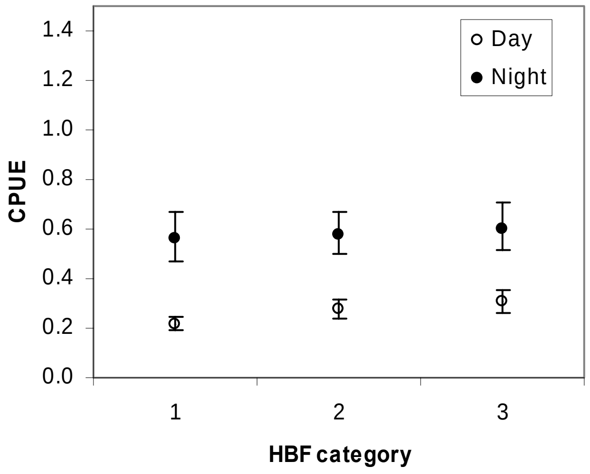


Figure 7.3.8. Predicted catch rates of bigeye tuna (number per 1000 hooks) and confidence interval by HBF category (1, 5–7; 2, 8–9; 3, 10–20), diurnal period, and moon phase from the southern fishery interaction model.

Catch rates declined sharply in July, particularly between 21-26°S, although higher catch rates were achieved in the north (27-32°S) and south (around 20°S) of this (Figure 7.3.9.). Between August and March, average bigeye catch rates remained at a low level throughout the fishery.

These trends in catch rate are suggestive of northern movement of fish during April-May to aggregate within the northern area of the fishery during May-June and then subsequently disperse southward and possibly northward during July.

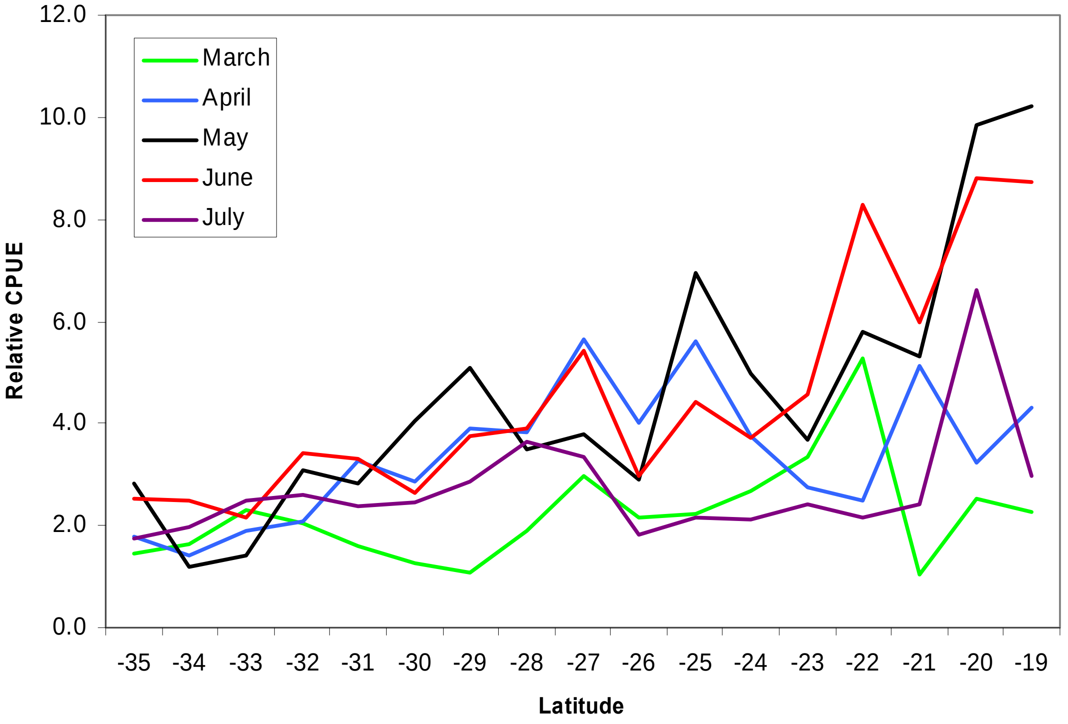


Figure 7.3.9. Relative CPUE indices derived from the interaction terms between month and latitude included within the generalised linear model of bigeye CPUE for the southern fishery.

Catch rates were low throughout the northern fishery during December-March (Figure 7.3.10.). Catch rates generally increased in April in the southern area of the study area (around 17°S) and continued to increase in this vicinity in May and June. During May, catch rates were also high further north at approximately 13°S (Figure 7.3.10.). During June-July, highest catch rates were achieved across the area of 16-17° S. Catch rates at around 13°S peaked again in August, while catch rates between 16-17° S declined.

During September-December, catch rates were considerably lower than the previous months and there was an indication of a shift in the main distribution of fish from around 17°S to around 15°S (Figure 7.3.10.). There were also exceptionally high catch rates achieved further north during September (at 12°S), although data from the area are limited and, consequently, the index is poorly determined. These trends in catch rate for the northern fishery indicate that the main aggregation of fish occurs in the southern area of the fishery during May to July. A separate aggregation develops around latitude 13°S in May and this aggregation may augment the southern aggregation, given the decline in catch rates in the area in June-July and subsequent increase in CPUE in August. The main aggregation appears to dissipate during August and there appears to be a general northward movement of fish from August to November, with an associated decline in CPUE. However, localized areas with exceptionally high CPUE are evident from August to November (see Section 7.3.3.3.). Due to the localised distribution of these aggregations, this component of the fishery does not translate to a strong latitude/month interaction. Nevertheless, they are likely to partly contribute to the higher catch rates during October and December at around 15-16°S (Figure 7.3.10.).

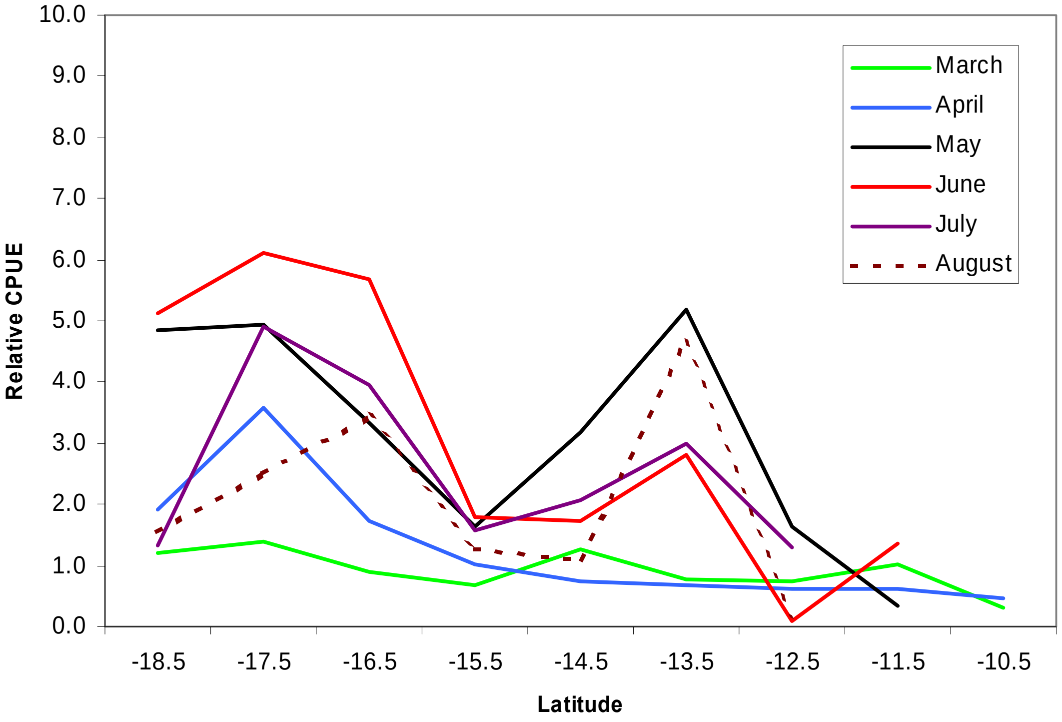
7.3.3.1.6. Fishing depth distribution

The predicted depth distribution of longline hooks, as derived from catenary geometry, was multimodal with each mode representing the predicted depth of hooks based on the distance of the branchline from the nearest floatline. Most (85 %) of the hooks appear to have settled within the 60-160 m depth range (Figure 7.3.11.) with only a small proportion of the hooks set deeper than 200 m. There was no apparent difference in the depth distribution between day and night (Figure 7.3.11.).

There was considerable overlap in the depth distribution of the three gear categories defined in this study (Figure 7.3.12.). Consequently, it is not surprising that large differences in the catch rate of bigeye were not observed between the three HBF gear configurations (see Figure 7.3.8.).

Limited observations of actual gear depths are available from a small number of TDRs deployed in the fishery (Table 7.3.1.). These results indicate that the predicted depths from catenary geometry substantially over-estimate the actual depth of the gear, particularly for hooks in the central position between floats.

Depth data collected from those bigeye for which ATs were still functional on recapture (n = 8) revealed that all fish were caught within the 50-160 m depth range (Table 7.3.2.). Most fish were captured between evening and early morning. An examination of the depth profiles of the bigeye indicated that one fish was captured shortly after a return to the shallower surface water following excursions into deeper waters greater than 400 m (e.g. Figure 7.3.13), while all other fish were caught either at night (ATs 99-190, 99-243, 99-224, 99-216, 00-112) or during the day during periods in which they were demonstrating surface behaviour (99-262, 99-213, 99-237).



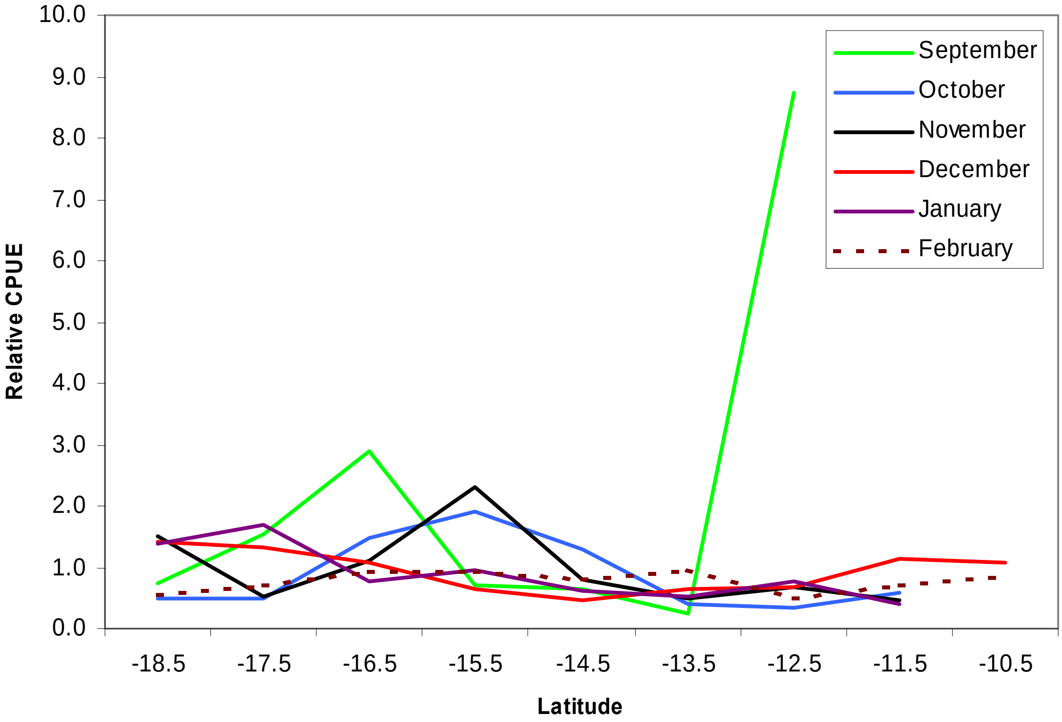


Figure 7.3.10. Relative CPUE indices derived from the interaction terms between month and latitude included within the generalised linear model of bigeye CPUE for the northern fishery.

7.3.3.2. Archival tag analysis

7.3.3.2.1 Bigeye depth distribution

Archival tag data reveal bigeye are generally restricted to the surface waters (< 150 m) during the night, with about 84 % of all records in depths of less than 100 m (Table 7.3.3.and Figure 7.3.14.). In contrast, during day-time bigeye tuna released in the Coral Sea were distributed over a much wider depth range, with most depth recordings falling into two distinct ranges 0-150 m (14 % of all records) and 250-500 m (77 %).

Table 7.3.1. A comparison of average depth (m) recorded from TDRs (+ branchline length) deployed in the Australian domestic longline fishery for different gear configurations and predicted depths from catenary geometry. Source of TDR data: Bruno Leroy and Steve Beverly, SPC, unpublished data.

Date of fishing	HBF	Location of TDR (hook no.)	Line shooter	True hook depth (m)	Predicted hook depth (m)
30/03/2004	12	6	No	69	220
25/04/2004	20	1	Yes	64	77
02/05/2004	20	10	Yes	164	336
28/04/2004	10	1	Yes	54	76
15/08/2000	10	5	?	84	191
16/08/2000	8	4	?	72	162
16/08/2000	8	4	?	90	162

A seasonal trend is evident in the observed day-time depth distribution of bigeye. During January to July, bigeye principally occurred in the 250-500 m depth range during the day, while in August-December the depth distribution was bimodal, with fish principally occupying the 10-150 m and 250-500 m depth ranges (Figure 7.3.15.). During August-December, almost all tagged fish exhibited an extended period of surface orientated activity (Figure 7.3.15.). This activity may persist for several months and for some fish may continue through October-December. Correspondingly, there was also lower proportion of time spent in the shallower depth range at night during August-September (about 50 %) compared to February-June (about 70 %; Figure 7.3.16.).

A detailed analysis of the diurnal and seasonal trends in depth distribution of bigeye is described in detail in Chapter 7.2.

7.3.3.2.2. Depth distribution in relation to lunar phase

The archival tagging data reveal that the depth distribution of bigeye during night-time is influenced by lunar intensity (Table 7.3.3. and Figure 7.3.17.). A higher proportion of time is spent in surface layer (0-50 m) during the new moon period than any other (night-time) period of the lunar cycle, and conversely, a higher proportion of time is spent in the deeper layer (50-150) during the full moon period than any other (night-time) period of the lunar cycle (Figure 7.3.17). Further, in more discrete periods of low lunar intensity outside of the new-moon period, i.e. when the moon is not present in the night sky, bigeye were recorded spending a significant proportion of the time in the 0-30 m depth range (Figure 7.3.17.). Also, during periods of high luminosity outside the full moon period (i.e. between moon rise and set), bigeye were distributed at greater depth, principally in the 50-80 m depth range (7.3.17.).

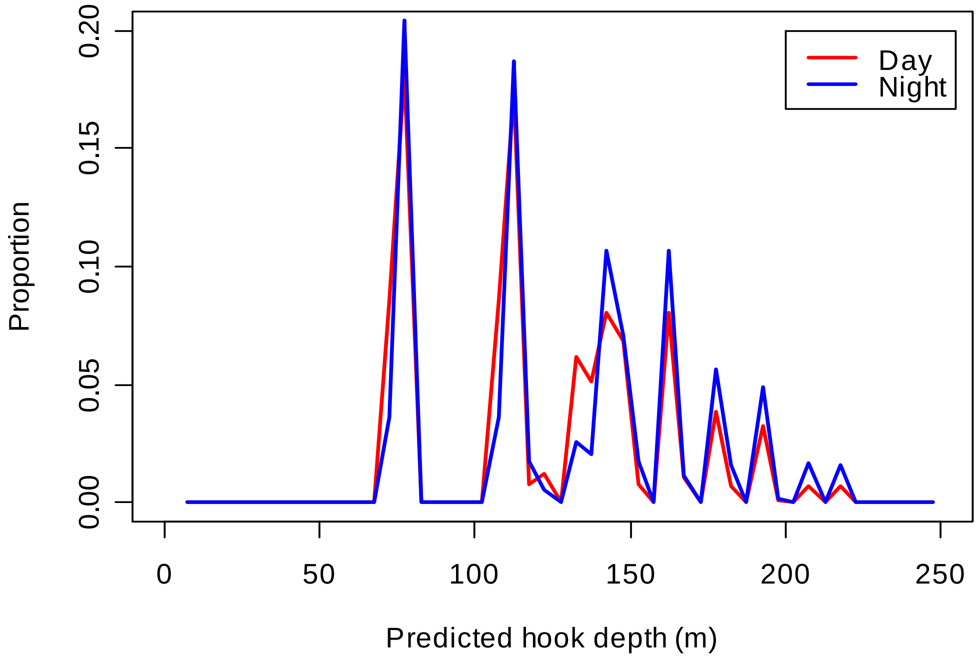


Figure 7.3.11. Predicted distribution of hook depths (m) for day and night longline sets from all years combined. Hook depths were predicted from catenary geometry.

The night-time depth profiles of an individual tagged bigeye tuna (99-237) illustrate the relationship between depth and light intensity (Figure 7.3.18). During the period following the setting of the moon, this fish undertook repetitive forays into very shallow depths (about 10 m) followed by a number of deeper dives (to about 100 m). Forays of this nature were less frequent while the moon was visible in the sky and tended to only occur immediately prior to the setting of the moon when the moon was at a low angle and, therefore, light intensity was low (Figure 7.3.18). During the period of high lunar intensity, this fish tended to remain at a depth of about 50 m. The analysis could be refined further by looking at the level of cloud cover that will also affect the lunar intensity.

7.3.3.2.3 Archival tagging geolocation data

The predicted tracks of individuals suggest there is a close association of the bigeye tagged in this study with the north-western area of the Coral Sea (Figure 7.3.19.). There remains some concern regarding the accuracy of geolocation in determining the position of an individual (see Chapter 7.1. for a more detailed discussion of this). This was particularly evident in Kalman filter-derived position estimates, with thee estimation of the position of one individual incorporating time spent on the land mass of continental Australia (Figure 7.3.19.).

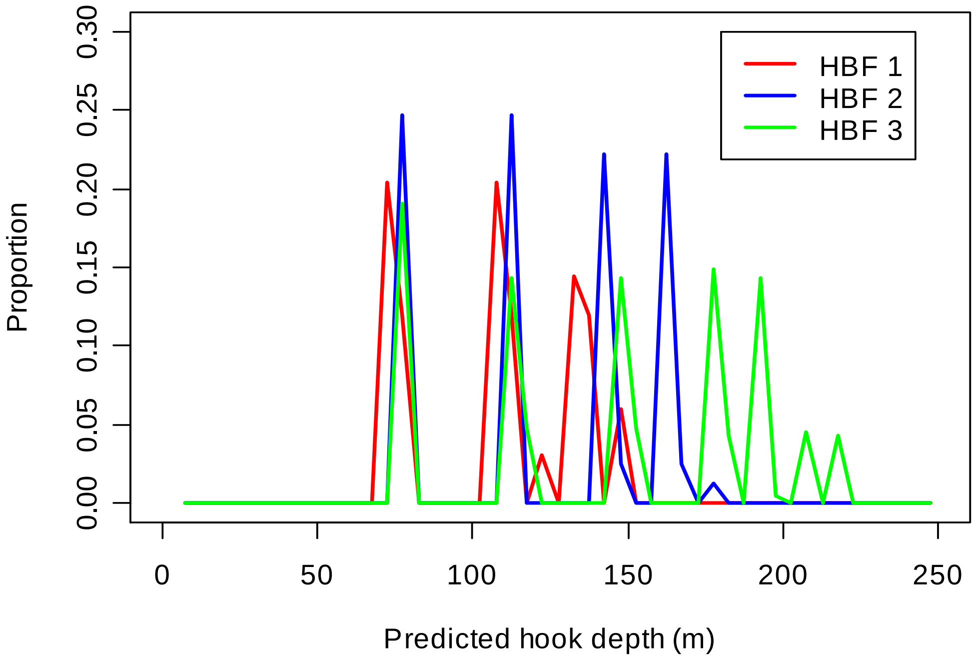


Figure 7.3.12. Predicted distribution of hook depths (m) for the three HBF categories from all years combined. Hook depths were predicted from catenary geometry.

The majority of ATs deployed on bigeye in this study were released in the northern area of the longline fishery (around 17°S, 147°E). Of those tagged, only two fish (98-353 and 99-213) undertook long distance migrations from the tagging site, while the remaining bigeye remained within 500 km of their release location (Figure 7.3.20.). All fish (except 99-190) were tagged during October and migrated from the tagging site soon after release attaining the greatest distance from the tagging site during December-April before converging on the area of tag release during May-July (Figure 7.3.20.). However, care must be taken in interpreting this return movement as position estimates derived via Kalman filter techniques are constrained by release and recapture information. Most fish were recaptured during this period, although one fish (98-363) remained in the area throughout summer and subsequently migrated northward from the area in July.

One fish (99-213) undertook a large-scale migration and then returned to the area of tagging briefly in October 2002 before undertaking another period of long-distance migration (Figure 7.3.20.). The light sensor on this tag failed in December 2002 with the fish remained at liberty until October 2003 when it was recaptured again in the vicinity of the release site.

Table 7.3.2. Recapture details for individual tagged bigeye.

Tag number	Date of recapture	Time of recapture	Depth of recapture (m)
98479	21/11/1999	20:11	120
99190	9/06/2001	02:43	160
99243	22/05/2002	02:22	75
99224	22/06/2002	00:07	59
99216	28/09/2002	23:48	84
99262	26/09/2002	08:54	59
00112	29/09/2002	16:22	97
99213	10/09/2003	10:45	123
99237	10/07/2003	07:18	123

An examination of monthly gross movements of the bigeye tagged in this study indicates that bigeye were least mobile during June, coinciding with the seasonal peak in catch rates from the fishery (Figure 7.3.21.). Limited data were available for the July-October period. Following tagging in October, most bigeye migrated either northward or south-eastward during November. There was no consistent trend in the direction of movement during the subsequent months with the exception of a generally southern movement during March (Figure 7.3.21.). Most of these fish were all north of 17°S during the period, while the predominantly northward movement in May was from bigeye south of 17°S.

7.3.3.3 Fishery interaction

Limited information is available concerning the depth distribution of longline gear, although the best available information indicates that most longline hooks are deployed within the 50-150 m depth range. Gear configuration, in terms of HBFs, has remained relatively constant over the last decade however; fishermen are likely to employ individual setting strategies in an effort to vary the depth of the gear. The result of this is a variability in setting depth unable to be included in the analyses presented here.

There has also been an observed shift in the time of day and lunar phase of fishing activity that have increased the efficiency of longline fishing effort with respect to targeting bigeye. In the northern fishery, average weekly catch rates of bigeye, particularly during the night, generally increase on the full moon, while catch rates are lowest during the new moon (Figure 7.3.22. and Figure 7.3.23.). The increase in catch rate (catchability) of bigeye during the full moon is consistent with the high overlap between the night-time depth distribution of bigeye and the assumed depth range of the longline gear (50-150 m). Conversely, during the new moon period, bigeye spend a higher proportion of their time in shallower water (less than 50 m) and, consequently the overlap with the depth distribution of longline gear (and therefore their catchability) is lower.

The peaks in CPUE around the full-moon in day-time sets (e.g. Figure 7.3.22.) are difficult to explain from the information available on the depth distribution of bigeye. One possible explanation is that the set start time recorded in the catch and effort data was incorrect due to confusion between recording times using the 12-hour or 24-hour clock; for example, a longline set at 05:00 PM may have been incorrectly recorded as 05:00 rather than 17:00. A cursory examination of some logbook data suggests that such errors may have occurred but these issues require further investigation.

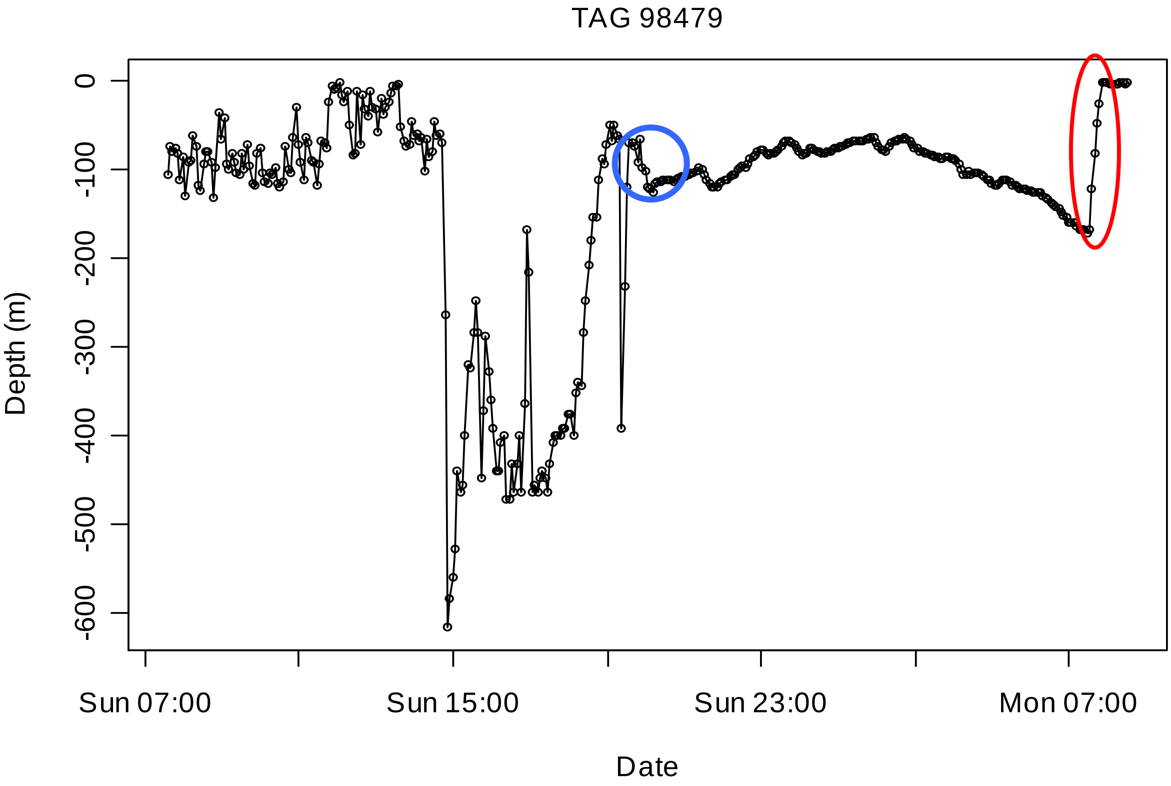


Figure 7.3.13. An example of a depth profile of a tagged bigeye (AT 98-479) during the period around the time of capture. The fish was caught at 120 m at 20:00 on Sunday night (blue circle) and hauling of the line commenced at 08:00 Monday morning (red oval). Time is Australian eastern standard time (UTC+10 hours).

During September-December, there was often a limited period of exceptionally high catch rates in the north-west Coral Sea fishery, although the duration and timing of this period varies between years (Figure 7.3.23.). During this period, highest catch rates tend to be associated with the full moon period, as previously observed. Catch rates during the day-time are exceptionally high compared to the remainder of the year and in many weeks exceed the corresponding night-time catch rates (Figure 7.3.23.). This period overlaps to some extent with the observed increased activity of bigeye in shallower waters across the late winter/early spring period (see Figure 7.3.15.).

Table 7.3.3. Proportion of recorded times of bigeye with archival tags for selected periods and depth ranges, all data combined.

Depth range (metres)	% of time spent
Day	
0-150	14.2
150-250	5.3
250-500	76.9
Night	
0-100	83.8
0-150	94.7
Night with moonlight	
0-30	11.7
0-50	22.7
50-100	62.4
0-100	85.1
Night without moonlight	
0-30	31.6
0-50	45.8
50-100	37.5
0-100	83.3

The shift in the day-time depth distribution of bigeye between July and October provides an explanation for the increase in fleet CPUE (approximately five-fold) due to the increased overlap between the depth distribution of the fishing gear and the bigeye population. The increase in surface activity during the day also means that the fish aggregations are more easily detected and fishing vessels can more readily target their sets in the areas of higher bigeye abundance. Sets with very high catch rates, exceeding one fish per hundred hooks, generally occurred in a discrete location during an individual month (Figure 7.3.24.) supporting the assertion that high CPUE in the latter period of the year is attributable to localised aggregation of bigeye.

In general, catch rates from night-time fishing operations also increased markedly during these periods, although in some months night-time catch rates were actually depressed (Figure 7.3.24.). Additional factors to those presented here clearly influence the relative catchability of bigeye. These factors may include an increase of the overall abundance of fish in the area (availability), localised aggregation of fish, and/or increased feeding activity resulting in a greater probability of individual fish taking hooks.

Monthly geolocation data from individual tagged bigeye were compared to monthly distributions of fishing effort in the northwestern Coral Sea to investigate the broader scale seasonal interaction between bigeye tuna and the longline fishery. During January and February, fishing effort is relatively low and more widely distributed, mainly in the area to the north of the main fishing ground (centered at 17°S, 147°E; Figure 7.3.25.). Geolocation derived position estimates also indicated that tagged bigeye were distributed further north during this period. From January to May there was a general southward movement of fishing effort. Fishing effort became increasingly concentrated in the main fishing ground in tandem with a shift in the location of the individual tagged fish (Figure 7.3.25.). The geolocation positions suggest that tagged fish were tightly aggregated in the vicinity of the main fishery area during May and June.

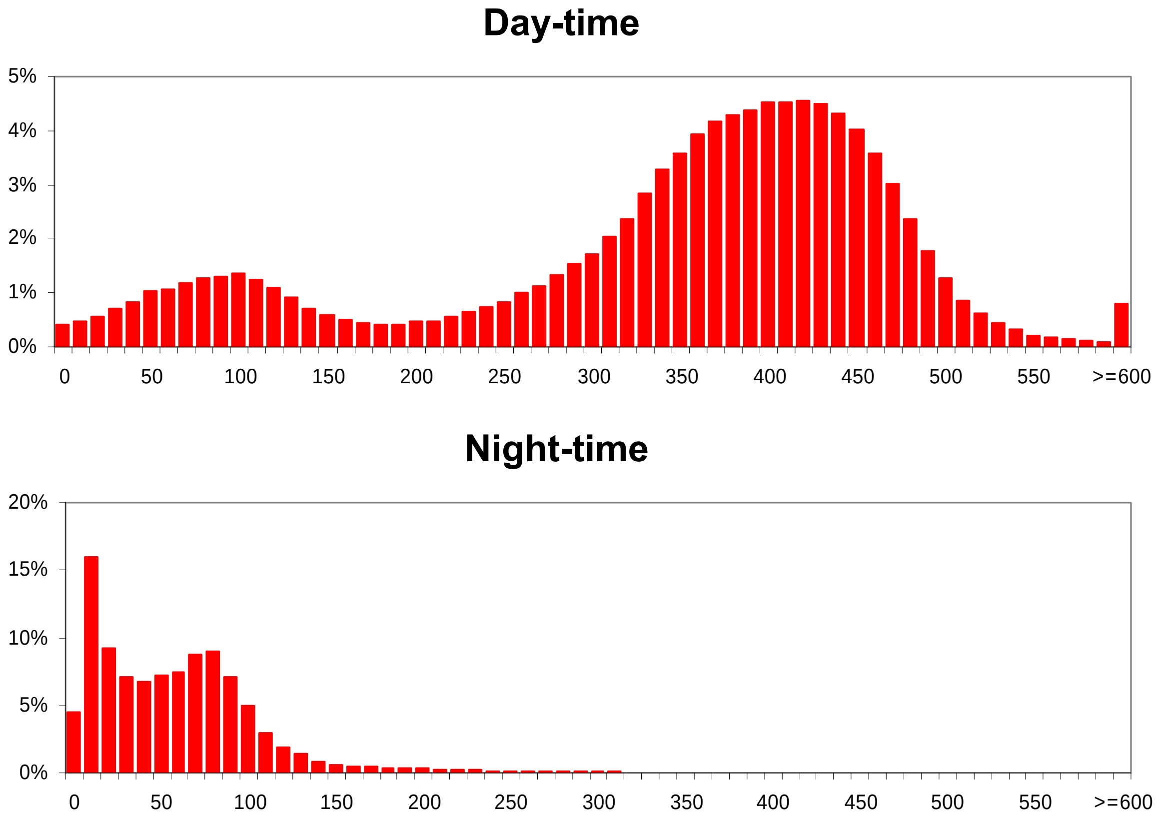


Figure 7.3.14. Distribution of recorded times of bigeye with archival tags by depth for day-time (top) and night-time (bottom) periods, all data combined.

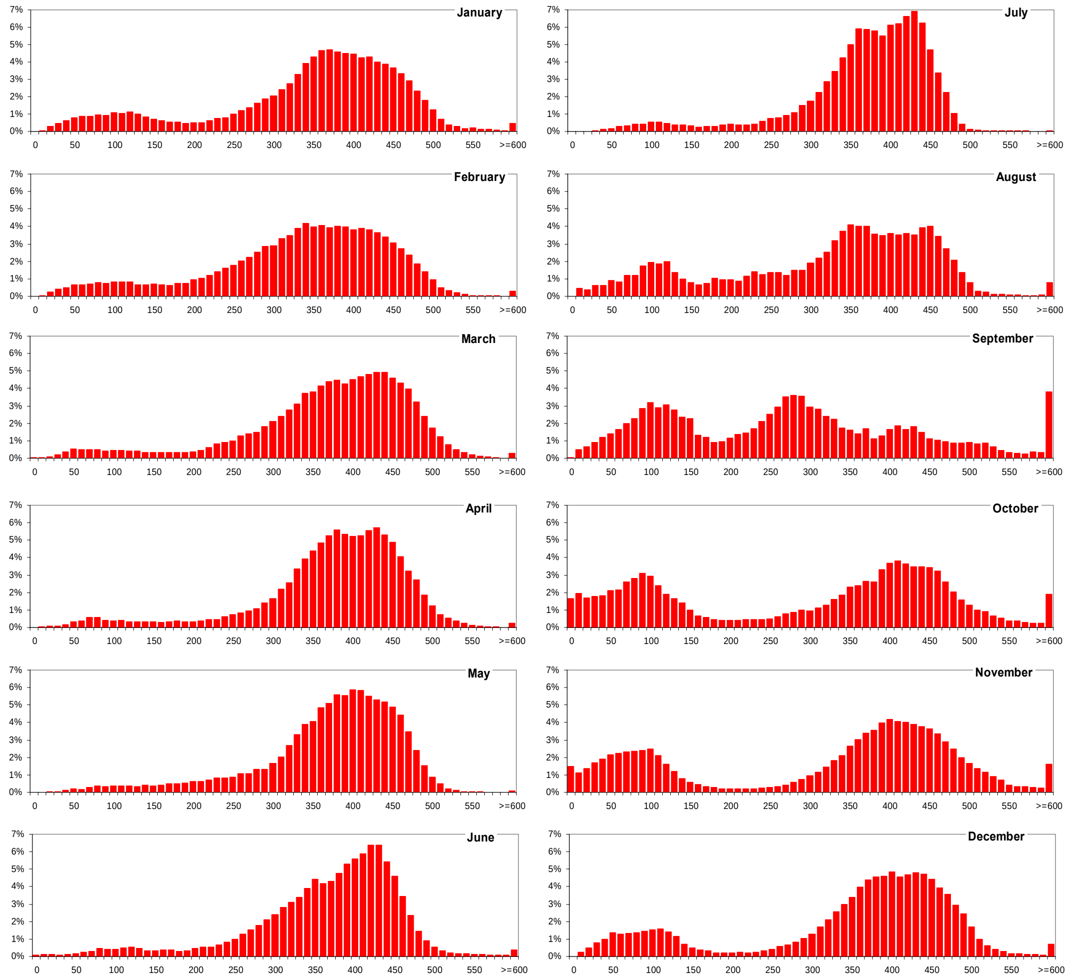


Figure 7.3.15. Monthly distribution of recorded times of bigeye with archival tags by depth for day-time periods only, all data combined.

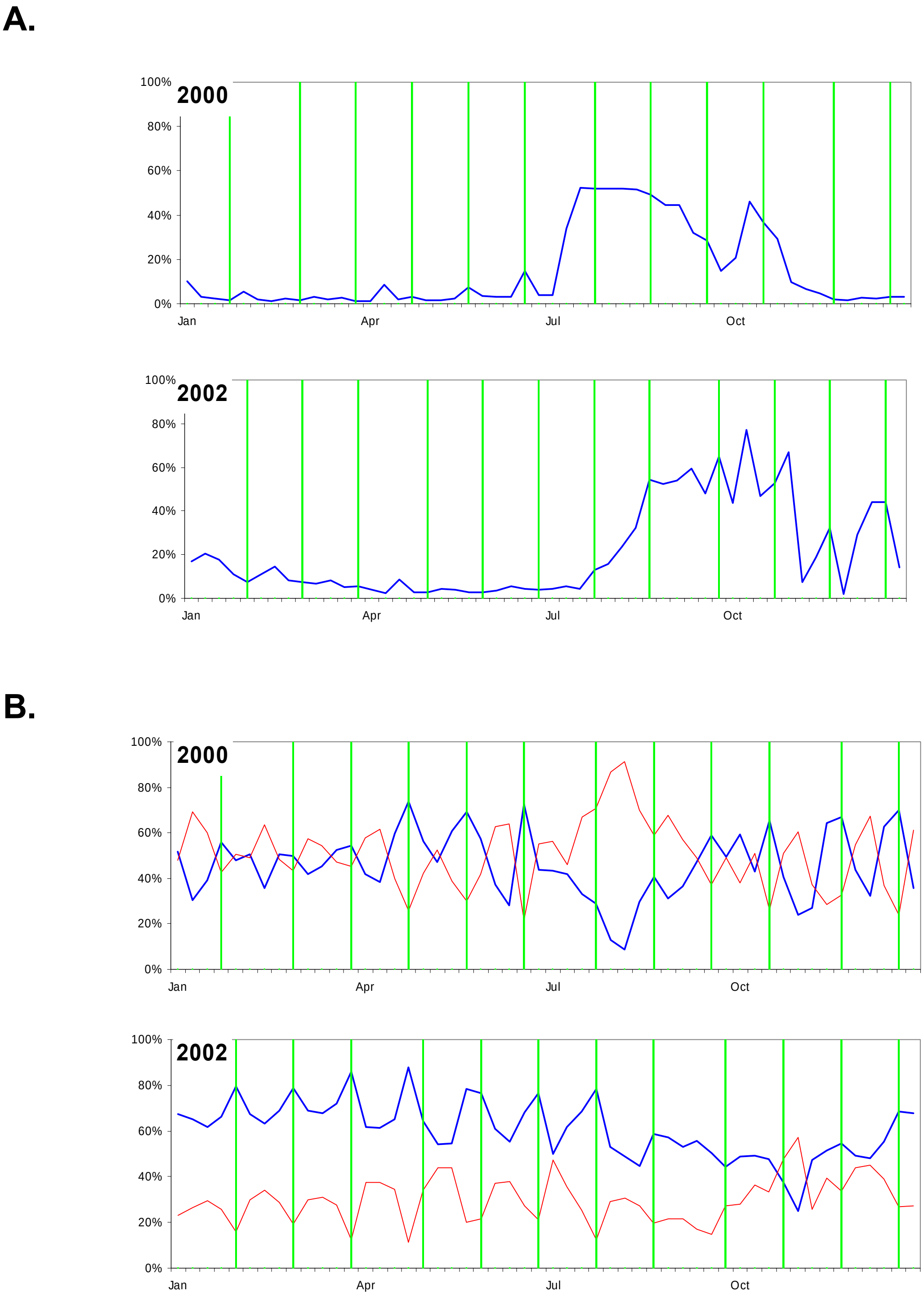


Figure 7.3.16. (a) weekly trends in the percentage of time spent in the 0–150 m depth range by tagged bigeye during the day for 2000 (top) and 2002 (bottom); (b) weekly trends in the percentage of time spent in the 0–50 m (red) and the 50–150 m (blue) depth range by tagged bigeye during night for 2000 (top) and 2002 (bottom). Green lines represent the full-moon week.

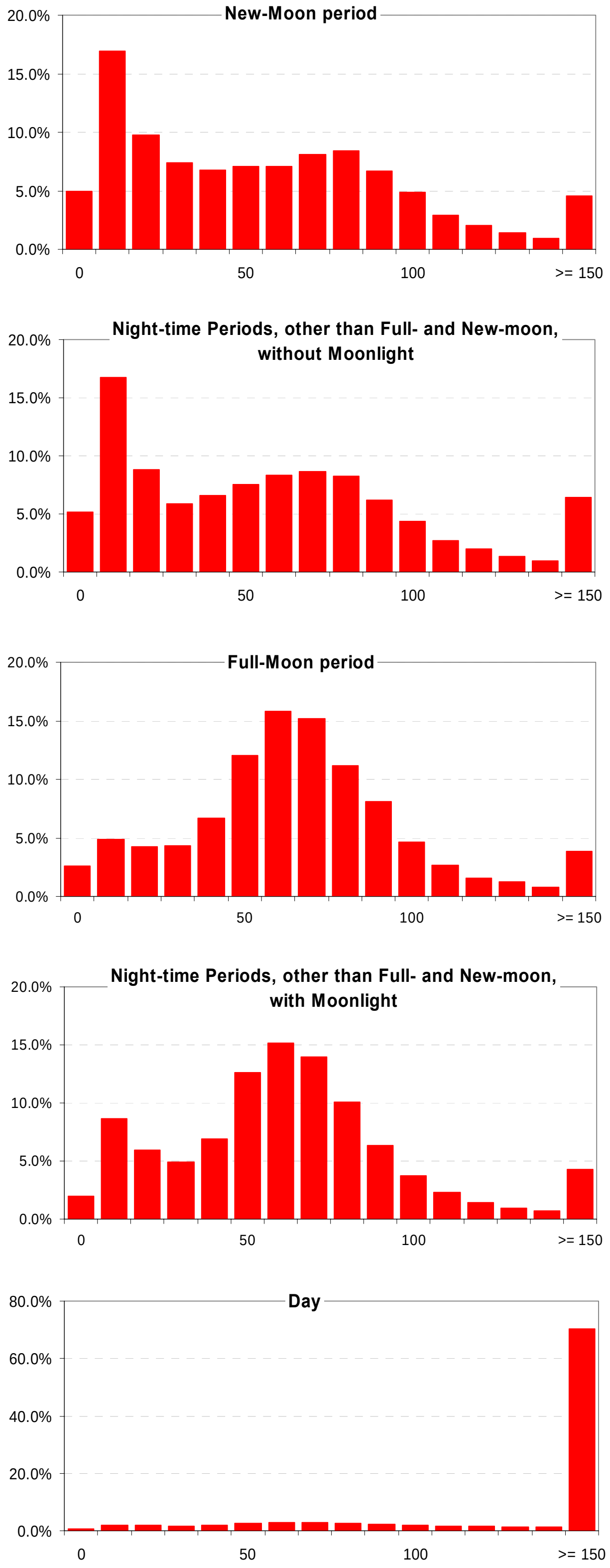


Figure 7.3.17. Frequency of recorded times of bigeye tuna with archival tags by depth for selected periods of the night/ day, and lunar cycle, all data combined.

Fishing effort remained concentrated in the main fishing ground from July to September. During this period, tagged bigeye appeared to be more dispersed, although the data were limited to a small number of fish (n = 3). Bigeye appeared more highly aggregated around the main fishing area in October and November, although individuals appeared to disperse northward and to the southeast during November and December (Figure 7.3.25.).

Position estimates derived from Kalman filtered geolocation data suggest an increasing aggregation of fish during May and June, which may be associated with high catch rates achieved by the longline fleet during this period. However, the data are confounded by the fact that the recovery of tags was dependent on the operation of the fishery and, therefore, increased fishing activity in one area will increase the probability of fish in the area being captured. Similarly, the apparent high degree of aggregation of fish in the area during October is likely to be highly influenced by releases of tagged fish in the area at that time.

7.3.4. Discussion

The analysis of catch and effort data from the longline fishery and movement and behavioural data derived with the use of ATs provide insights into the seasonal and temporal interactions between bigeye tuna populations and the fishery off north-eastern Australia. However, some of the conclusions are likely to be applicable to the longline fishery operating along the more southern area of the east coast of Australia and, potentially, to longline fisheries operating in the wider area of the western and central Pacific Ocean.

For the purpose of this chapter, catchability is defined as the combined effect of vertical vulnerability and spatial vulnerability. There are also likely to be range of other environmental, behavioural, and operational factors that also influence the catchability of bigeye; for example, seasonal differences of the feeding behaviour or differences in fishing gear configuration/deployment. These issues are beyond the scope of the current analysis due to limitations of the available data. Availability is defined as the proportion of the population that is present within the broader area of the fishery.

The diurnal trends in the depth distribution of bigeye observed from the archival tagging data provide insights into the daily trends in catch rate from the longline fishery. During the day, bigeye spend a high proportion of the time at depths substantially deeper than the assumed depth range of the longline gear (50-150 m). However, at night there is substantial overlap between the depth distribution of the longline gear and the bigeye population. The nocturnal increase in vertical vulnerability relates almost directly to the increase in the observed catch rate of bigeye at night.

Vertical vulnerability at night is further influenced by the intensity of moon light. During the new moon period (i.e. low lunar intensity), vertical availability to the longline gear is reduced as fish are distributed higher in the water column, and spend significant periods at depths shallower than the longline gear (about 10 m). In contrast, during the full moon period and/or during higher lunar intensity, fish are distributed mainly within the depth range of the longline gear and vertical vulnerability is increased.

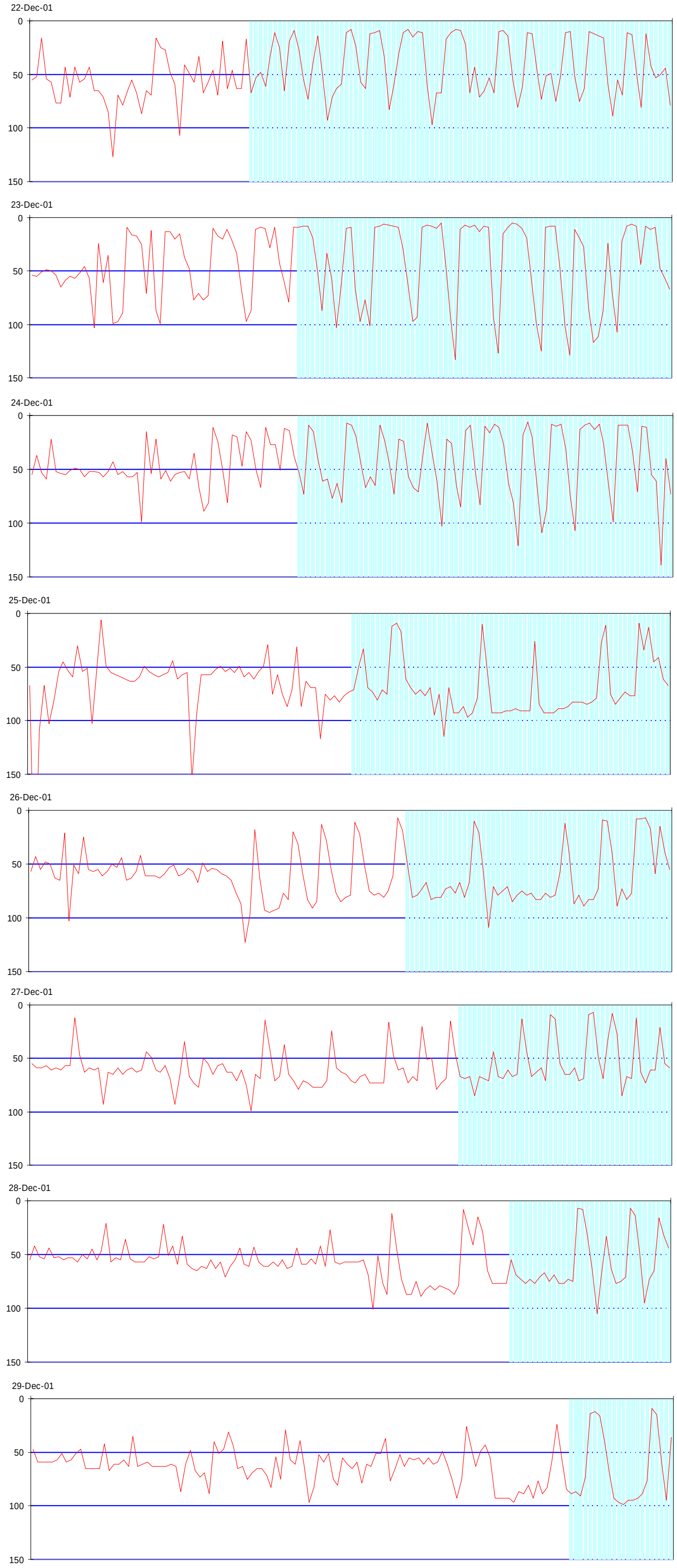


Figure 7.3.18. Depth (m) of bigeye (99-237) by four-minute intervals during the nights of the period 22– 29 December 2001. The light-blue shading represents the period of each night when the moon was not present in the night-sky (i.e. the moon had set).

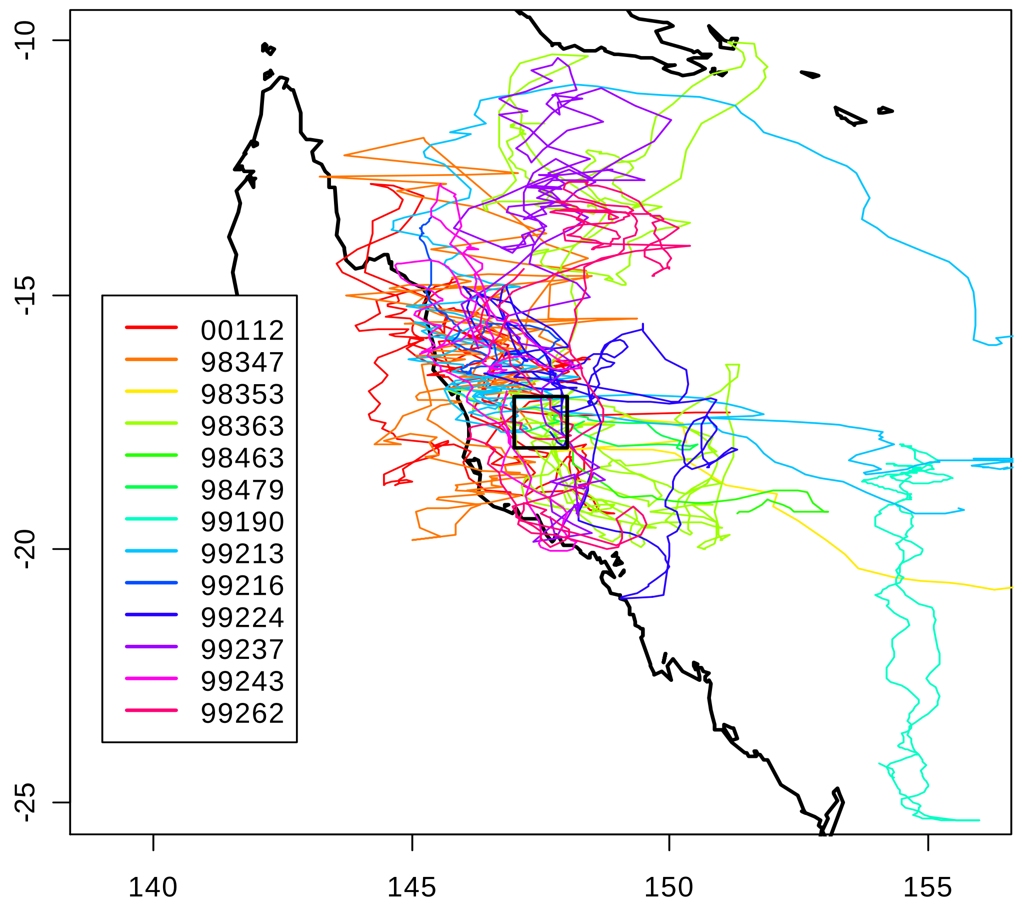


Figure 7.3.19. Daily position of individually tagged bigeye from geolocation estimates within the vicinity of the north-eastern Australian coast. The black square represents the area where the majority of bigeye were released.

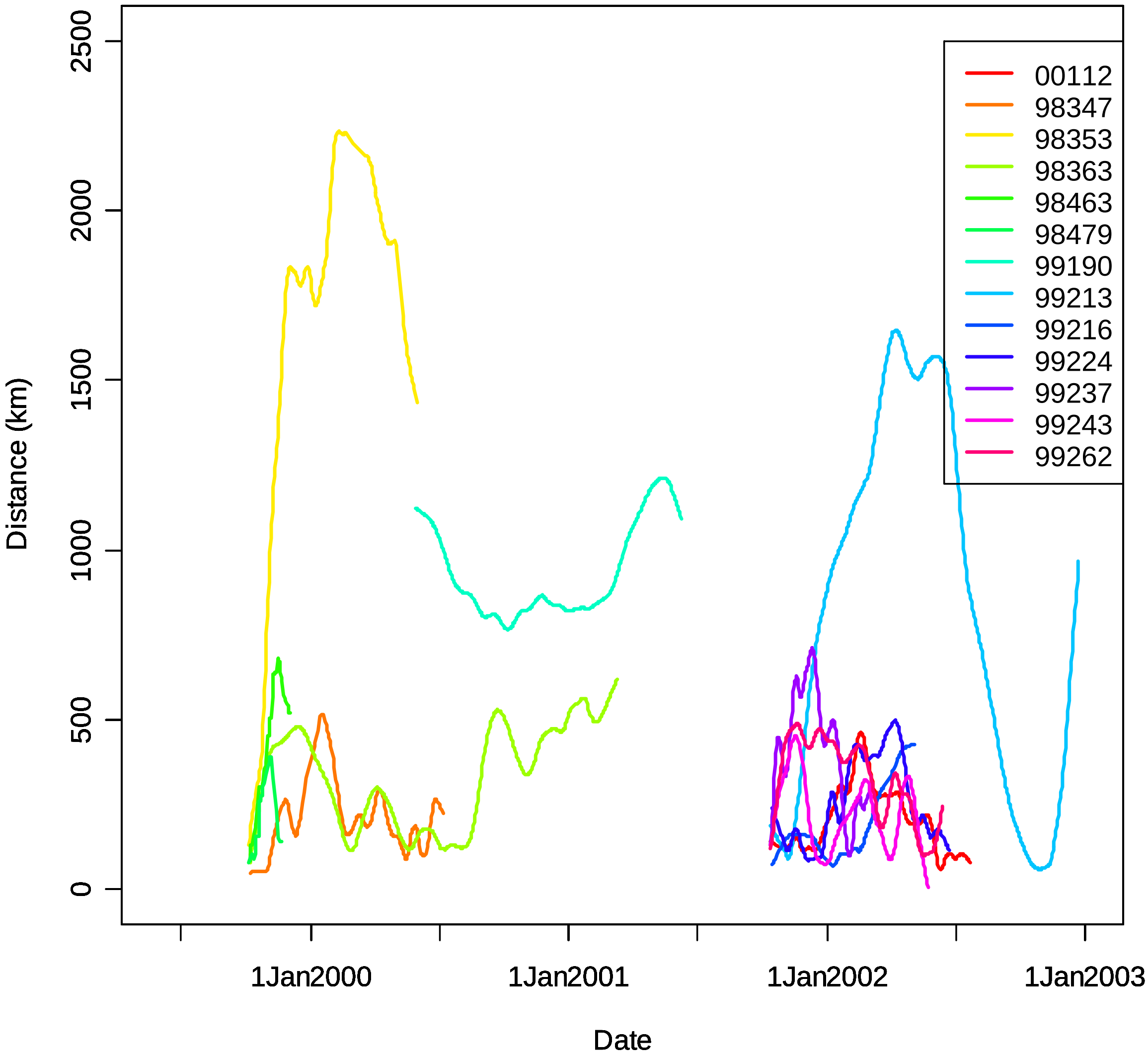


Figure 7.3.20. Estimated distance (km) of individual tagged fish by date from the vicinity where almost all tagging was conducted (around position latitude 17°S, longitude 147°E).

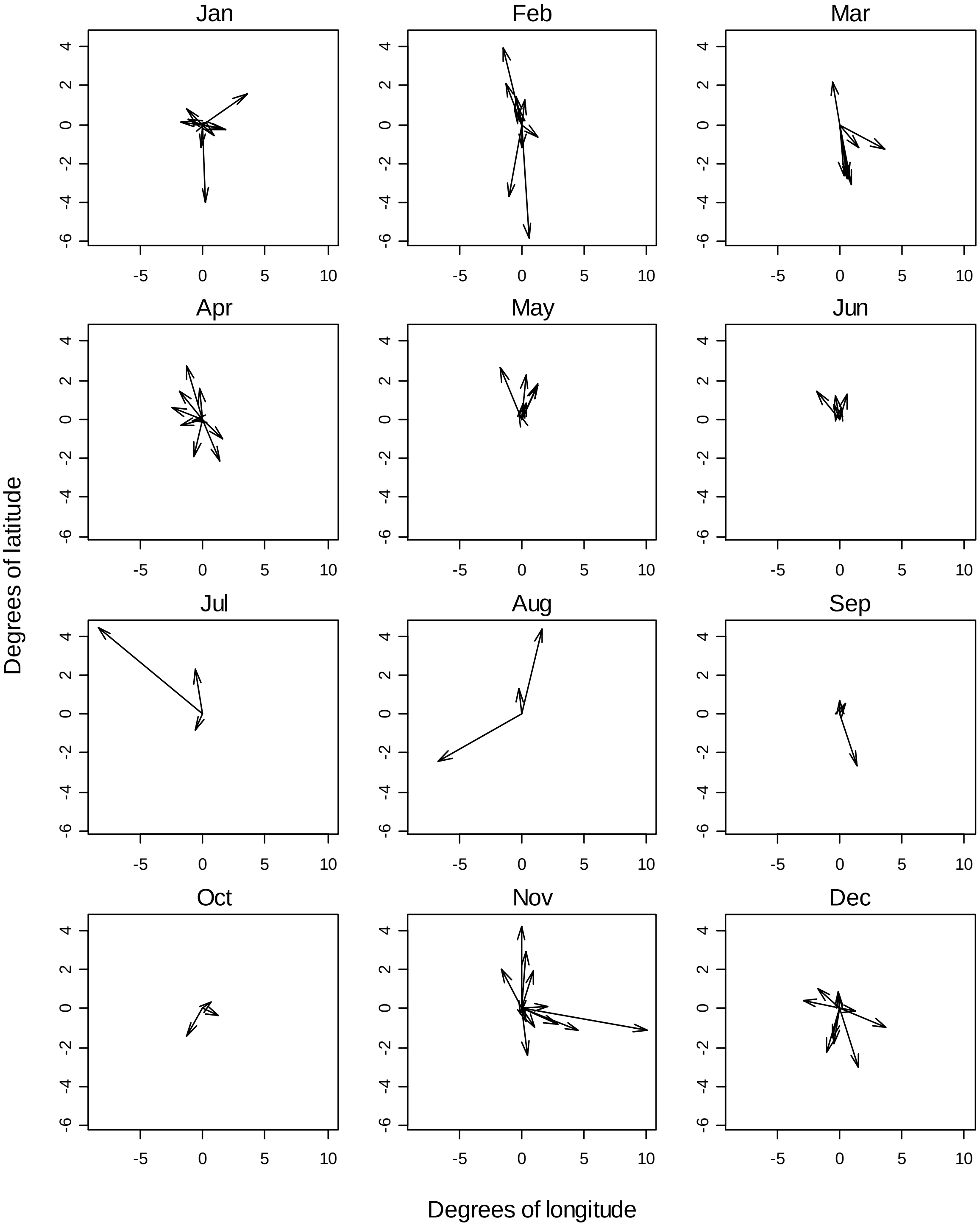


Figure 7.3.21. Displacement of individual tagged fish by month based on Kalman filter geolocation estimates.

The general diurnal trend in depth distribution of bigeye differed somewhat during August-October, when fish spent a higher proportion of the time in the shallower depth range during the day. This change in behaviour may be related to feeding and/or spawning and may partly explain the increased catch rates of bigeye in day-time hours during this period (i.e. increased vertical vulnerability). However, the day-time catch rates at some discrete locations exceeded the level expected solely from the increase in vertical vulnerability. At these locations, catchability may have also increased due to an increase in spatial vulnerability attributed to fishing activity directed at surface aggregations.

An understanding of the diurnal changes in the vertical vulnerability of bigeye is likely to be further enhanced with an increased understanding of the depth distribution of longline gear. Currently, we assume a relatively broad depth range for the longline gear based on a number of limited data sources. However, direct measurements of the depth distribution of longline gear for the main various gear configurations and setting procedures (principally using TDRs) would substantially improve our understanding of the operation of longline fishery. Similarly, detailed catch and effort data from scientific observers, in particular the hook location of bigeye catches (given that the depth of hooks varies along the longline), in tandem with TDR information would further refine our understanding of the dynamics of the fishery.

Additionally, experimental longline fishing could be undertaken to further investigate the depth distribution of bigeye at different levels of light intensity (day period and moon phase). For example, AT data reveal bigeye are distributed close to the surface at night during the new moon period. Catch rates from the longline fishery may be enhanced by setting gear very shallow during this period. Similarly, longline catch rates of bigeye during the day may be increased with the adoption of deep setting techniques.

In the north-west Coral Sea, there is a strong seasonal trend in bigeye catch rate, with peak catch rates generally occurring in May and June and more sporadic periods of high catch rate occurring during September-November. The increase in catch rates during May and June appears to coincide with an increased aggregation of bigeye in the core area of the fishery, with indications of a southern migration of local fish into this area between January and May (i.e. thereby increasing the spatial vulnerability of these fish). During the May and June peak fishing period, bigeye appear to be more static and, presumably, more easily targeted by the longline fleet.

This increase in spatial vulnerability also appears to be augmented by the return of fish that have migrated large distances beyond the area of the fishery (and have therefore increased their availability to the fishery), although only limited observations (two fish) are available for this component of the fished population and it is therefore difficult to extrapolate this to the larger population. The timing of these return migrations is more consistent with the increase in catch rates observed later in the year (September-November). These sporadic periods of high catch rates appear to occur in highly localised areas suggesting higher levels of aggregations of bigeye for relatively short periods. Behavioural changes in the depth distribution of bigeye also occur during this period, with increased surface activity during the day. These aggregations of bigeye have been associated with large spawning aggregations of the lanternfish *Diaphus* sp. (McPherson 1988).

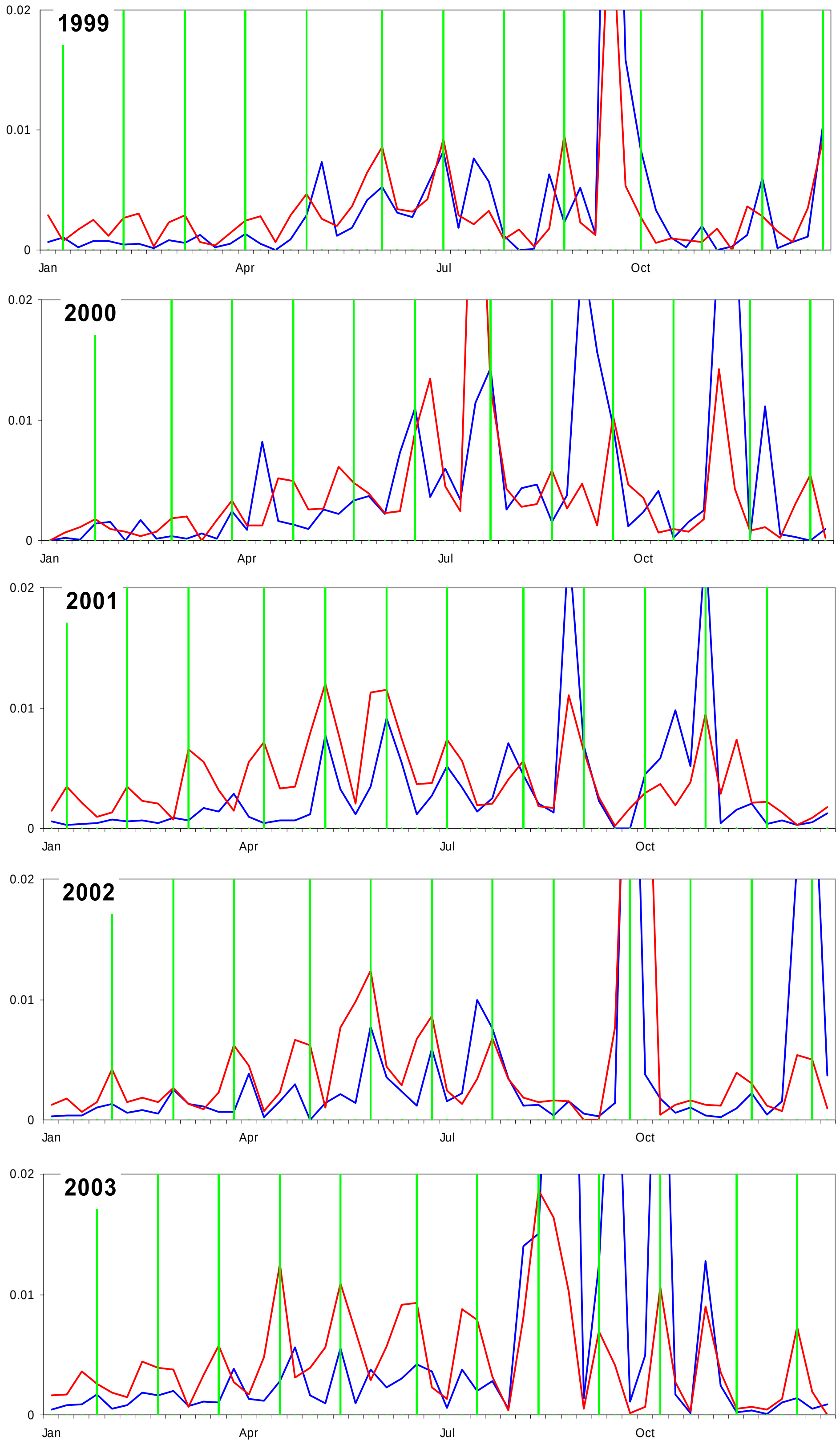


Figure 7.3.22.Weekly trends in bigeye CPUE (number of fish per hook) for night (red) and day (blue) setting strategies for the Australian longline fleet fishing in the Coral Sea, north of 23°S, 1999-2003 (the green lines represent the full-moon week). The y-axis is truncated to more clearly present the data from outside the peak fishing period.

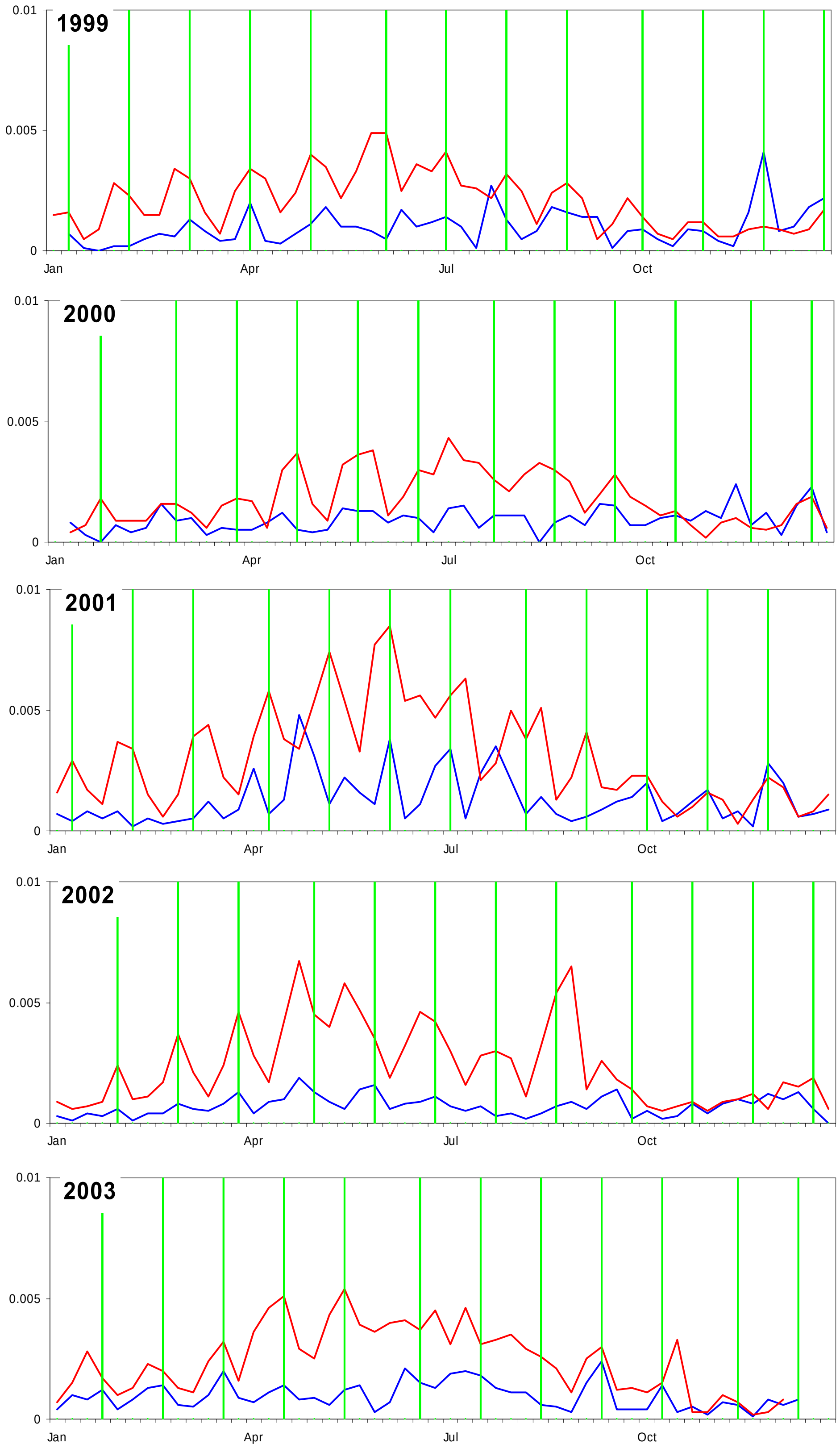


Figure 7.3.23. Weekly trends in bigeye CPUE (number of fish per hook) for night (red) and day (blue) setting strategies for the Australian longline fleet fishing off the east coast of Australia from 23-30°S, 1999-2003 (the green lines represent the full-moon week).

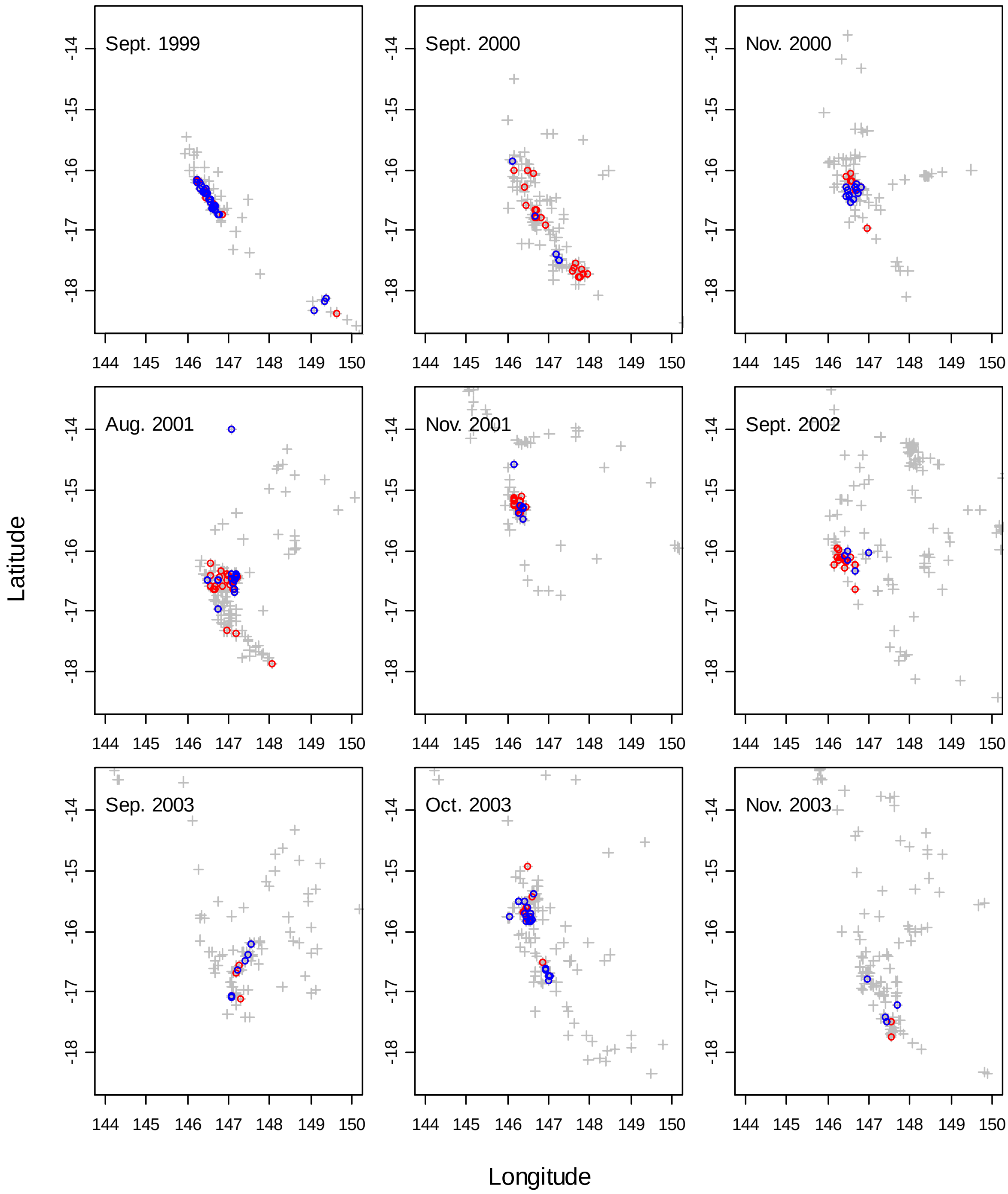


Figure 7.3.24. Location of longline sets in the northern fishery in months when high catch rates were achieved (weekly catch rates exceeding 0.01 bigeye per hook). The location of all sets is presented in grey; day sets with high CPUE (>0.01) in blue; night sets with high CPUE in red.

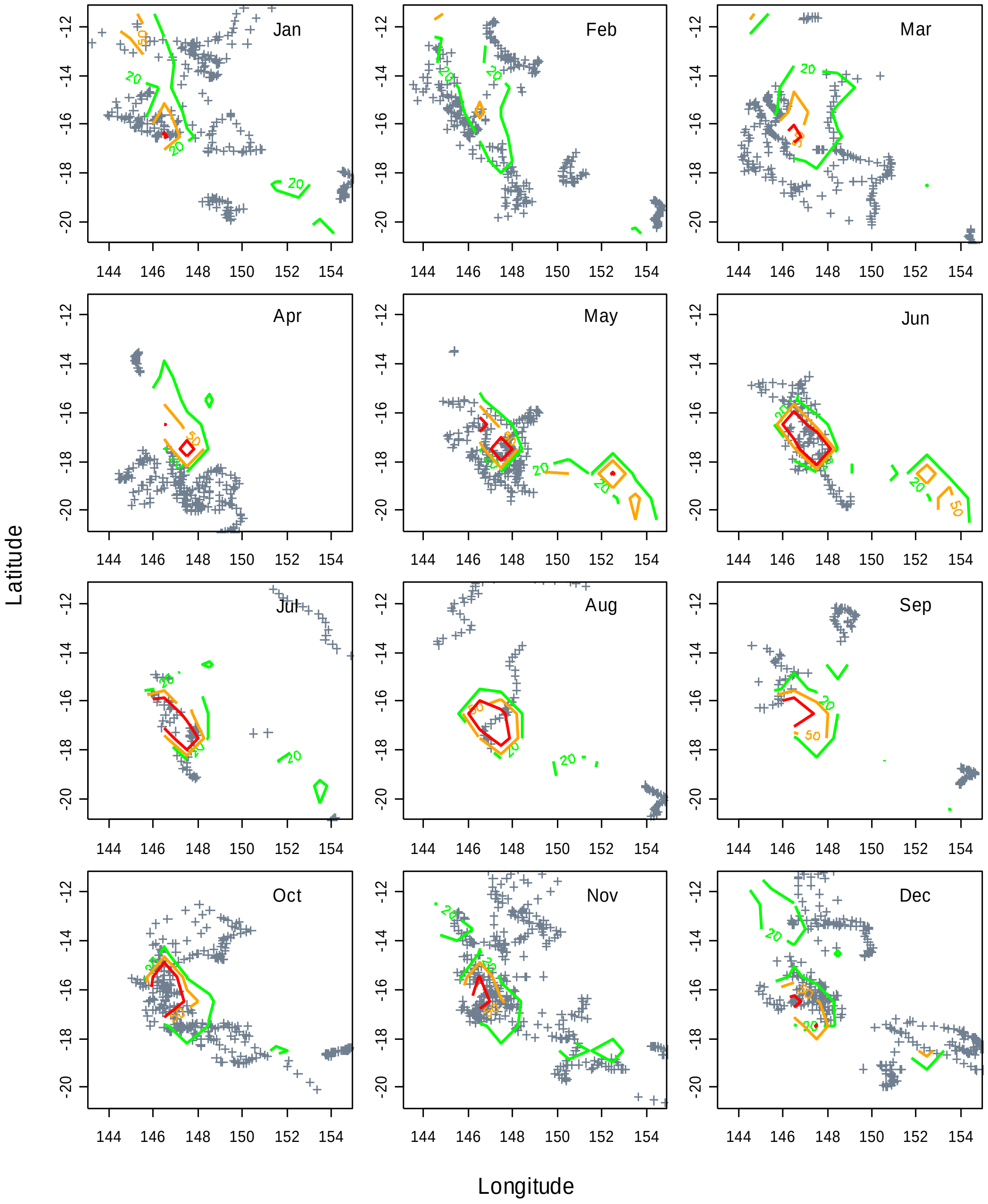


Figure 7.3.25. Aggregated monthly plots of the daily geolocation of individual tagged fish (points) compared to the distribution of longline fishing effort in the north-western Coral Sea (contour lines). The contour lines represent the monthly number of sets conducted by degree of latitude and longitude from 1998 to 2003; green, 20 sets; orange, 50 sets; red, 100 sets.

The overall decline in catch rates observed during the last quarter of the year and the relatively low catch rates throughout December-March is consistent with a dispersal of fish from the core area of the fishery. This is evident from the tagging data that reveals a movement of fish from the main tagging site during the October-February period both on a relatively small scale (declining spatial vulnerability) and on the broader scale (declining availability). There is some indication from the distribution of fishing effort and archival tag data that the movement of local fish occurs both northward and to the south-east, while fish undertaking long distance migrations rapidly move eastward.

The eastern migration of fish from the north-western Coral Sea observed from archival tagging data is consistent with the displacement of conventional tags observed in previous studies (Hampton & Gunn 1998). There is clearly also some wider scale mixing of bigeye from the area as indicated by the large-scale movement of conventionally tagged fish. However, this study provides additional information to indicate that some of the migrating bigeye population in the north-west Coral Sea maintain an affinity for the area. While these results are limited by small sample size from the ATs, this study suggests that at least some of these migrating fish are returning annually to the northwest Coral Sea. The two bigeye that migrated eastward were observed to return, or had partially returned, westward into the western Coral Sea during the latter half of the year (perhaps possibly to spawn). The available data does not enable the proportion of the fish exhibiting this “homing” behaviour to be determined due to the low sample size and the lack of any tag returns from the area beyond the Coral Sea.

The tagging data tends to indicate that the bigeye population in the north-west Coral Sea is comprised of both local and transitory fish returning to the main study site during the May-September period. Nevertheless, it is important to note that the current archival tagging data set is based on a relatively small number of individual fish (13). It is unknown how representative these fish are of the entire north-west Coral Sea bigeye population. Further, while the tags indicate the seasonal importance of the main tag release site to the population, the recoveries are potentially biased by the relatively high intensity of fishing effort in this specific area and therefore a higher likelihood of recoveries in the area.

Nevertheless, the data suggests that the bigeye in the north-western Coral Sea may represent a sub-population of the broader regional bigeye stock. The rate of mixing between the sub-population and the wider area is unknown although the tagging results indicate a significant proportion of the population remains resident in the north-western Coral Sea, at least over the duration of the recovery period of the tagging programme (approximately one year). This stock hypothesis has implications for the management of the fishery in the north-western Coral Sea. A high degree of residency of bigeye and, conversely, low regional stock mixing, would mean the sub-population in the north-western Coral Sea is more vulnerable to depletion, particularly given the relatively high level of fishing effort in the area in recent years (Hampton et al. 2004; Ward & Bromhead 2004) and earlier estimates of the exploitation rate of bigeye in the fishery (Hampton & Gunn 1998).

7.4. Integration of the habitat preferences of bigeye tuna into CPUE models for the longline fishery in the western Pacific Ocean.

This chapter is divided into two parts. The first part covers an analysis of relative abundance trends for bigeye tuna that covers the entire western and central Pacific Ocean (W/CPO) on a 5° spatial scale. The second part details the results of an initial analysis conducted at a finer (1°) spatial scale and focusing only on the Coral Sea region. Both parts utilise two Habitat Based Standardisation (HBS) methods to analyse abundance trends. This methodology uses archival tag (AT) and oceanographic data to model the likelihood that animals are present given oceanographic covariates and adjusts the catch per unit effort (CPUE) data accordingly. Part one of this chapter also incorporates more conventional standardisation methods using Generalised Linear Models (GLMs) into the analyses. A comparison of the differing models is included.

The first part of this chapter incorporates all available archival tag data for bigeye tuna while in the second, only those archival data for bigeye for the Coral Sea region and held by CSIRO/SPC are used.. The analysis in the second part is a more detailed investigation into how the uncertainties in geolocation and spatio-temporal differences in behaviour affect the results of habitat standardisation. Geolocation results from Chapter 7.1. are incorporated and used to spatially divide the W/CPO region into strata within the MULTIFAN-CL (MFCL) Area 4. Separate time series of relative abundance are produced and comparisons with the analyses of MFCL Area 4 are given.

7.4.1. Relative abundance indices of the Japanese longline fishery for bigeye tuna: analysis of data from the western and central Pacific Ocean

K. Bigelow, A. Langley, T. Patterson, N. Miyabe

7.4.1.1. Introduction

Catch and fishing effort data from the Japanese longline fleet have been a key component of the fishery data used in recent stock assessments of bigeye tuna in the W/CPO (Hampton et al. 2003). Assessments to date have been undertaken using MULTIFAN-CL (MFCL) software (Fournier et al. 1998) across the region from 120°E to 150°W and 35°S to 45°N stratified into five areas (Figure 7.4.1.).

Of these five areas, Areas 1 and 3 represent the majority of fishing effort and in association, the largest catch of bigeye tuna for the Japanese longline fishery across the region (Table 7.4.1.). Areas 4 and 5 represent the lowest catches and in addition are areas of higher proportions of zero catches. Areas 2 and 3 are represented by low zero catch records, while Area 1, converse to the high catches in this area, is a region of higher zero catch records (~ 7 %).

Electronic tagging of bigeye tuna has been conducted in a number of places throughout the Pacific by several national agencies (CSIRO/SPC: Evans et al. 2003, this report; National Marine Fisheries Service (NMFS) Pacific Islands Fisheries Science Center: Musyl et al. 2001, Schaefer & Fuller 2002; National Research Institute of Far Seas Fisheries (NIRFSF): Matsumoto et al. 2003, N. Miyabe unpublished data). Such electronic tagging provides information not only on the movement patterns of individuals through time, it also provides information on the habitat preferences of these animals and how these may change through time. Changes in the behaviour and habitat preferences of bigeye tuna are likely to influence catch rates by varying both the availability of individuals to the fishery and also the catchability of an individual through time and space. By incorporating these data into CPUE standardisation methods, more accurate CPUE indices and therefore more accurate stock assessments may be made. Here we compare the results of traditional statistical methods of assessing CPUE and two methods involving the incorporation of behavioural and environmental data.

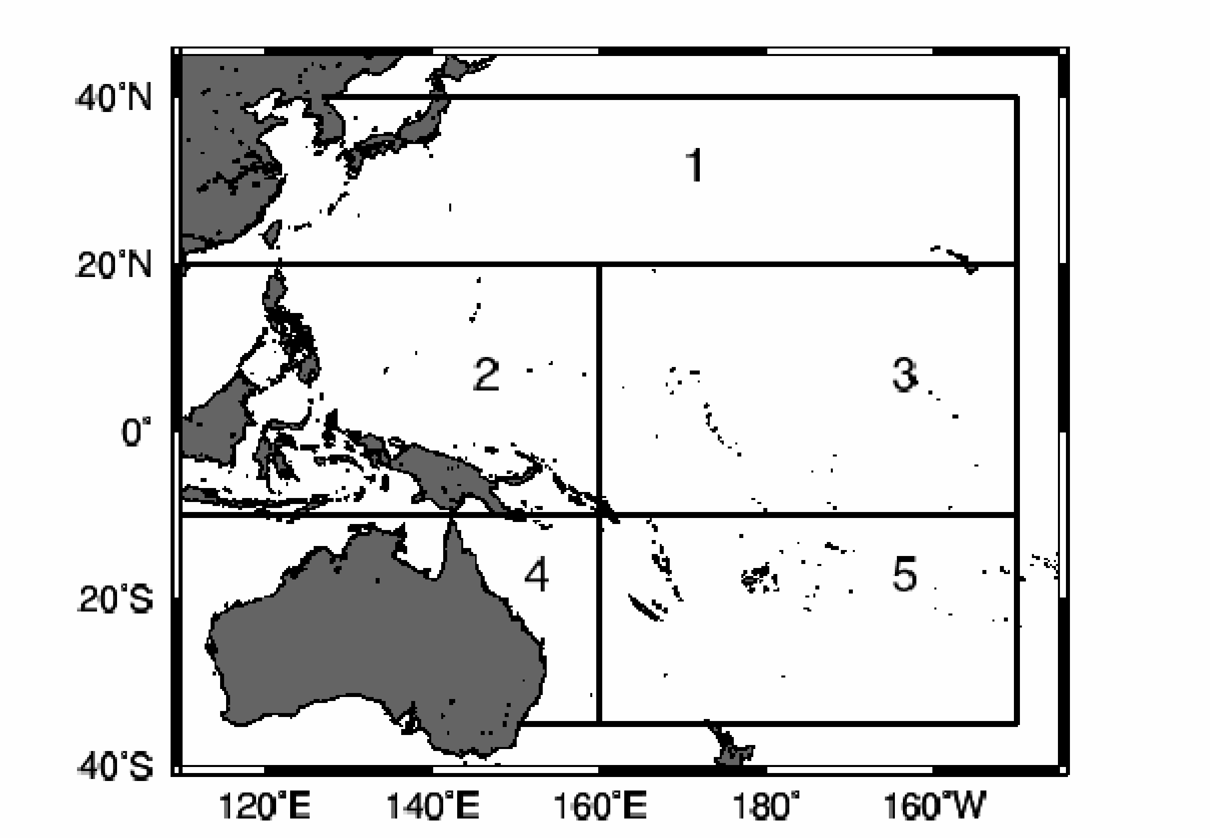


Figure 7.4.1. MFCL areas, spatial strata used in recent bigeye stock assessments.

In the 2003 assessments for bigeye tuna, separate analyses were conducted using different estimates of longline effective (or standardised) effort (Hampton et al. 2003). The effort series used were those estimated using four differing models: a general linear model (GLM; Langley 2003), two deterministic HBS (Bigelow et al. 2003), and a statistical habitat-based standardisation (statHBS, Bigelow et al. 2003). These assessments indicated that the trend in effective effort was similar to the trend in nominal fishing effort for each of the standardisation methods.

This chapter provides a comparison of three standardisation approaches (GLM, HBS and statHBS) to estimate effective effort and relative abundance indices of the Japanese longline fishery for bigeye tuna in the W/CPO. The HBS and statHBS methods are extended by incorporating contemporary information of habitat preferences for bigeye tuna based on ATs and pop-up satellite archival tags (PSAT).

Table 7.4. 1. Summary of fishery statistics for the Japanese bigeye tuna longline catch and effort data aggregated by 5° latitude and longitude, month and hooks between floats category.

	MFCL area				
	1	**2**	**3**	**4**	**5**
Dataset 1 (1975–2002)					
Total number of 5°-month and HBF records	29,337	24,508	35,505	4,040	3,375
Catch (fish*1000)	3,579	3,316	8,999	361	328
Zero records (%)	7.4	2.3	1.0	5.8	6.7
Fish/100 hooks	0.3	0.5	0.8	0.2	0.2
Dataset 2 (1952-2002)					
Total number of 5°-month and HBF records	29,115	22,102	31,180	4,815	6,381
Catch (fish*1000)	12,147	7,714	19,275	709	908
Zero records (%)	7.1	2.6	1.1	5.4	6.4
Fish/100 hooks	0.4	0.5	0.9	0.2	0.2

7.4.1.2. Methods

7.4.1.2.1. Dataset

Two datasets from the Japanese longline fleet were used in the effort and CPUE standardisation. Data were aggregated by month and 5° of latitude and longitude resolution and provided by NIRFSF.

Dataset one was compiled to compare model results for the period from 1975 to 2002 when gear configuration information (number of Hooks Between Floats of the longline gear; HBF) was available. Variables in the model included year, month, latitude, longitude, each individual HBF category; the total number of hooks set and the catch of bigeye tuna in number of fish. Data associated with five to 22 HBF categories were used in modeling the effort series.

Dataset two was compiled from 1952 to 2002 to reflect the entire historical time-series of the fishery. Due to missing data, prior to 1975, gear configuration was assumed to be five HBF; thereafter data were divided into six HBF categories: 5-6, 7-9, 10-11, 12-15, 16-20, and > 20 HBF. Explanatory variables were similar to dataset one.

7.4.1.2.2. Effort standardisation methods

Traditionally, catch and effort data have been fit by GLMs, a statistical approach that directly attempts to account for the variation in nominal CPUE by fitting a predicted CPUE to observed CPUE. While GLMs are general in scope, they are unable to incorporate information on the knowledge of the structure of relationships among explanatory variables such as variations in environmental conditions and the fishes' response to them.

More recently, two additional standardisation approaches have been utilised in pelagic fisheries assessments. The HBS method (Hinton & Nakano 1996) represents a deterministic modeling approach whereby effective longline effort is modeled as the joint probability of the vertical distribution of hooks in the water column and the distribution of the species in the water column. The vertical distribution of a species within HBS is based on habitat preferences (e.g. temperature, oxygen) in combination with environmental data. The statHBS model allows parameter estimation (e.g. habitat preferences and factors modifying the behaviour of the gear or species) based on fitting the model to observed catch and effort data. Habitat preferences from the HBS approach are used as priors in the statHBS within a Bayesian context.

7.4.1.2.2.1. GLM method

Explanatory variables followed those of previous assessments (Langley 2003) and considered the categorical variables of year, month and HBF category and the continuous variables of latitude and longitude. Interactions were also considered in the stepwise fitting procedure and the final formulation for dataset one (1975-2002) was based on modeling CPUE as:

ln(CPUE + constant) ~ f(Year.Quarter + poly(longitude,3) + interaction(HBF, latitude) + interaction(HBF, longitude)+ interaction(latitude, quarter) + e)

Catch per unit effort, expressed as number of fish per 100 hooks, was chosen as the dependant variable to allow comparison with other standardisation methods. A constant of 0.0001 was added to the CPUE to account for null catches as these pose a problem in the estimation. Longitude was modeled as a third degree polynomial, with *e* representing a random error term.

The formulation for dataset two was similar to dataset one, with catch comprising the dependant variable instead of CPUE:

ln(number of fish) ~ f(ln(number of hooks) + Year.Quarter + poly(longitude,3) + interaction(HBF, latitude) + interaction(HBF, longitude)+ interaction(latitude, quarter) + e)

Each record in the 1952 to 2002 analysis was weighted in the fitting procedure by the level of effort (number of hooks) in a particular year/month/latitude/longitude/HBF stratum. Effort was included as an offset variable in the model and a constant of 0.1 was added to all catches to account for null records.

7.4.1.2.2.2. Habitat-based and statistical habitat-based methods

Inputs to the HBS and statHBS models included three variables:

vertical distribution of hooks in each HBF category;

vertical distribution of ambient temperature or depth distribution of isotherms from the surface layer; and

vertical distribution of oxygen.

For each stratum, the Simple Ocean Data Assimilation (SODA) and Ocean General Circulation Model (OGCM; Carton et al. 2000a; 2000b) were used to generate the vertical distribution of temperature, while oxygen data were obtained from a climatology database (Levitus & Boyer 1994).

In previous HBS applications, bigeye tuna were vertically distributed according to time-at-temperature distributions derived from AT data from fish tagged in Tahitian (Dagorn et al. 2000) and Hawaiian waters (Musyl et al. 2003). Following a recommendation from the 2003 Standing Committee on Tuna and Billfish (SCTB 16), additional time-at-temperature data were obtained from contemporary AT and PSAT tagging studies to construct habitat preferences for each MFCL area. These data were derived from the international fisheries agencies CSIRO, NMFS Pacific Islands Fisheries Science Center, NRIFSF and the SPC, all of which have ongoing AT and PSAT programs. Data for juvenile fish or fish associated with FADs were not incorporated for two reasons. Firstly, the behaviour of fish associated with floating objects or FADs has been demonstrated to be distinctly different to that of fish unassociated with objects in pelagic waters such as those caught by the longline fishery (Schaefer & Fuller 2002). Secondly, very few juvenile bigeye are caught by the longline fishery and so therefore data derived from adults provide more accurate representations of the ambient temperature habitat of longline caught tuna (Molony 2004).

Of all bigeye for which time at depth/temperature were available, the largest number were located in MFCL Areas 3 and 4, whilst MFCL Areas 1 and 2 were represented by only one fish each (Table 7.4.2.). Two bigeye tuna tagged in Area 4 subsequently migrated into MFCL Area 5. Area-specific temperature preferences were incorporated into the HBS standardisation. Oxygen was also incorporated to constrain vertical distribution following Bigelow et al. (2002).

Table 7.4.2. Details of bigeye tuna tagged with archival and pop-up satellite archival tags.

MCFL area (region)	Number of bigeye	Days at liberty	Source of data
1 (Japan)	1	7	NRIFSF
2 (Papua New Guinea)	1	47	SPC
3 (Hawaii)	19	643	NMFS
4 (Coral Sea)	14	2,909	CSIRO
5 (New Caledonia)	2	673	CSIRO

Within the statHBS, habitat preferences were structured as parameters. Fifteen ambient temperature preferences derived from the HBS at 2°C intervals from 3.5°C to 33.5°C were used as priors. Fifteen priors derived from the HBS were also used for oxygen at 0.5 ml l^{-1} intervals from 0 to 7.5 ml l^{-1}. All priors were non-informative (uniform distribution) with a mean of zero.

A likelihood function (a log-transformed least squares) was used as a measure of how well the predicted catch from the various effort series fit the observed catch:

$$L = (\ln(C_{i,y} + \delta) - \ln(\hat{C}_{i,j,y} + \delta)P)^2$$

where $C_{i,y}$ is the observed catch for observation *i* in year *y*; $\hat{C}_{i,j,y}$ is the predicted catch for observation *i*, effort series *j* and year *y*. Similar to the GLM analysis of CPUE, a constant ($\delta = 0.0001$) was added to the observed and predicted catch to avoid computational problems when observed catch was zero.

For individual observations (*i*) from an effort (*E*) series *j*, an estimate of catch (*C*) in year *y* is obtained as:

$$\hat{C}_{i,j,y} = E_{i,j,y} q_j B_y$$

where *q* is overall catchability and *B* is abundance. Year effects ($\theta_y = qB_y$) are estimated because both *q* and *B* are unknown.

The contribution of habitat priors to the objective function are:

$$\Theta_h = \Sigma\varepsilon^2/2\sigma^2$$

where ε are residuals of the habitat preferences and σ is the standard deviation of the prior distribution which has mean μ. The negative log-likelihood is minimised by simultaneously estimating various parameters with the function minimiser in AD Model Builder (www.otter-rsrch.com). The HBS and statHBS models were applied to CPUE from 1975 to 2002 when gear configuration was known. Predicted habitat from the statHBS results were then applied to the 1952 to 2002 time-series.

A separate analysis was undertaken for each MFCL area for each method.

7.4.1.3. Results

7.4.1.3.1. Behaviour of bigeye tuna

Most bigeye tuna tagged displayed what has previously been reported as characteristic diurnal behaviour (Schaefer & Fuller 2002; Musyl et al. 2003). During the day, a large proportion of time was spent at cool, deep depths with regular brief forays into warm, shallow depths, whilst at night, time was largely spent in warm, near-surface waters (Figure 7.4.2.). Aggregated data of 19 bigeye tuna tagged in Hawaii indicate a daytime distribution of individuals in warmer waters than the one adult fish reported in Musyl et al. (2003) also from Hawaii. The warmer daytime aggregate distribution of the 19 Hawaiian fish could result from three possibilities: (1) differing oceanographic conditions between the areas, (2) ontogenetic differences in the physiology of the fish and their temperature tolerance or (3) a higher proportion of time spent in surface waters.

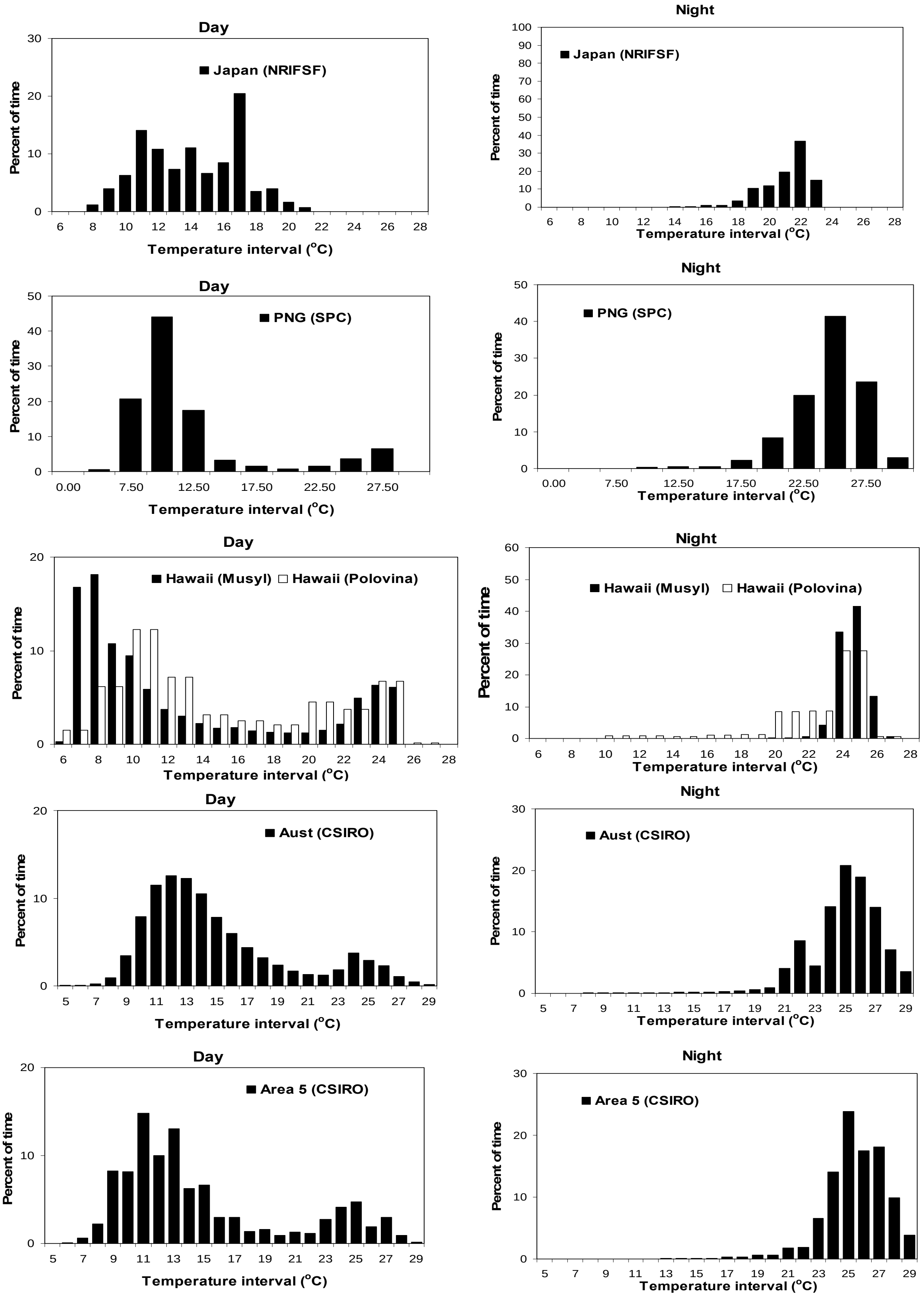


Figure 7.4.2. Time-at-temperature (°C) histograms for adult bigeye tuna during the day (left) and night (right). Source: CSIRO, NMFS, NRIFSF and SPC. The five figures from top to bottom correspond to MFCL areas 1 to 5.

Disaggregating the data by month indicated a unimodal time-at-temperature distribution from February to September and a bimodal distribution from October to January indicating surface aggregation behaviour during the months of October to January. For the purposes of the HBS, it was decided to use an annual time-at-temperature distribution, as the Japanese fleet is most active from May to September, though a monthly preference could be considered in future work.

7.4.1.3.2. Estimation of CPUE and model comparison

Ambient temperature preferences estimated by the statHBS differed between MFCL areas (Figure 7.4.3.). However, in all areas depth preferences demonstrated a distinct diurnal pattern involving cooler (8-15°C) water temperature preferences during the day and warmer temperatures during the night, similar to that described by the AT data.

A larger percentage of the variance (8-45 %) was explained by the GLM when fitting catch rate across 1975-2002 and positive catches across 1952-2002 (Table 7.4.3.). The StatHBS described the variance in an intermediate (2-24 %) manner and the HBS and nominal models described the lowest variance. The HBS explained a larger percentage of the variance in three of the five MFCL areas compared to nominal CPUE; however, the GLM and statHBS approach are preferred. The HBS for MFCL Area 3 is problematic as the 19 tagged fish actually represent Area 1 or the northern border of Area 3. As a result, no information is available for the dominant equatorial distribution.

The year effects from the CPUE models were similar in all models for most areas (Figures 7.4.4. and 7.4.5.). However, in comparison with nominal trends, the GLM indicated a greater downward trend in Areas 1, 4, and 5. The results of fitting catch by GLM were similar to those modeling CPUE (Table 7.4.3., Figure 7.4.5.); with the GLM indicating a greater downward trend in Areas 1, 4, and 5. In comparison to the 2003 assessment, results were similar with models explaining 79-91 % of the variation in catch. The slightly lower explanatory power in Areas 1, 4, and 5 could be attributed to the higher proportion of low catches (less than 20 fish per stratum) recorded in these areas compared to Areas 2 and 3 (Langley 2003). The HBS and statHBS produced trends that were similar to the GLM trends for Areas 2, 3 and 4, although deviated in Area 4 in the last five years of the time-series.

Both the GLM and statHBS models underestimated catches when compared to observed catches (Figures 7.4.6. and 7.4.7.) In particular, the GLM model had difficulty predicting the catch in MFCL Areas 1 to 3 across the initial 15 to 25 years, similar to variability observed across this period in previous assessments.

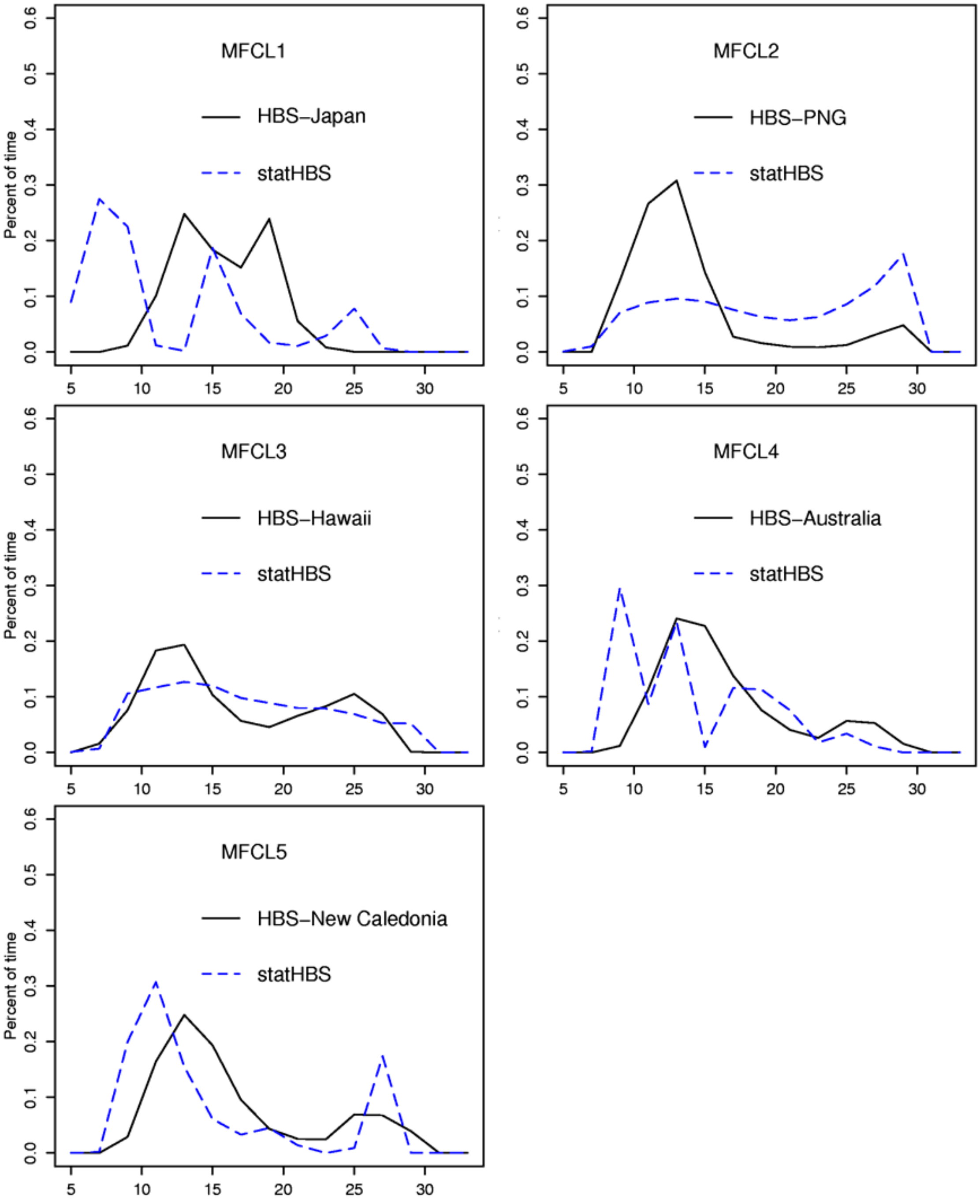


Figure 7.4.3. Bigeye tuna habitat-based ambient temperature preferences from archival or PSAT tags compared with temperature preferences estimated using statHBS for the each MFCL area.

Table 7.4.3. Comparison of models to estimate standardised CPUE for the Japanese bigeye tuna longline fishery (1975–2002) and GLM models to estimate catch (1952–2002).

Effort series	**Nominal**	**GLM**	**HBS**	**statHBS**
MFCL Area 1				
Null deviance = 307,805; df = 29,336				
Residual deviance	304,196	169,508	258,318	233,325
Parameters	27	481	28	58
Pseudo-R^{2}^	0.01	0.45	0.16	0.24
MFCL Area 2				
Null deviance = 89,613; df = 24,507				
Residual deviance	85,969	74,764	90,323	81,144
Parameters	27	350	28	58
Pseudo-R^2	0.04	0.17	0.00	0.09
MFCL Area 3				
Null deviance = 66,905; df = 35,504				
Residual deviance	65,927	61,886	67,333	65,257
Parameters	27	390	28	58
Pseudo-R^2	0.01	0.08	0.00	0.02
MFCL Area 4				
Null deviance = 30,428; df = 4,039				
Residual deviance	29,490	23,196	29,137	27,974
Parameters	27	215	28	58
Pseudo-R^2	0.03	0.24	0.04	0.13
MFCL Area 5				
Null deviance = 30,260; df = 3,374				
Residual deviance	29,470	21,528	28,631	26,498
Parameters	27	276	28	58
Pseudo-R^2	0.03	0.29	0.05	0.12
1952–2002	**MFCL Area 1**	**MFCL Area 2**	**MFCL Area 3**	**MFCL Area 4**
Pseudo-R^2	0.85	0.89	0.91	0.79

^Pseudo-R^2: Null deviance-residual deviance/Null deviance.

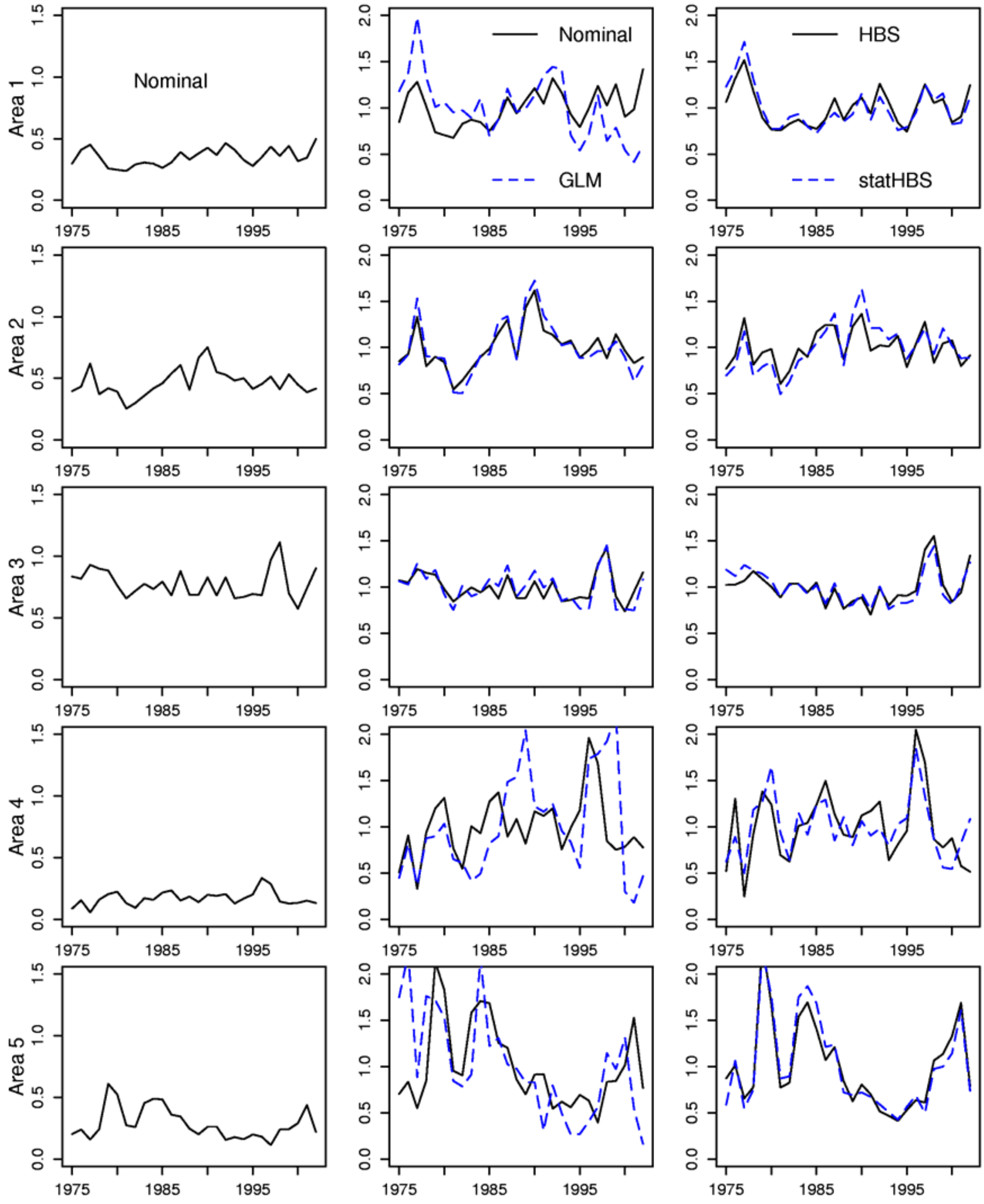


Figure 7.4.4. Bigeye tuna annual indices (1975–2002) by MFCL area. Left: Nominal CPUE (Σbigeye catch/Σlongline effort). Centre: Nominal and GLM standardised CPUE. Right: HBS and statHBS standardised CPUE. Four series (centre and right) have been scaled to the mean of the series for comparison.

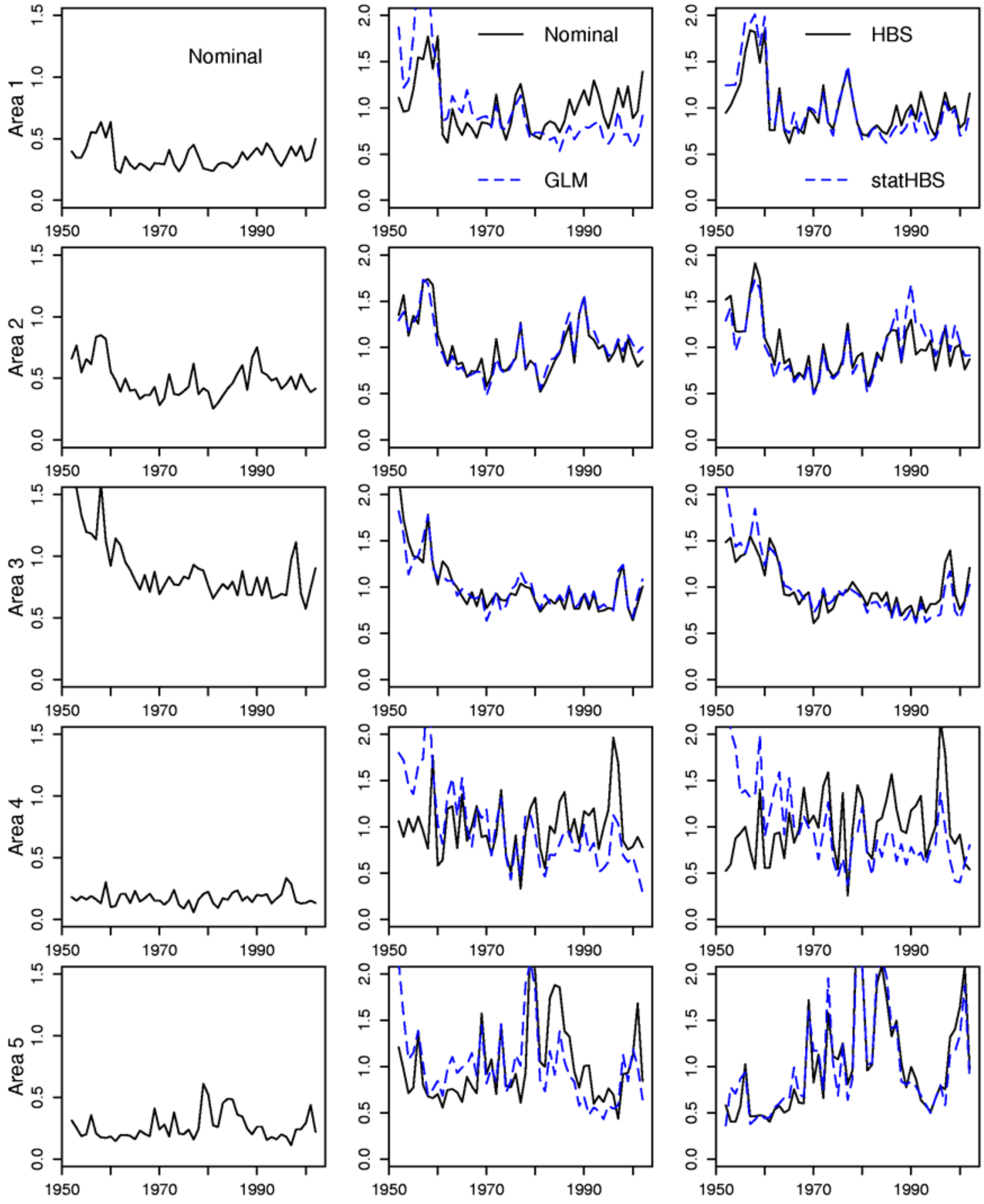


Figure 7.4.5. Bigeye tuna annual indices (1952–2002) by MFCL area. Left: Nominal CPUE (Σbigeye catch/Σlongline effort). Centre: Nominal and GLM standardised CPUE. Right: HBS and statHBS standardised CPUE. Four series (centre and right) have been scaled to the mean of the series for comparison.

7.4.1.3.3. Incorporation of finer scale data and the influence of oceanographic conditions

Catch and effort data available at a resolution of 1° latitude and longitude were used in a repeat of the statHBS in MFCL area 3 to investigate the influence of prevailing oceanographic conditions. As was observed in the 5° per month analysis, the residuals of the fit to the fine-scale model have a long tail, indicating that the model was substantially underestimating the larger bigeye catches (Figure 7.4.8.). The spatial distribution of the large positive residuals was examined relative to the prevailing monthly oceanographic conditions described by the depth of the 27ºC isotherm (calculated from NCEP data; source NOAA/.NCEP/.EMC/.CMB/.Pacific/).A qualitative examination of the relationship between the spatial distribution of the large positive residuals and monthly prevailing oceanographic conditions indicated that the highest statHBS residuals generally occurred at steep gradients in the depth of the 27ºC isotherm (Figure 7.4.9.). Further development of the statHBS approach should incorporate additional variables that describe the prevailing oceanographic condition in the area fished and in the adjacent areas.

7.4.1.3.4. Comparison with 2003 relative abundance indices

Estimation of the relative abundance indices using the HBS and statHBS models in 2003 and 2004 involved the following:

HBS	2003: Used only the Tahiti-based bigeye HBS time-at-temperature hypothesis.
	2004: Used MFCL area specific bigeye HBS time-at-temperature hypotheses.
statHBS	2003: Estimated single Pacific wide bigeye or time-at-temperature hypothesis. Oxygen was not incorporated as an estimated parameter.
	2004: Estimated MFCL area specific bigeye time-at-temperature hypothesis. Incorporated oxygen as an estimated parameter.

Relative abundance trends for the bigeye in the HBS and statHBS analysis in 2003 and 2004 are illustrated in Figures 7.4.10. and 7.4.11. respectively.

7.4.1.4. Discussion

7.4.1.4.1. Estimation of CPUE and model comparison

For each standardisation method, the relative trend in effective effort targeting bigeye was similar to the trend in nominal fishing effort suggesting both poor explanatory power of the methods and a lack of inclusion of explanatory variables not currently recognized as important or for which too few data are available.

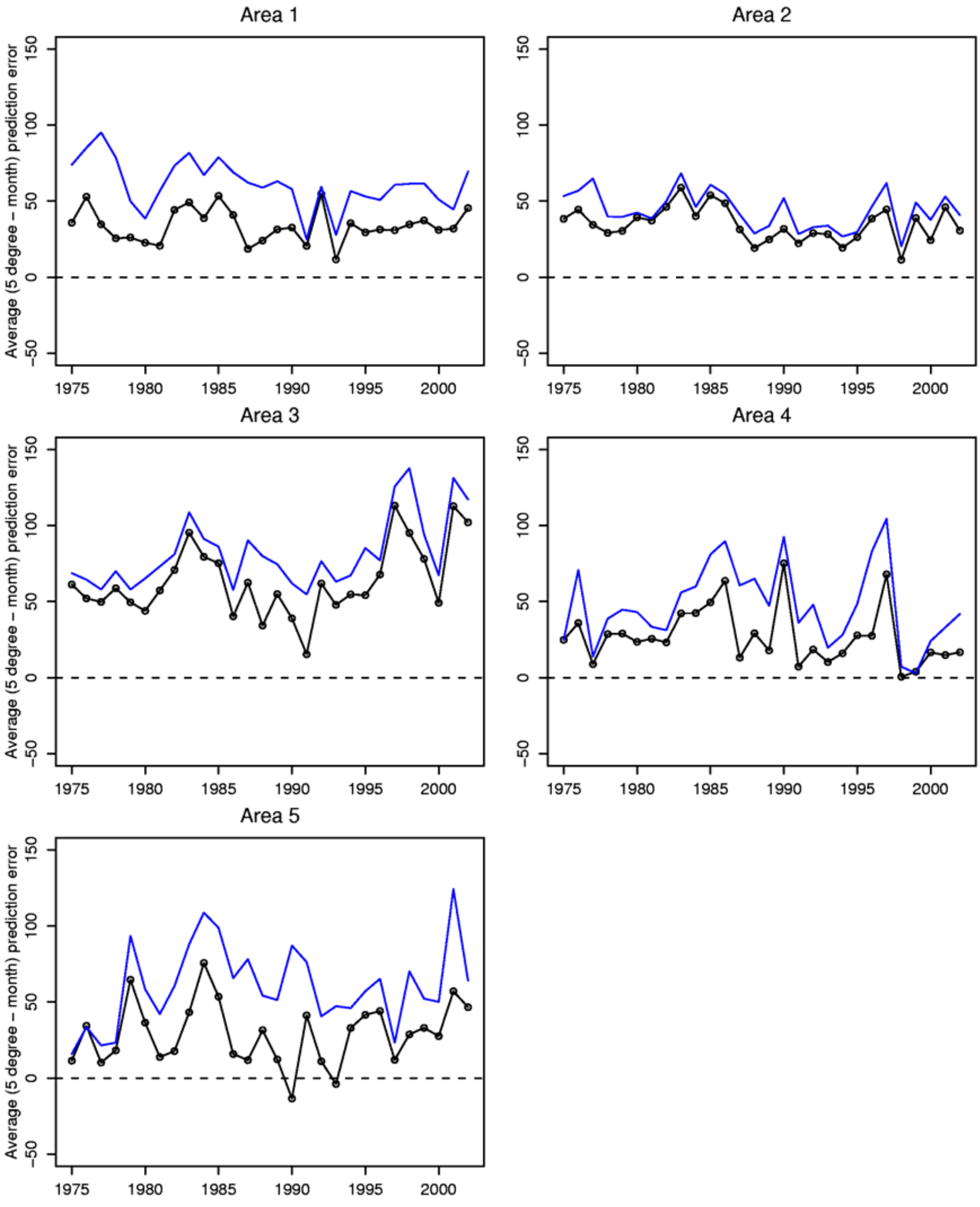


Figure 7.4.6. Average (5°–monthly) prediction error (actual catch-predicted catch) for bigeye tuna from GLM (in black) and statHBS (in blue) models from 1975 to 2002.

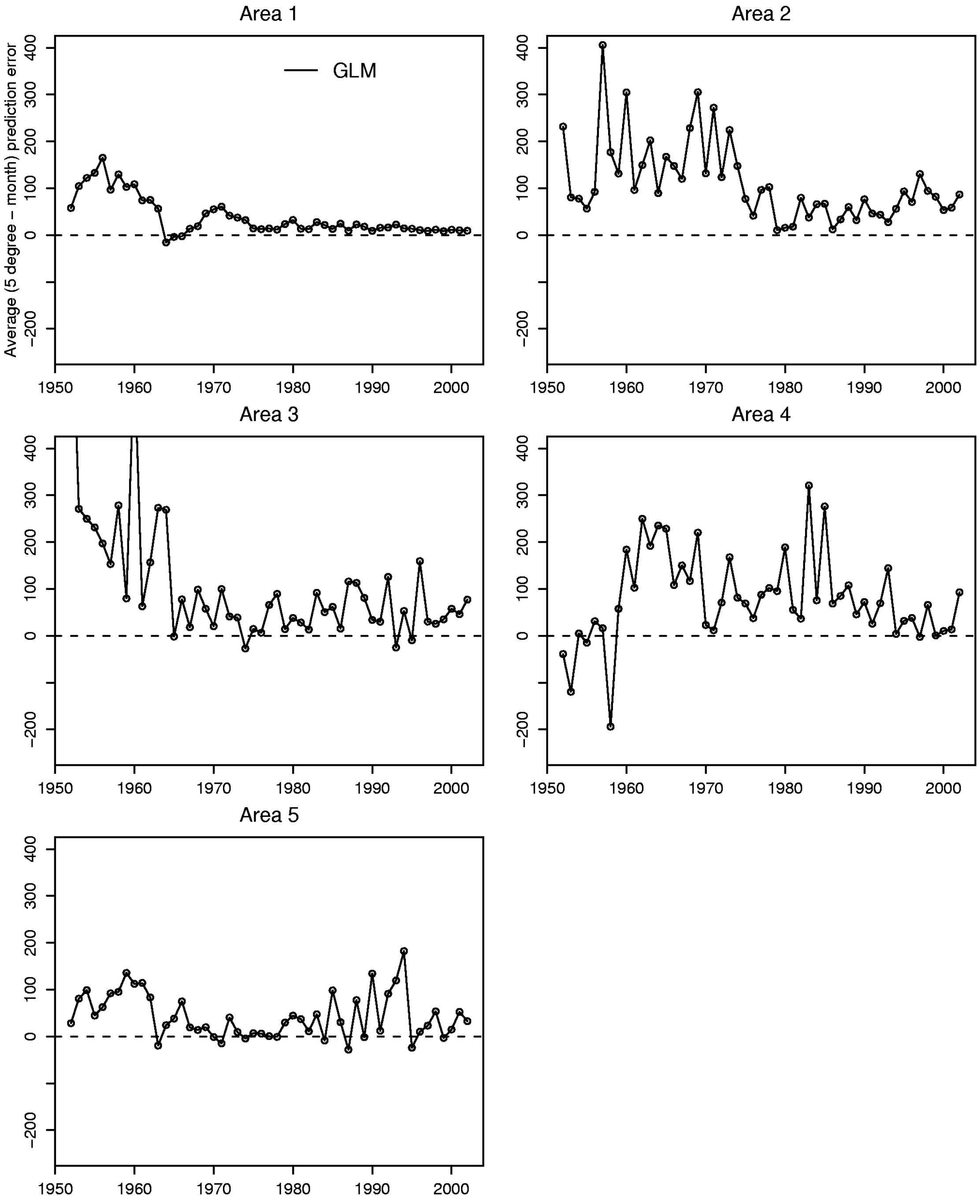


Figure 7.4.7. Average (5°–monthly) prediction error (actual catch-predicted catch) for bigeye tuna from GLM models from 1952 to 2002.

As currently implemented, the HBS effort standardisation method predicts catches poorly in comparison to either the GLM or statHBS. There may be several reasons for the poor performance of the HBS, the most prominent of which is that the habitat preferences derived from electronic tagging may differ markedly from actual depth and temperature distribution of catches within the fishery. Other possible caveats include: (1) an incorrect assumption of vertical distributions in developing a composite longline index involving the combination of both day and night distributions because of differing catchability (and distributions) between day and night; (2) incorrect gear depth assumptions; (3) geographical constraints whereby the vertical distribution of an individual is not representative of the population in a particular MFCL stratum, and (4) the potential for other environmental factors, not included in the model parameterisation, to significantly influence the relative depth and temperature distributions of bigeye tuna. Given the current caveats, the HBS method is probably not appropriate for CPUE estimation until better habitat preference indices can be developed.

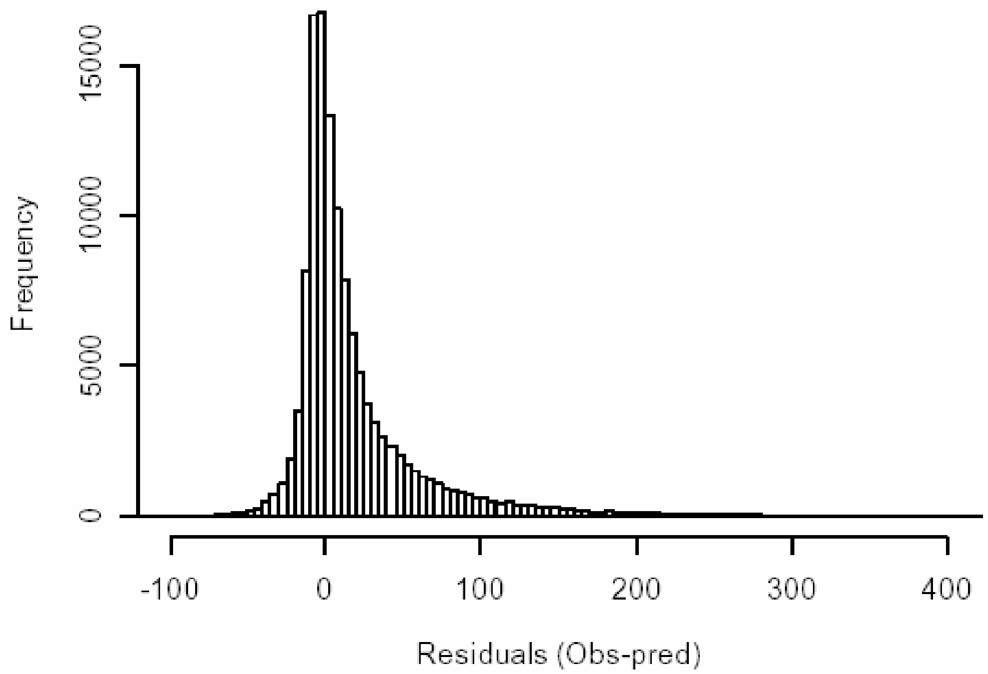


Figure 7.4.8. Frequency distribution of the residuals from the bigeye statHBS model for MFCL Area 3 using high resolution (1°) catch and effort data.

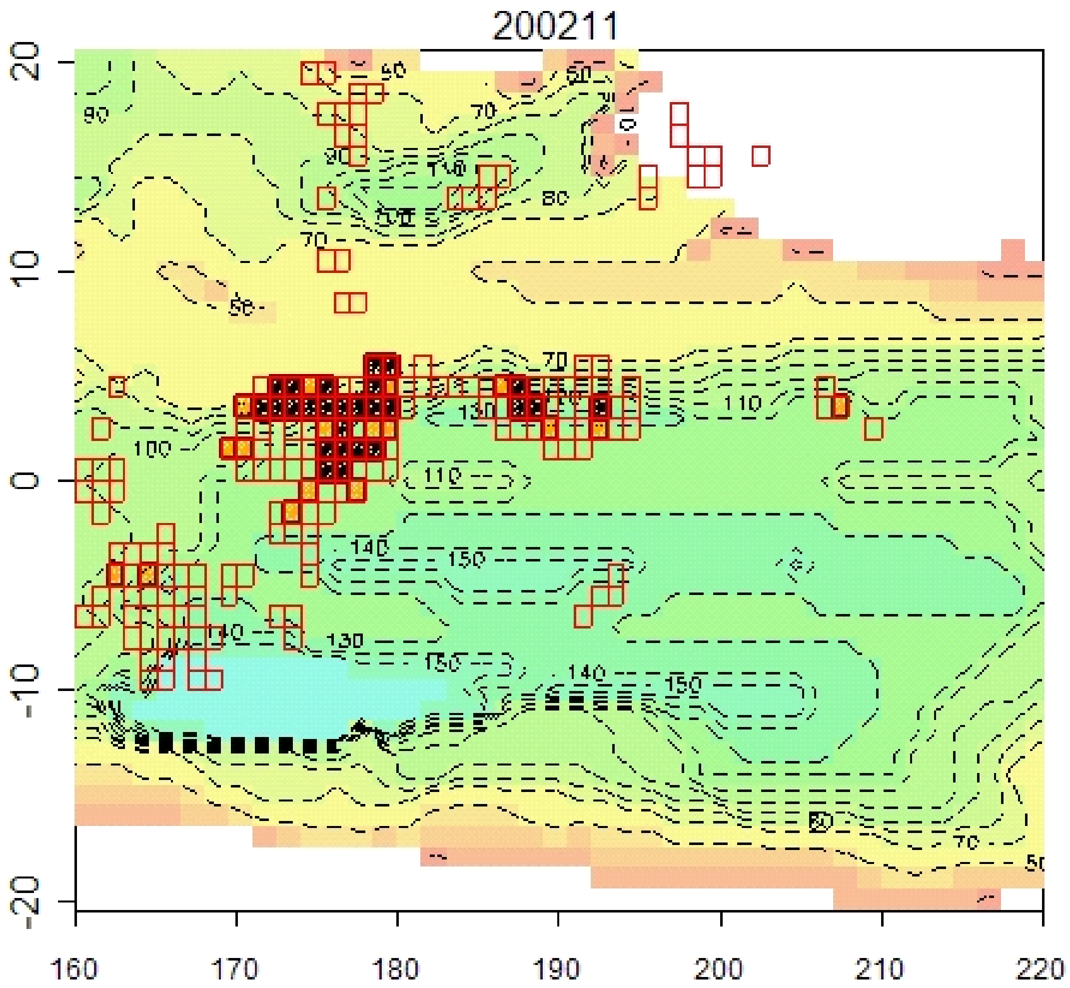


Figure 7.4.9. An example of the relationship between high positive residuals from the bigeye statHBS model and prevailing oceanographic conditions (November 2002, MFCL area 3). The location of monthly fishing effort by 1° of latitude and longitude is presented by the red squares and squares with high (above the 90 % quartile; orange stars) and very high positive residuals (above the 95 % quartile; black stars) are highlighted. The depth of the 27°C isotherm during the corresponding month period is presented as background (increasing depth of the isotherm from brown-yellow-green-blue) and by the associated depth contours.

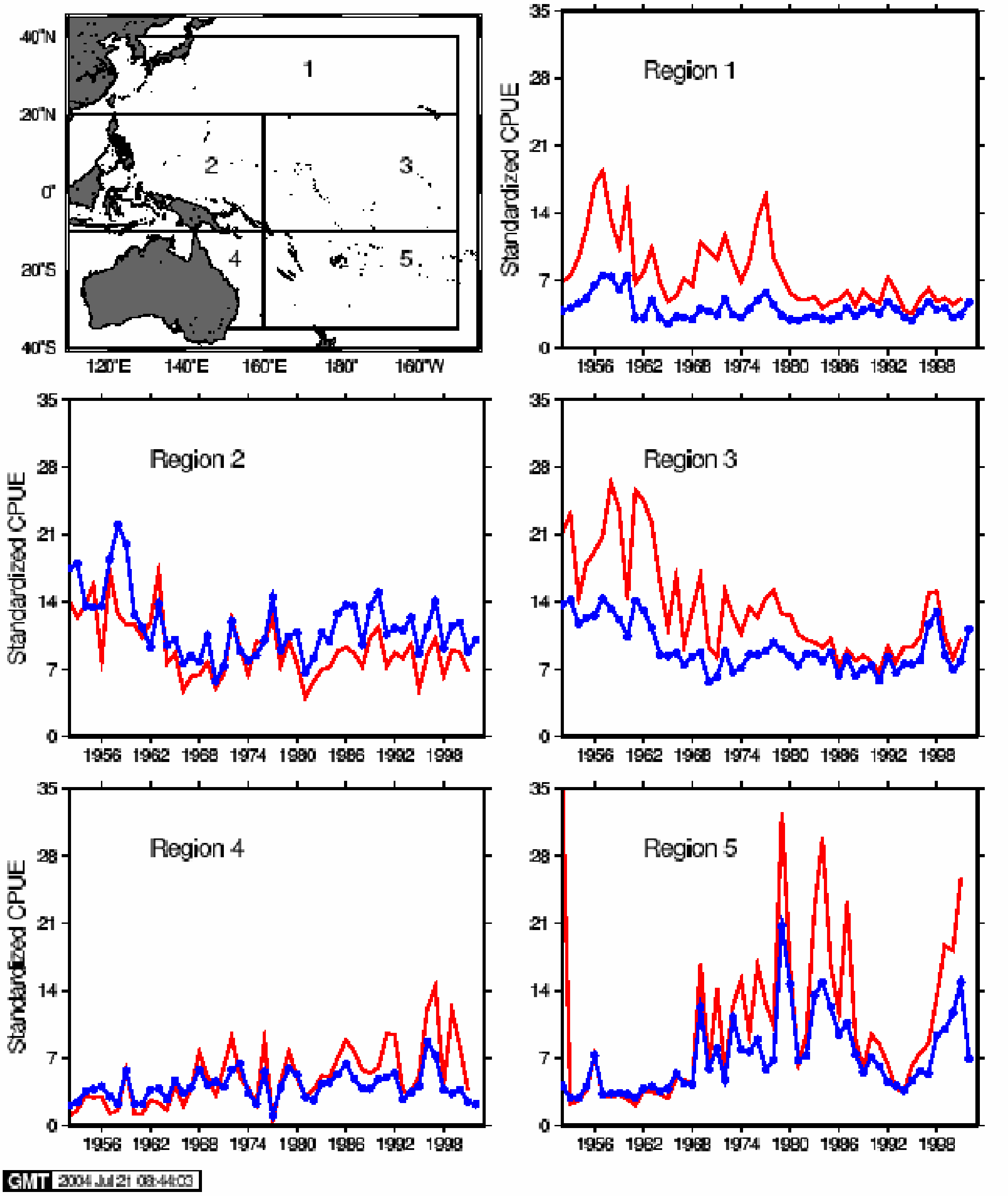


Figure 7.4.10. Comparison of relative abundance indices for bigeye tuna from HBS models in 2003 (red line) and 2004 (blue line).

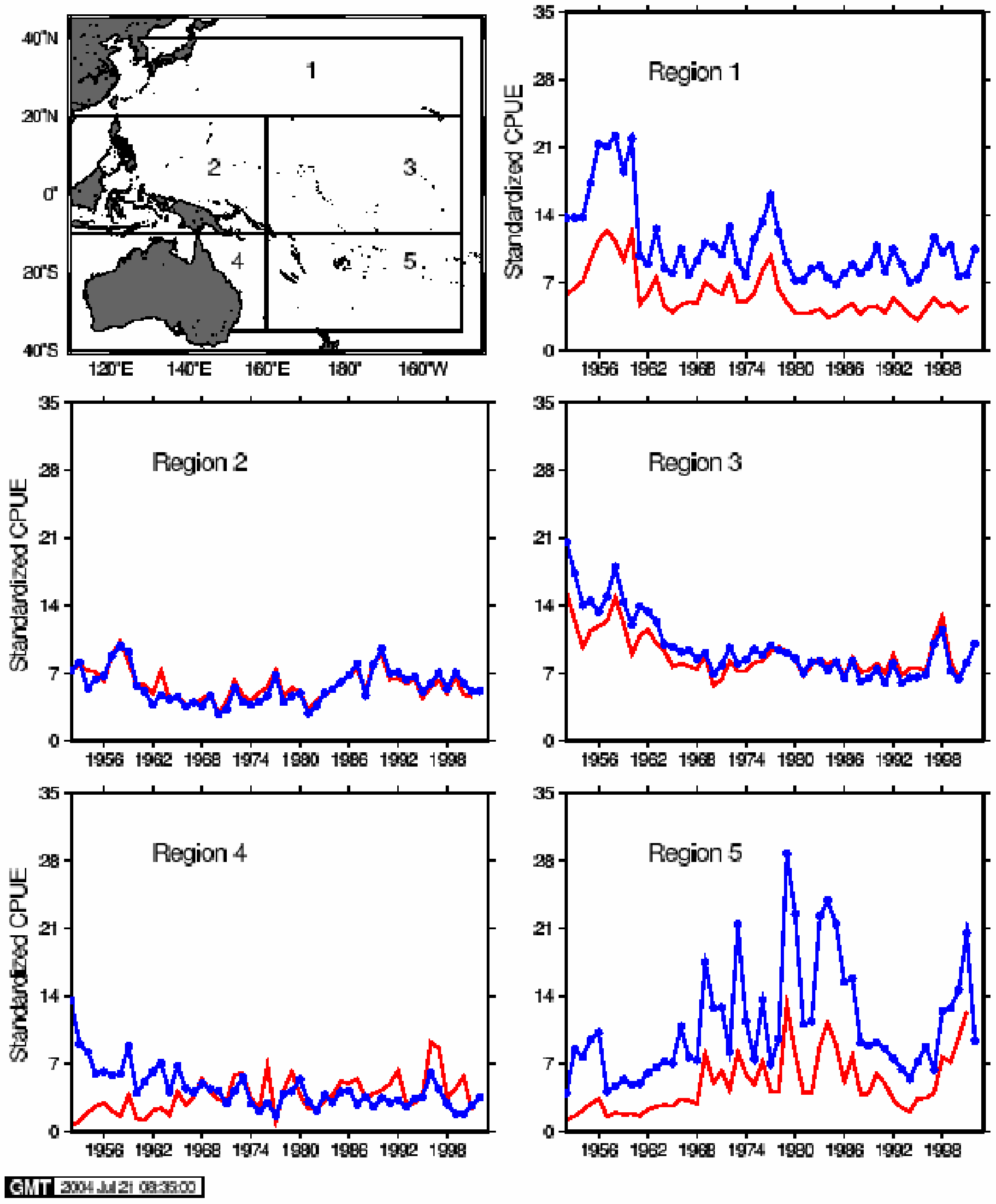


Figure 7.4.11. Comparison of relative abundance indices for bigeye tuna from statHBS models in 2003 (red line) and 2004 (blue line).

While the statHBS provided realistic ambient habitat values (Figure 7.4.3) for bigeye tuna, problems remained when the model estimated the population distribution based on the distribution of isotherms relative to the mixed layer. Improvements to the understanding of model performance for these distribution hypotheses could be attained through further simulations. A sensitivity analysis of the assumptions of gear depth could also be conducted in an effort to improve the performance of the model.

A prediction error statistic demonstrated difficulty in predicted catch in the initial 15 to 25 years of the fishery. In light of this, further improvements could also concentrate on model diagnostics for effort standardisation methods and these diagnostics could be expanded to evaluate the residuals for various spatio-temporal, gear, or oceanographic factors.

Finally, the spatial stratification of the effort standardisation could be altered from the MFCL area configuration to one with more ecological value. The spatial stratification could be developed as bio-ecological provinces that better represents a species environmental variability.

7.4.1.4.2. Incorporation of finer scale data and the influence oceanographic conditions

Fine-scale (1°–month) data for the fishery exists for the years 1975-2003 and may better describe the relationship between environmental conditions and catch rate. Analyses with these fine-scale data are given in the second part of this chapter.

7.4.2. Fine scale analysis of bigeye tuna relative abundance in the Coral Sea

T. Patterson and K. Bigelow

7.4.2.1. Introduction

In this, the second part of this chapter, we examine sources of observational uncertainty and how they may affect the habitat based standardisation process by examining the CSIRO/SPC AT data for bigeye tuna in conjunction with fisheries and oceanographic data. In addition, this section is a first attempt to apply the deterministic HBS and Statistical Habitat Standardisation (statHBS) methods at finer spatial resolutions. For the most part, these analyses follow on from those contained in the first part of this chapter (Section 7.4.1); with a reduction in the spatial extent of the fisheries data to roughly that of MFCL area 4 an area reflective of broad-scale geoposition estimates collected from the CSIRO/SPC AT data.

Previous chapters have demonstrated substantial differences in behaviour, both in terms of movement and habitat (depth and temperature) preference, between individual bigeye tuna at different times of the year. A key goal of the analyses contained in this chapter therefore is to enhance our understanding the effect of spatial and temporal variation in behaviour on the final standardised relative abundance time-series. If fish are behaving in a markedly different fashion between areas, this is likely to affect the output of the effort standardisation process. In the larger scale analysis using the MFCL areas, data from bigeye from across the Coral Sea were used simultaneously within a given month – for instance, all the CSIRO/SPC data was aggregated within MFCL Area 4. In this analysis individual tags are allocated to three finer-scale spatial strata within the Coral Sea and W/CPO.

It should be noted that error associated with geoposition estimates adds further uncertainty to the ability to assess the effect of behavioural variability on standardised relative abundance time-series. Because both the HBS and statHBS approaches rely on describing depth and temperature preferences in a given region, poor estimates of geoposition have the potential to bias the results of these standardisation methods. Chapter 7.1. detailed significant problems with the determination of geoposition estimates using archival data from tagged bigeye, which could not be completely solved using post-calculation filtering methods. Therefore, without more detailed work, beyond the scope of this project, it is impossible to characterise the effect of true spatio-temporal variation in behaviour on standardisation processes.

Despite these problems, the aim of this section is to attain a better understanding of the factors that influence the results generated by such methods as HBS/statHBS and identify areas of critical uncertainties requiring further research. In examining the possibilities for finer scale analysis we determine where the limits of the current dataset and methodologies lie. For this analysis we used the Japanese longline (JPL) dataset due to the availability of relatively comprehensive spatial and temporal coverage of catch, effort and gear configuration data.

7.4.2.2. Methods

7.4.2.2.1. Choice of spatial strata

Spatial strata within MFCL Area 4 (see Section 7.4.1. for a description of this Area) were chosen on the basis of two main factors (1) the distribution of effort within the area and (2) the distribution of geoposition estimates throughout the area..

Density plots of geoposition estimates derived from a filtered sea surface temperature (FSST) method (see Chapter 7.1.) for each month of the year were generated using two-dimensional kernel smoothing methods (Venables & Ripley 2001). It was assumed that none of the fish tagged made significant northward migrations so therefore any geoposition estimates north of the equator were excluded from the spatial strata determination. Clear areas of high density of geoposition estimates were then identified and incorporated with effort data to define spatial strata for subsequent analyses. Using geoposition estimates for a given month individual bigeye were then assigned to each of the spatial strata and the associated behavioural data incorporated into subsequent analyses. However, due to the degree of uncertainty associated with the accuracy of geoposition estimates, definitive allocation of individual bigeye to a particular stratum was not a straightforward procedure. Often the spatial resolution of geoposition estimates for a given bigeye during a given month was such that inidividuals spanned multiple strata. As a result we adopted a simple method of allocating a tag to the stratum that it was estimated to have spent the most time in for any given month. A brief comparison with location estimates derived using a state-space extended Kalman filter (KF) statistical model (see Chapter 7.1) was conducted, but the FSST method was used to be comparable with the analyses given in previous chapters.

The coefficient of variation:

CV = SD (ŷ) / mean (ŷ), where ŷ = proportion of observations in depth/temperature bin

was computed for each of the depth and temperature bins within a month as a simple way to assess the variability at depth and temperature between strata in each month.

7.4.2.2.2. CPUE standardisation

The analysis utilised the StatHBS and HBS methods as per Section 7.4.1. Five separate models were fit to the catch rate data from the JPL. These consisted of a nominal CPUE model, HBS models with monthly temperature and annual temperature data (see section 7.4.2.2.3. below) and statHBS models again using these inputs. Data from the tags were aggregated annually or by month accordingly.

Model fits were assessed using Akiake's Information Criterion (AIC; Burnham & Andersen 1998) and, in the case of the statHBS models, by examining the model fits to observed temperature preferences from the archival tags. Spatial plots of the residuals of observed and predicted catch were also examined to compare the fine scale results to model fits to the 5° given in Section 7.4.1.

7.4.2.2.3. Data sources

The fisheries datasets used consisted of fine-scale (1°) catch, effort and Hook Between Float data (HBF) from the JPL (as used in the W/CPO analysis) from 1975 to 2002. Data prior to 1975 were not included in analyses due to a lack of HBF data and the differing spatial scales of data collected between 1952 and 1965 (collected at a spatial resolution of 5°, which was considered too coarse for this finer-scale analysis). Data from within MFCL Area 4 for 1975 onwards were compared with the full time series to examine if there were significant differences in the two datasets.

As bigeye tagged with archival tags were not estimated to have moved south of approximately 28°S and the fishery in this area is considerably different from that in the Northern Coral Sea, CPUE data from latitudes south of 35°S were excluded from this analysis. The fishery to the south of 35°S is known to target other species (for example, southern bluefin tuna, *Thunnus maccoyii*) and is also subject to different oceanography with much cooler water and the influence of the eddy systems associated with East Australia Current (EAC).

Oceanographic data were extracted from the NODC World Ocean Atlas/Database (http://www.nodc.noaa.gov/General/temperature.html). Instrument types used include: low resolution CTD (n = 11,842), high resolution CTD (n = 6,965), expendable bathythermograph (XBT; n = 50,507) and mechanical bathythermographs (MBT; n = 4,689). Data were extracted in approximately 20 m bins and combined in this analysis. The above sample sizes weight the data heavily in favour of the XBT dataset.

7.4.2.3. Results

7.4.2.3.1. Spatial stratification analysis

Geolocation estimates derived by FSST and KF methods for each month for the 14 ATs deployed demonstrate three general centers of density – (1) the North western Coral Sea, (2) the eastern Coral Sea and (3) an area south of 20°S close to the Queensland coast (Figures 7.4.12. and 7.4.13.). The spatial grouping of these position estimates formed the basis for the boundaries which defined the spatial strata shown in Figures 7.4.12. and 7.4.13.

Both the KF and FSST methods produced a similar spatial distribution of tags. Although the numbers of tags estimated to be located in each stratum differed between methods, the percentage of the total tags in each stratum was relatively similar, resulting in some agreement in the relative densities of animals in each stratum (Figure 7.4.14.). Of all strata, stratum 1was estimated to contain the highest density of tags (Tables 7.4.4.). Averaging across months, the FSST method estimated 56 % of tags to be located in stratum 1 and the KF method estimated 62 %. In stratum 2, the FSST estimated 27 % compared to the KF method estimate of 25 %. The FSST method allocated 17 % of all locations in stratum 3 compared to 13 % from the KF estimates.

Using FSST methods, in all months other than November, individual bigeye were estimated to occur in the same spatial strata more than 75 % of the estimated days. Subsequently, tags considered to be located in a stratum 75 % or more of the time during an individual month were allocated to that stratum for analyses (Table 7.4.5.). In comparison to other months, the coverage of tags across strata was considerably reduced between the months of June to September with no bigeye allocated to stratum 3 in the month of September. To overcome the presence of zero values in a stratum for a given month, the depth and temperature profiles for the month were computed as the mean of the other two strata. Although other methods could be utilised in estimating appropriate data, this was considered a conservative approach to the problem.

7.4.2.3.2. Depth and temperature distributions

Depth and temperature profiles for each stratum were constructed based on the allocation of tags to strata given in Table 7.4.5. (Figures 7.4.15. and 7.4.16.). The diurnal signal that characterises the depth distributions of bigeye (i.e. at depth during the day and shallower at night) was present in all months and strata, although some variation between months and between areas was also evident. From October to January a bimodal daytime depth distribution occurred in strata 1 and 2 but was less apparent in stratum 3. The mode of the day- time depth distributions was approximately 400 m.

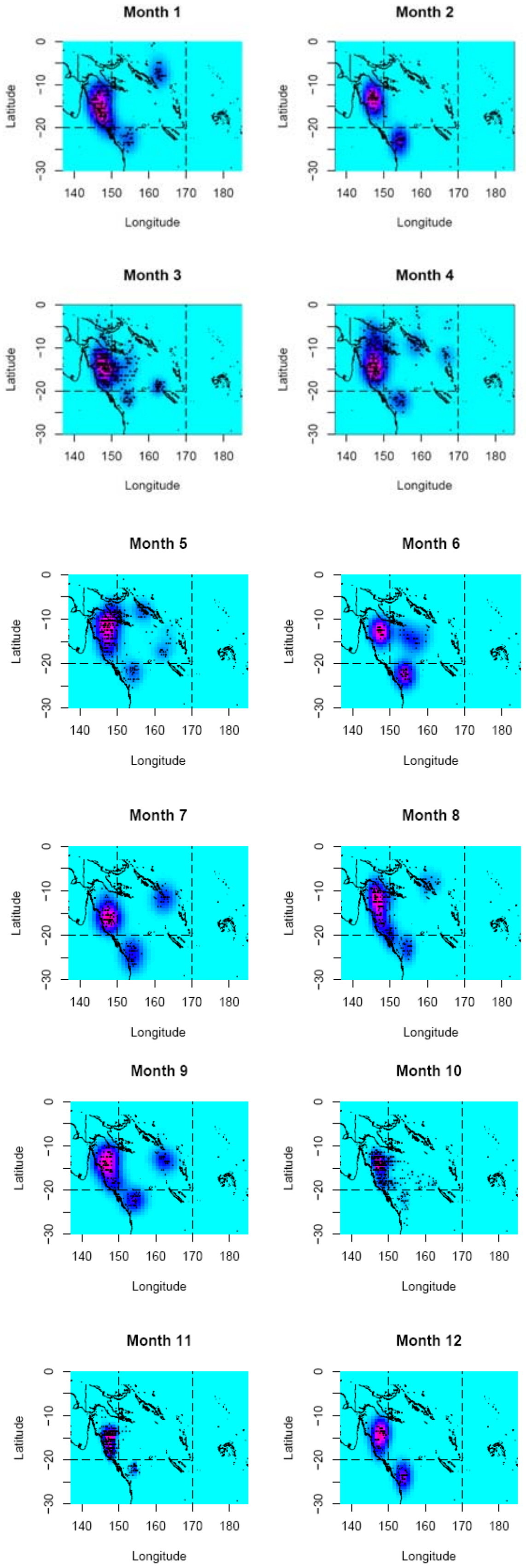


Figure 7.4.12. Filtered SST estimates of positions for all tags overlaid on the chosen spatial strata.

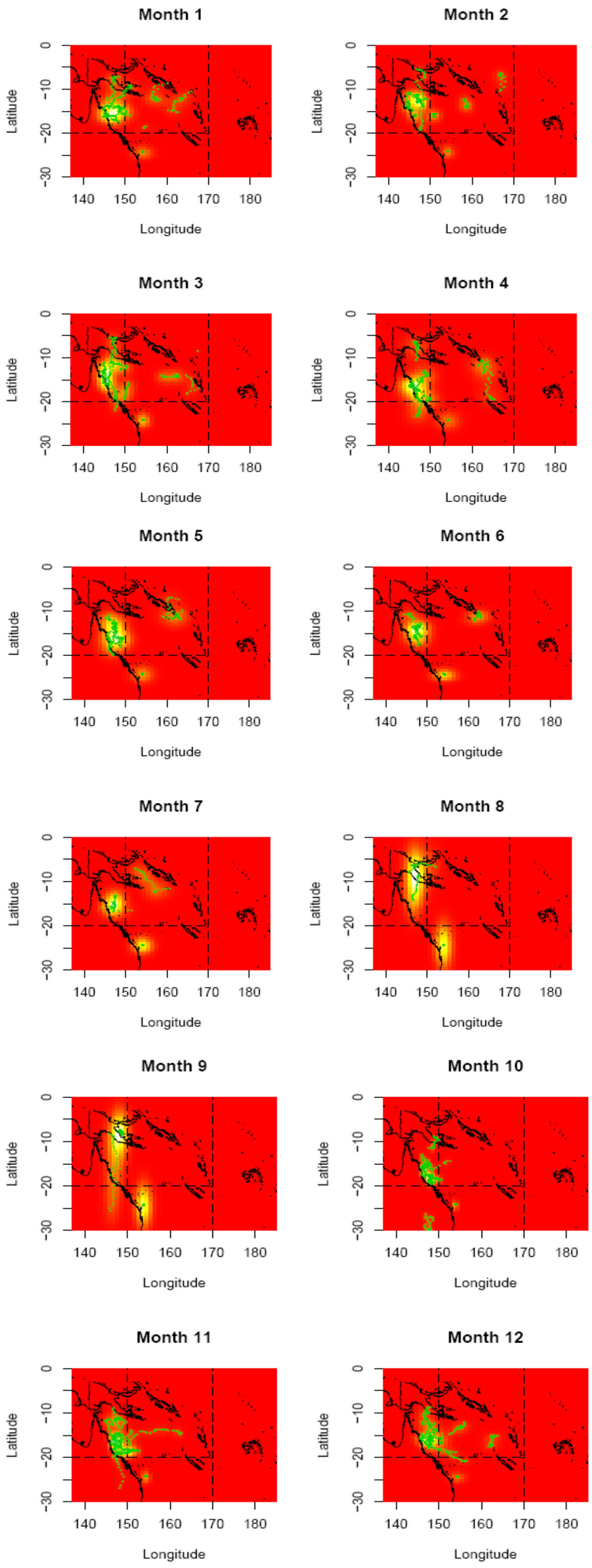


Figure 7.4.13. Estimates of positions for all tags calculated using a Kalman Filter and overlaid on the chosen spatial strata.

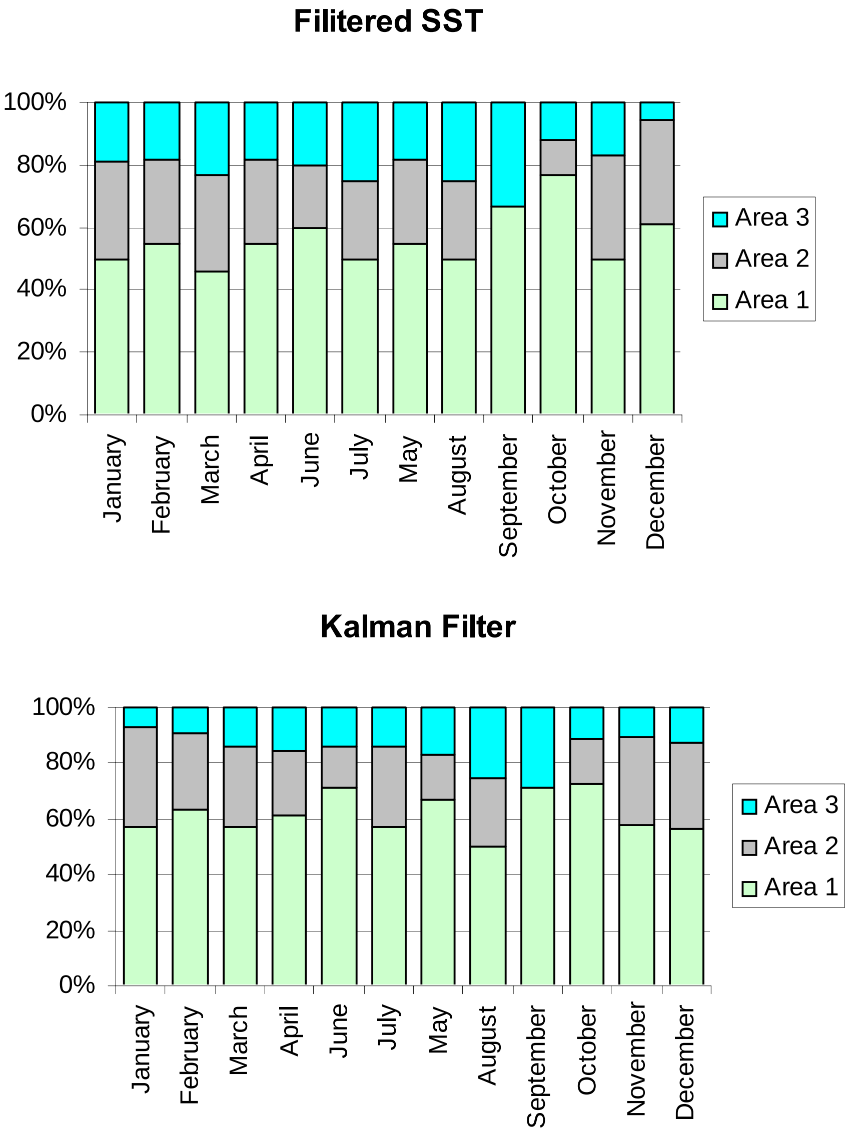


Figure 7.4.14. Percentages of the total visits to each stratum (1-3) by month.

Table 7.4.4. The number of tags per spatial strata by month.

Filtered SST

Month	**Strata**		
	1	**2**	**3**
January	8	5	3
February	6	3	2
March	6	4	3
April	6	3	2
June	3	1	1
July	2	1	1
May	6	3	2
August	2	1	1
September	2	0	1
October	13	2	2
November	12	8	4
December	11	6	1

Kalman Filter

Month	**Strata**		
	1	**2**	**3**
January	8	5	1
February	7	3	1
March	8	4	2
April	8	3	2
June	5	1	1
July	4	2	1
May	8	2	2
August	2	1	1
September	5	0	2
October	13	3	2
November	11	6	2
December	9	5	2

As observed in Chapter 7.2, daytime temperatures in each stratum were considerably colder than the surface orientated nighttime distributions. The effect of small sample sizes becomes evident in some months; August, in particular contains only one fish in each strata. During this month, tag 99-190 (allocated to stratum 3) exhibited what appears to be anomalous behaviour, undertaking periods of surface-oriented behaviour during the day- time, which although not particularly evident in time spent at depth profiles, skewed time spent at temperature profiles to those containing warmer water temperature preferences (Figure 7.4.16.). Whether this is representative of bigeye in this stratum or an individual behaviour cannot be determined without further archival tag data from this area.

Table 7.4.5. Assignment of archival tags to spatial strata (1-3). The criterion used was the spatial strata where the tag was estimated to have spent the most time. Note that in September, there are no tags estimated to be resident within stratum 3.

Tag	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00-112	1									1	1	1
98-347	1	1	1	1	1	1	1			1	2	1
98-353	2	2	2	2						2	2	2
98-363	2	1	1	1	1	1	1	1	1	2	2	2
98-372	3									1	2	2
98-463										1	2	1
98-479										1	2	
99-190	3	3	3	3	3	3	3	3	2	3	3	3
99-213	2	2	2	2	2	2	2	2	1	1	2	2
99-216	1	1	1	1	1					1	3	2
99-224	2	2	3	3	3	1				1	1	1
99-237	1	1	1	1	1					1	2	1
99-243	1									1	1	1
99-262	1	1	3	3	1					1	3	1

Variability at depth and temperature between strata in each month (Figures 7.4.17. and 7.4.18.) reflected the amount of data available in each stratum with the lowest CV's occurring in strata with the most depth and temperature data.

Depth ranges deeper than 600 m contained very few observations relative to the shallower depths, reducing the ability to interpret differences in the CV's of strata at these depths. Depth ranges shallower than 600 m demonstrated some difference between the months, with October demonstrating a considerable degree of variability despite having a relatively large number of tags overall. This is most likely caused by the low number of tags present in strata 2 and 3. The CVs calculated for temperature in each stratum were also quite variable. The periods from June to November (Figure 7.4.18.) demonstrated the most variable daytime and night time temperatures; however, overall, the night-time temperature preference profile suggests a preference for waters between 26 and 28°C for a large proportion of the year.

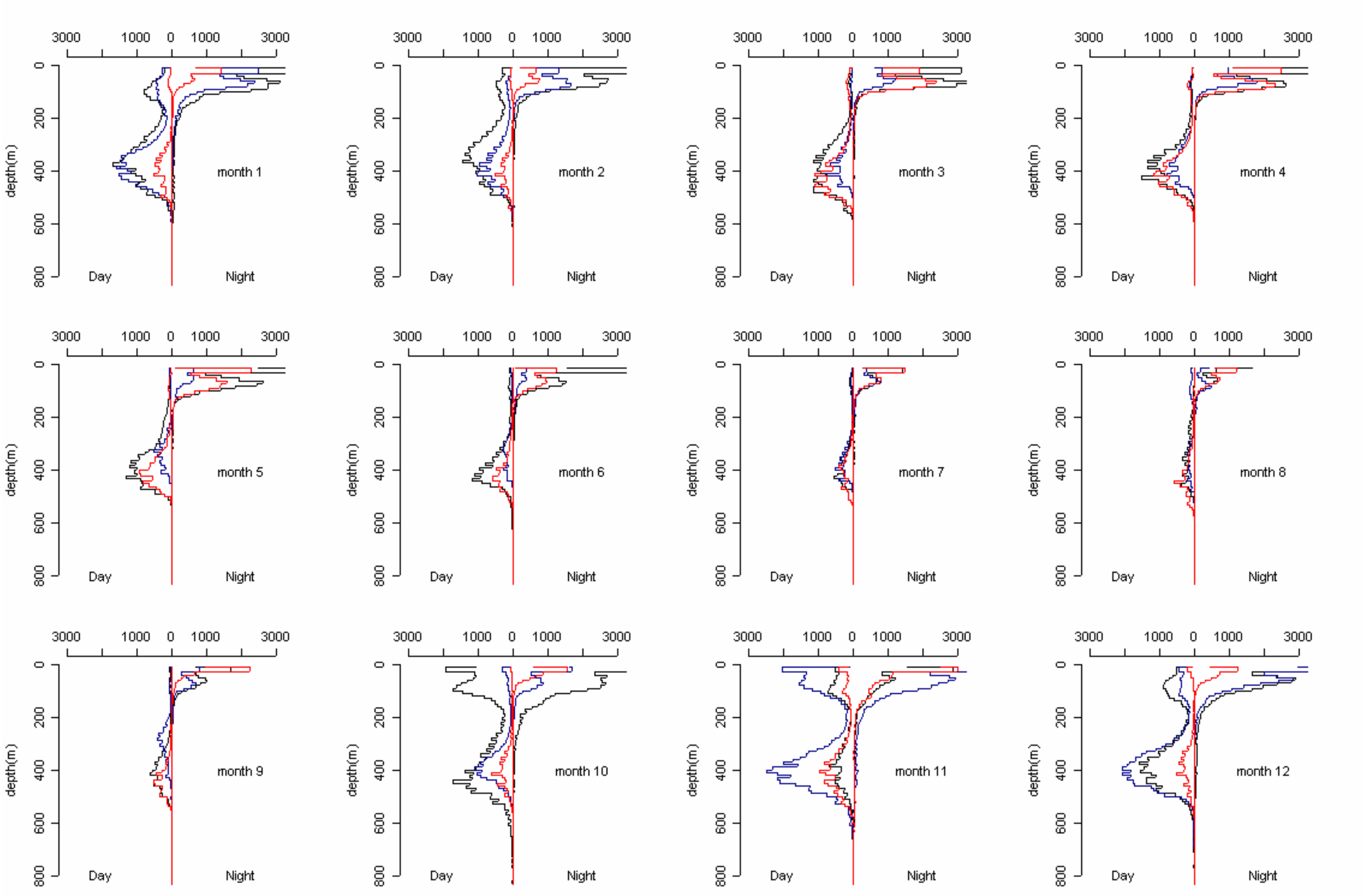


Figure 7.4.15. Depth Profiles for day and night for each month by spatial stratum (Black – stratum 1; Blue – stratum 2; Red – stratum 3).

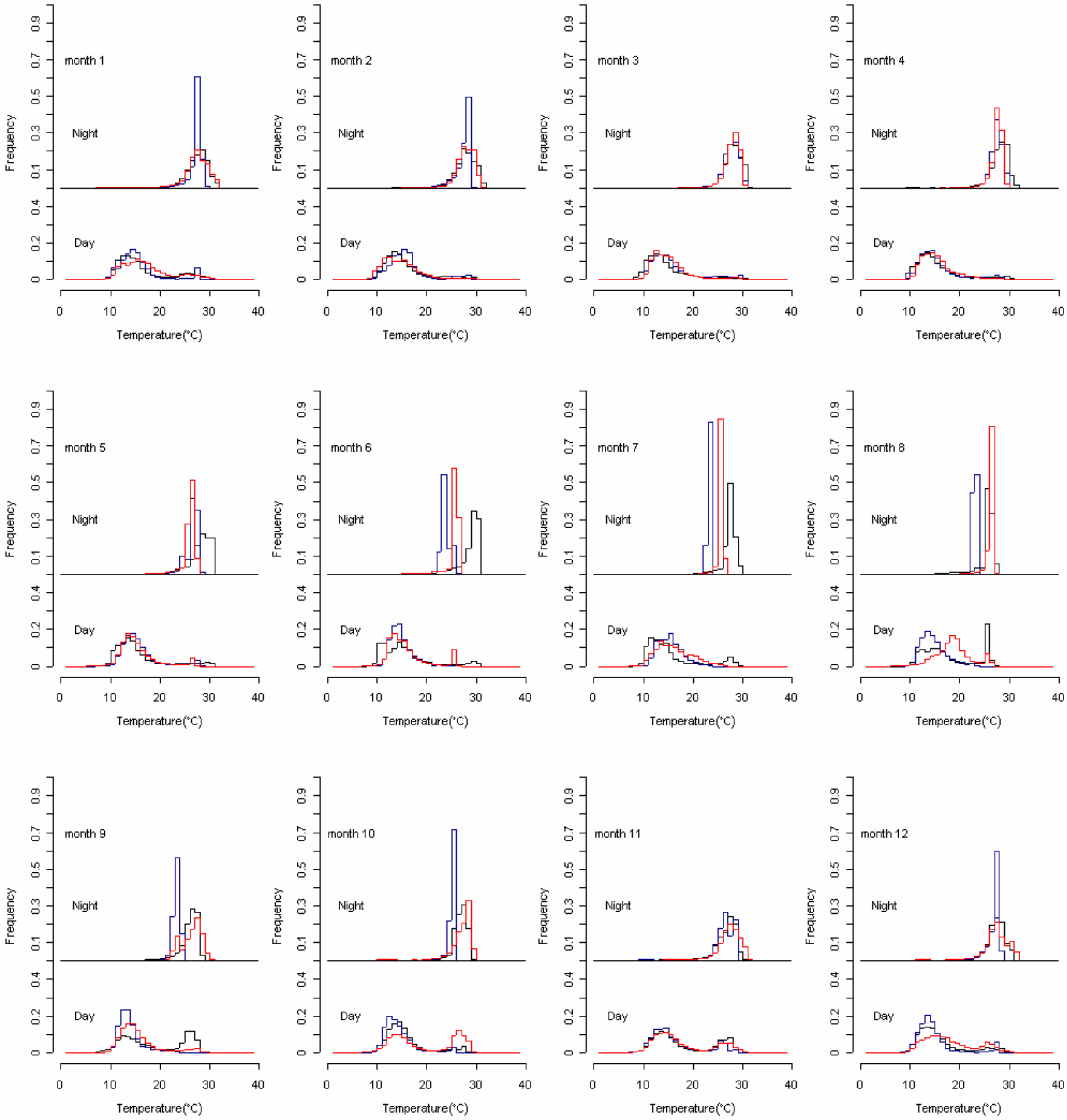


Figure 7.4.16. Temperature profiles for day and night split by spatial stratum (Black – stratum 1; Blue – stratum 2; Red – stratum 3).

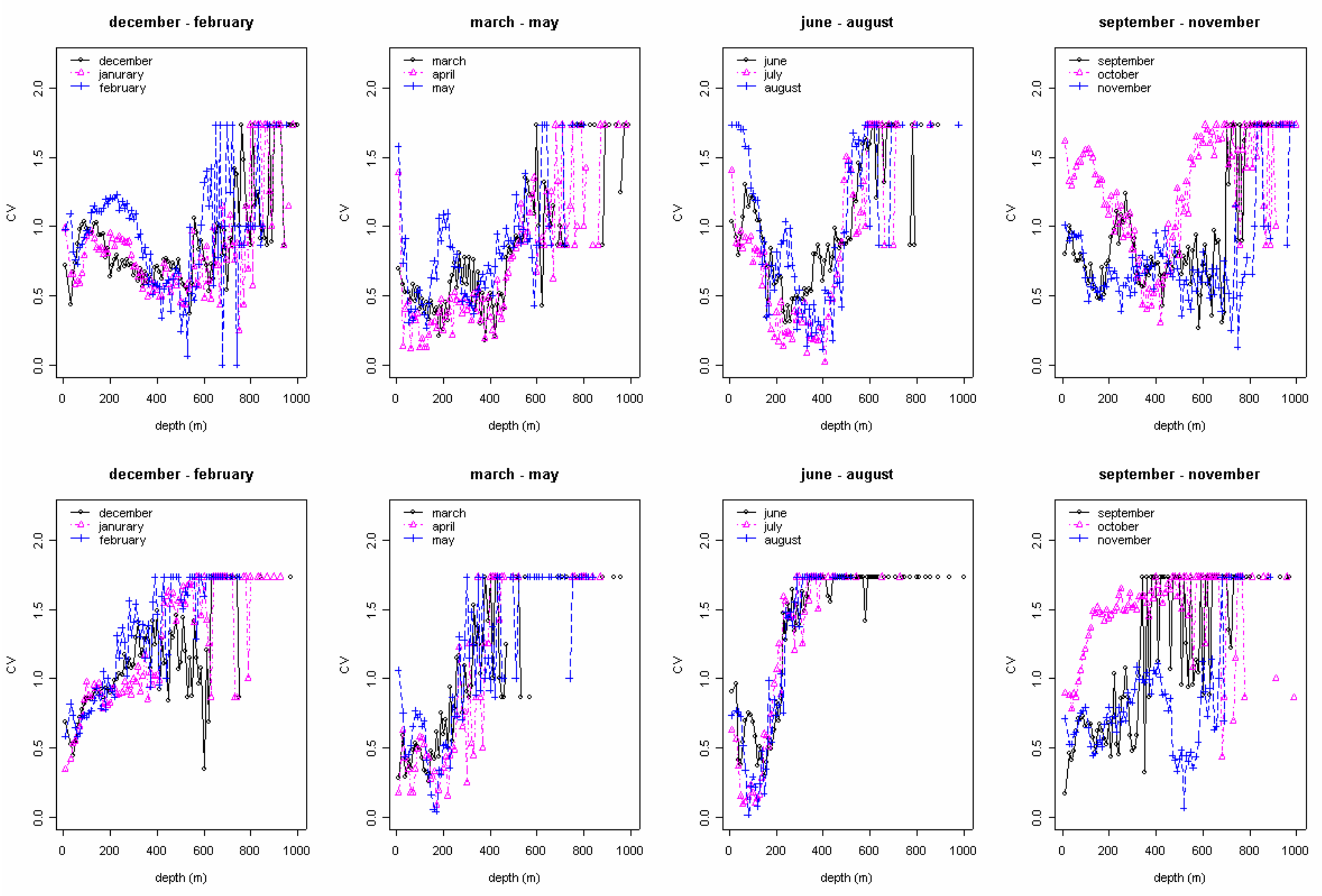


Figure 7.4.17. Coefficient of variation vs. depth (m) by month comparing the three strata during the day (top) and at night (bottom).

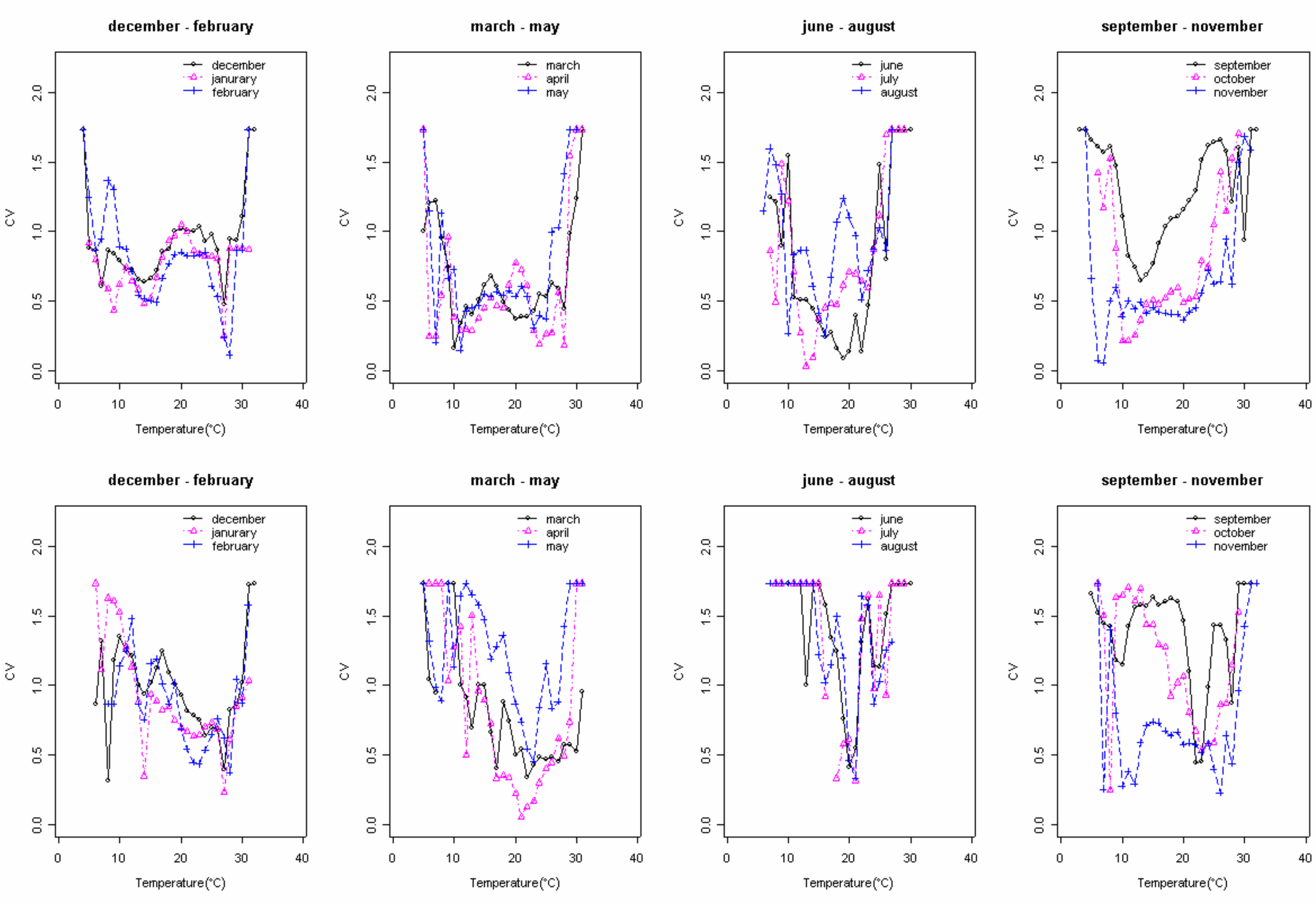


Figure 7.4.18. Coefficient of Variation vs. temperature (°C) during the day (top) and at night (bottom).

7.4.2.3.3. Oceanographic data

The CTD, XBT and MBT data for the three strata demonstrated some differences between the spatial strata (Figure 7.4.19.). Stratum 1 was typified by a distinct seasonal component in the depth of the 27°C isotherm, ranging from approximately 0-120 m across the year.

Despite being at the same latitude (Figure 7.4.19), the seasonality of the temperature of the water column across stratum 2 was less pronounced with the depth of the 27°C isotherm, in general, distributed between 60-100 m. The effect of a more southerly location is clear across stratum 3, with much cooler surface layers typifying these waters.

7.4.2.3.4. Catch and effort data

Catch and effort data for the three spatial strata are shown in Figure 7.4.20. and overall maps of effort for the three decades are given in Figure 7.4.21. The total effort series peaked in 1981 and then dropped to lower levels thereafter. The effort series were quite variable within the fine-scale analysis strata, but in general, the highest effort was located in stratum 2. Nominal CPUE was quite variable in each stratum, demonstrating no discernable trend. Overall effort varied around an average nominal CPUE of approximately 0.3 fish/100 hooks^{-1}.

Across time, a number of shifts were evident in the distribution of effort. In the first decade of the dataset (1975-1984) effort was concentrated in two general areas: the waters north of Papua New Guinea (PNG) and the Solomon Islands and also off the east coast of Australia in the northern Tasman Sea. This distribution was similar from 1985 to 1994, however, there was a reduction in effort in the area north of PNG. During 1995-2002, the JPL fleet moved outside the Australian Exclusive Economic Zone (EEZ) and in general, the effort distribution shifted further westward in response.

7.4.2.3.5. Comparison of spatial effort scales

A comparison of the full time series of catches (1952-2002) at the 5° spatial resolution with the 1° effort data (1975-2002) revealed minor differences between the two series. Small amounts of data appear to be missing from the 1° time series, but in general, there was reasonable agreement in catches between the two datasets (Figure 7.4.22.).

7.4.2.3.6. Effort and gear configuration

Depths of longline gear were modeled using a catenary function as per Bigelow et al. (2002). Using depth-of-gear estimations, the JPL across all strata demonstrated a trend toward deeper sets through time (Figure 7.4.23.).

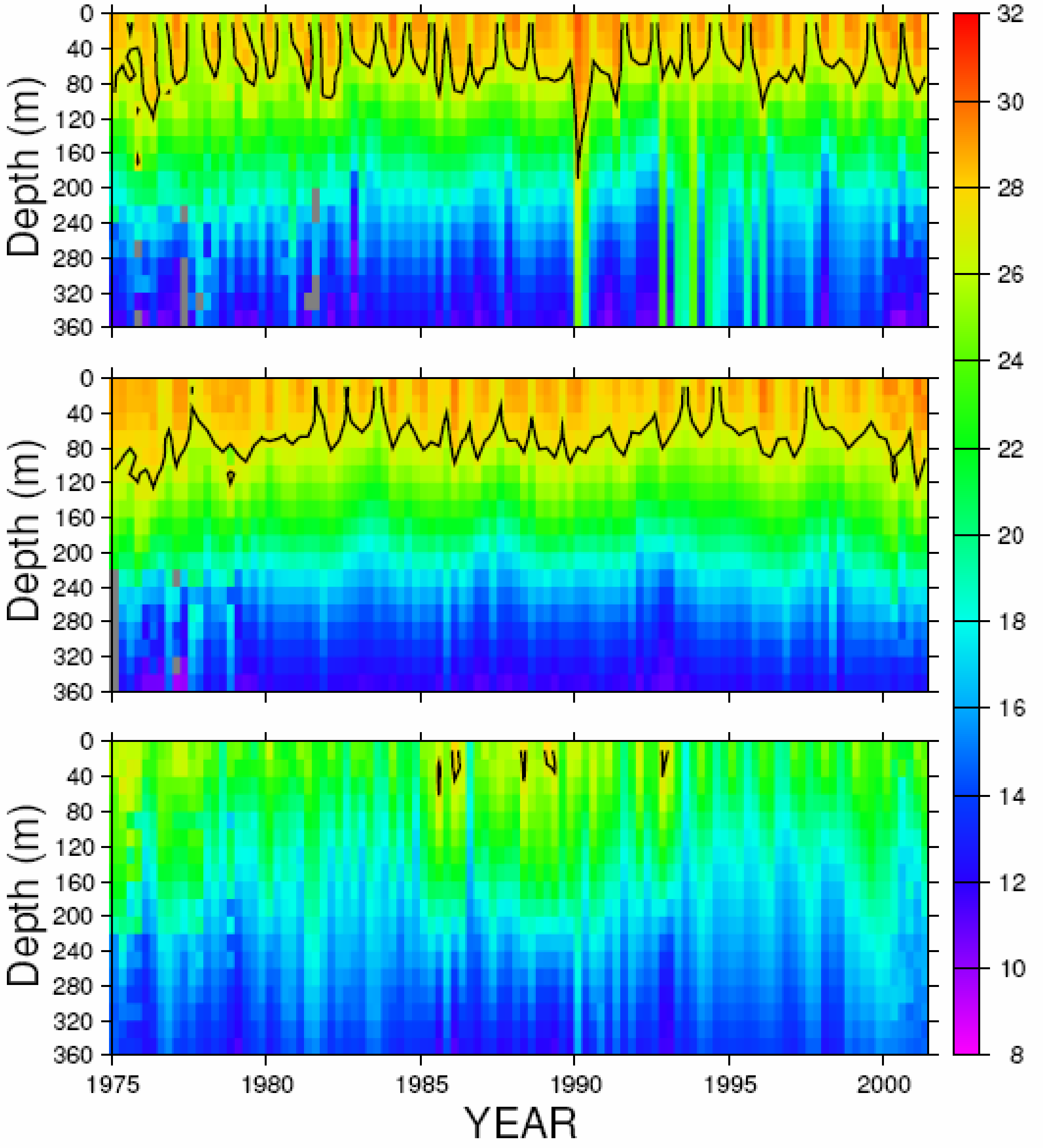
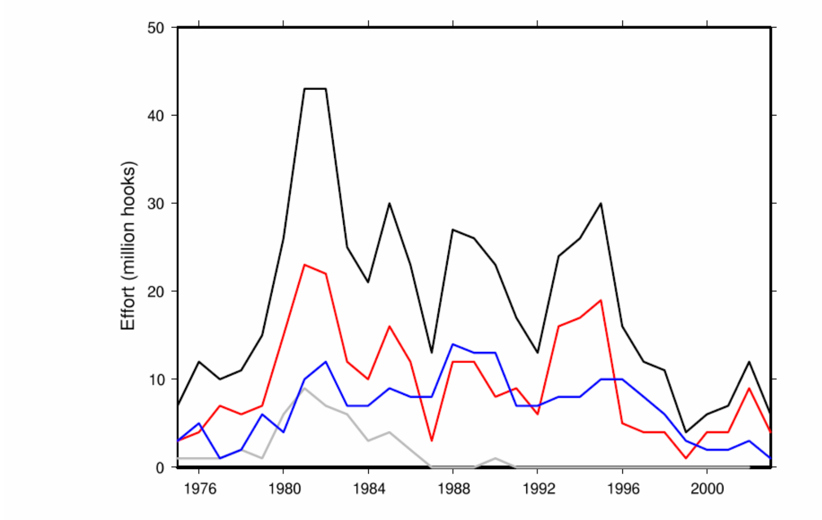


Figure 7.4.19.Time-series of temperature in the mixed layer and thermocline in each stratum (top – 1; middle – 2; bottom – 3). The line gives the 27°C isotherm. Data source: NODC.

A.



B.

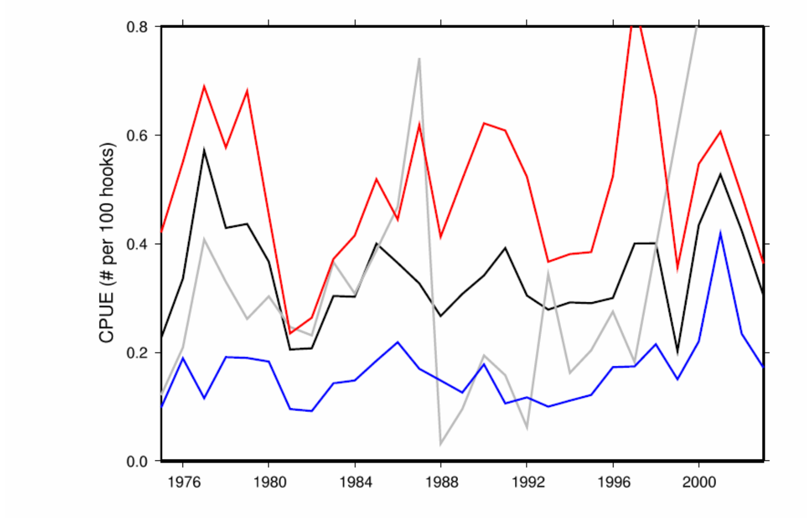


Figure 7.4.20. (a) Time-series of annual effort (million hooks) in the JPL from the equator to 35°S and 130 to 170°E. Black – total effort; grey – stratum 1; red – stratum 2; blue – stratum 3. (b) Time-series of nominal CPUE (# per 100 hooks) in the JPL from the equator to 35°S and 130 to 170°E. Black – total effort; grey – stratum 1; red – stratum 2; blue – stratum 3.

Spatial changes in effort and gear configuration were apparent in the distribution of the 1° dataset. Total effort across the three spatial strata peaked in 1981 at 17.7 × 10^6 hooks and declined steeply after 1995. In association, sets in the first decade (1975-1984) tended to be shallower with the 5-6 HBF categories dominating the data. The majority of effort was distributed north of PNG and the Solomon Islands as well as east of Australia in the Coral and Tasman Seas (Figure 7.4.23.). During the second decade (1985-1994) the effort north of PNG, apparent in the previous decade, shifted eastward becoming centred in the Tasman Sea and also in the region north east of the Solomon Islands. Effort was generally deeper, with Tasman and Coral Sea sets predominantly in 7-9 HBF category and those in the northern tropical regions deeper still (12-15 and 16-20 HBF). During 1995-2002, the spatial extent of high effort regions reduced with mostly deep sets in the tropics (16-20) and HBF values of 7-9 in the Tasman Sea.

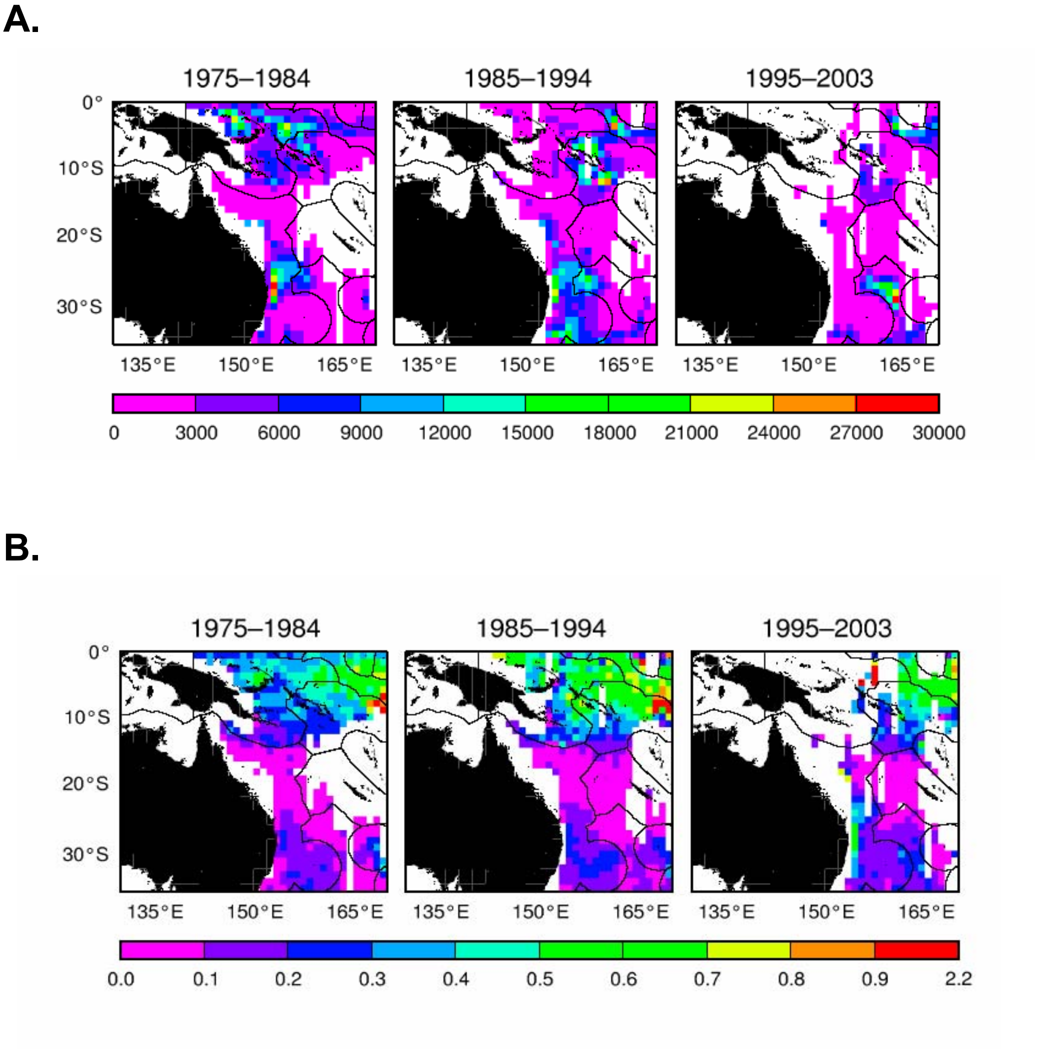
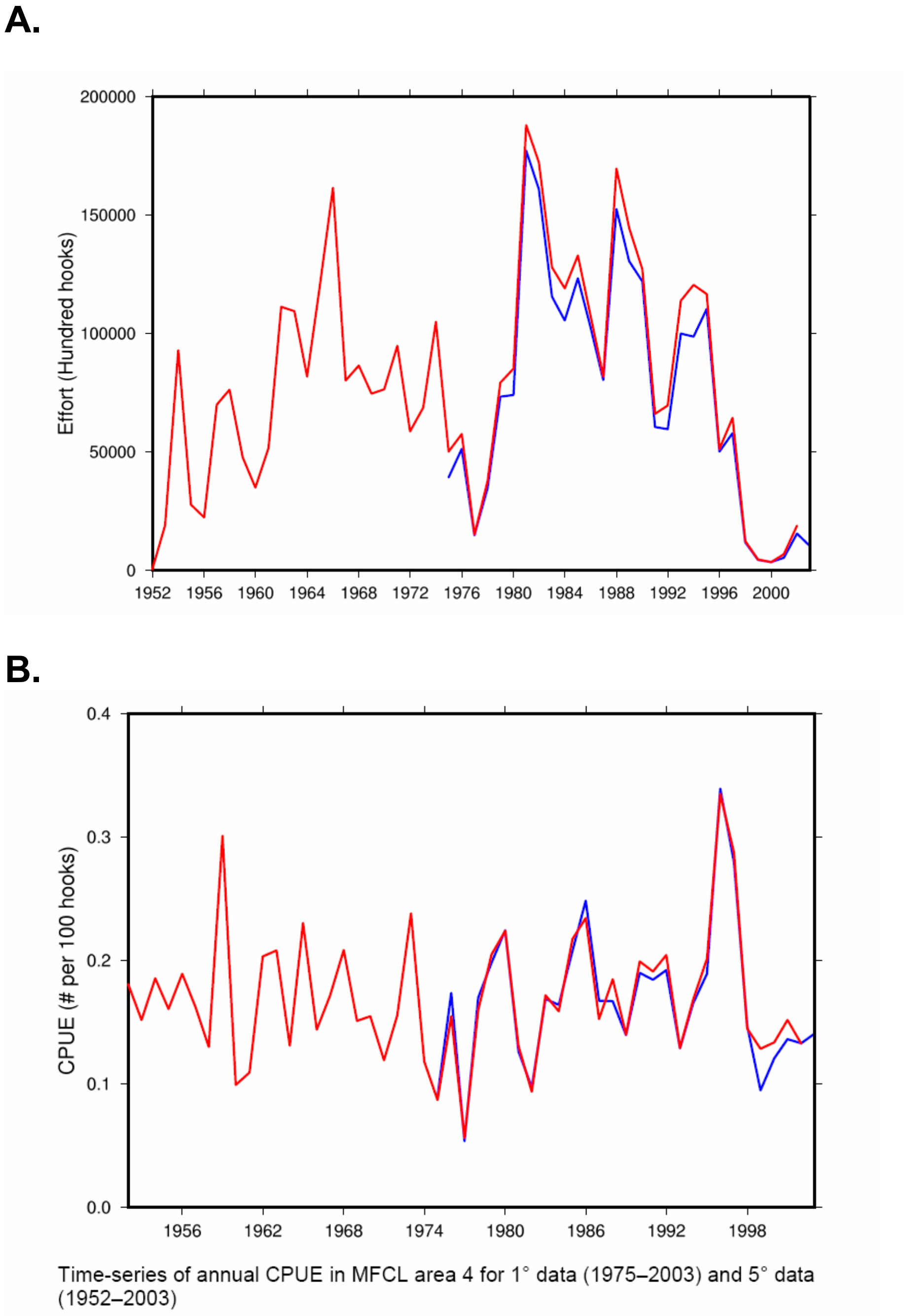


Figure 7.4.21. (a) Spatial distribution of Japanese longline effort (hundred hooks) for each 1° square from 1975–1984, 1985–1994 and 1995–2003. (b) Spatial distribution of mean nominal CPUE for each 1° square from 1975–1984, 1985–1994 and 1995–2003.



Time-series of annual CPUE in MFCL area 4 for 1° data (1975–2003) and 5° data (1952–2003)

Figure 7.4.22. (a) Time series of annual effort (hundreds of hooks) for the 5° data (1952-2002, red line) and the time series of annual effort for the 1° data from 1975-2003 (blue line). (b) Time series of annual CPUE (# per 100 hooks) for the 5° data (1952-2002, red line) and the time series of annual effort for the 1° data from 1975 to 2003 (blue line).

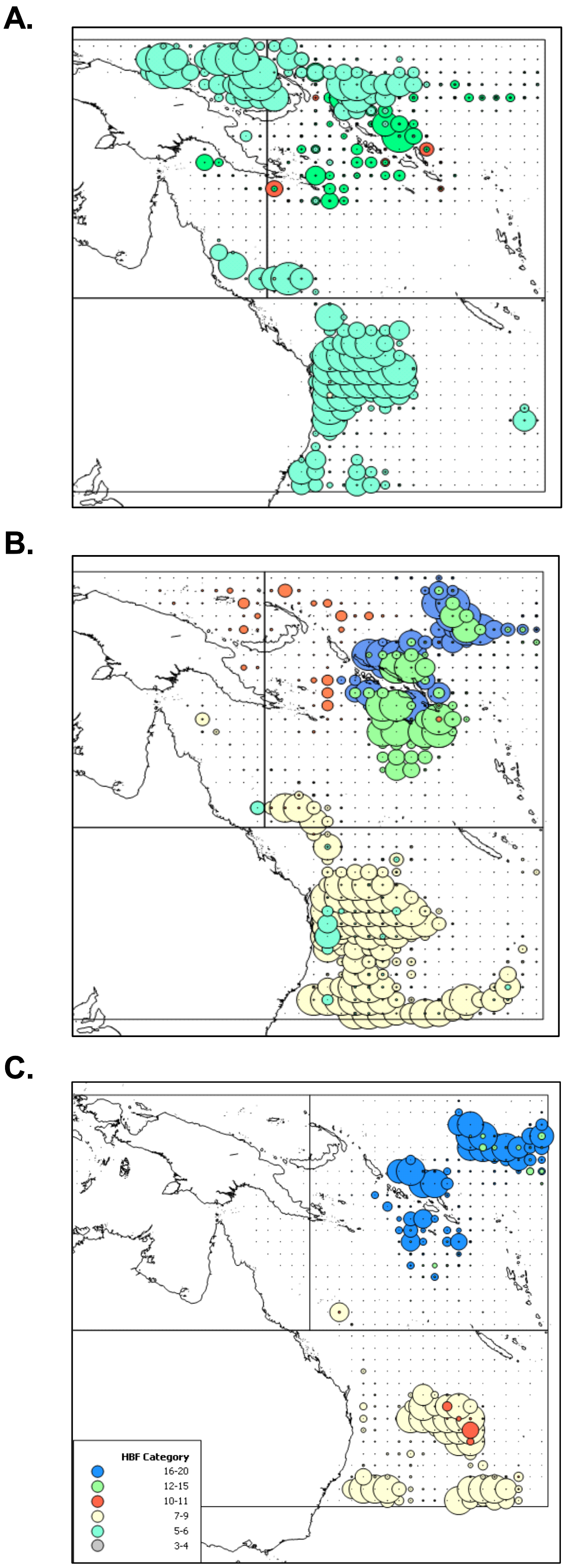


Figure 7.4.23. Spatial distribution of total effort (sum of hooks) in each 1 degree square aggregated by decade and HBF category (a) 1975-1984, (b) 1985-1994, (c) 1995-2003.

7.4.2.3.7. CPUE standardisation

Five models were fitted to the catch rate data for each spatial stratum (Table 7.4.6.). The statHBS model with monthly temperature parameters provided the best fit (as indicated by AIC values) for each of the strata, followed by a statHBS model with annual temperatures. The HBS model with monthly temperatures typically performed the poorest and the HBS model with annual temperatures performed only marginally better than the nominal effort series. In general, there was low explanatory ability for all the models.

Table 7.4.6. Comparison of standardization methods to estimate bigeye tuna catch in the Japanese longline fishery.

Effort series	**Nominal**	**HBS (annual)**	**HBS (monthly)**	**statHBS (annual)**	**statHBS (monthly)**
Stratum 1 (1975-1997)					
Null deviance = 62,53; df = 4,749					
Residual deviance	60,108	59,384	63,845	57,316	54,237
Parameters	22	23	23	38	203
Pseudo-R^2 (Null deviance-residual deviance)/Null deviance	0.04	0.05	0.00	0.08	0.13
AIC	-120,172	-118,722	-127,644	-114,556	-108,068
Stratum 2 (1975–2001)					
Null deviance =250,200; df = 30,643					
Residual deviance	242,732	231,992	256,560	220,711	217,665
Parameters	26	27	27	42	207
Pseudo-R^2	0.03	0.07	0.00	0.12	0.13
AIC	-485,412	-463,930	-513,066	-441,338	-434,916
Stratum 3 (1975–2001)					
Null deviance =207,493; df = 15,208					
Residual deviance	202,648	207,462	206,555	200,764	189,178
Parameters	26	27	27	42	207
Pseudo-R^2	0.02	0.00	0.01	0.03	0.09
AIC	-405,244	-414,870	-413,056	-401,444	-377,942

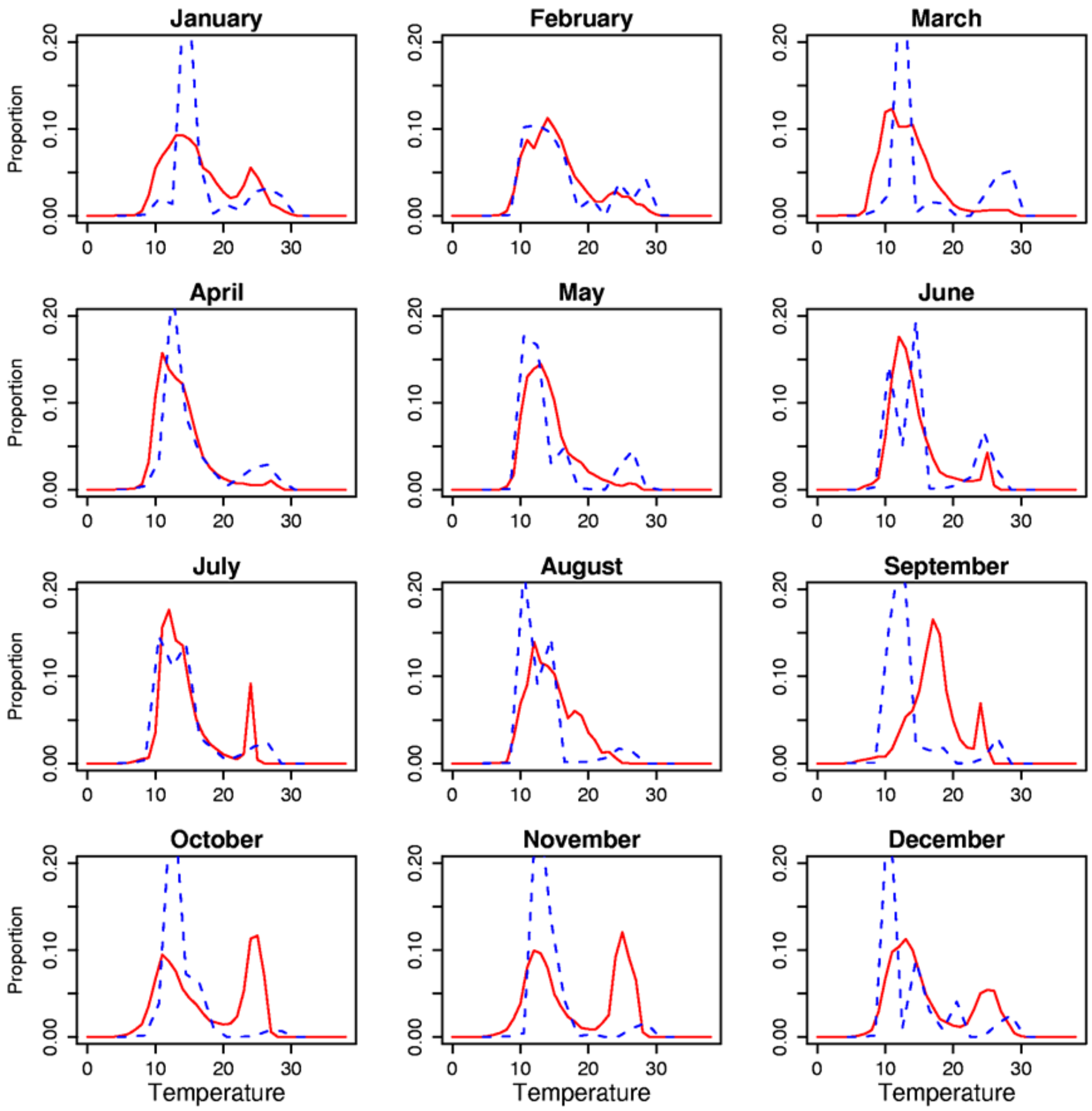


Figure 7.4.24. Estimated time-at-temperature for bigeye tuna in stratum 1 from archival tags during the day (solid line) and fitted estimates with a statistical habitat- based model (dashed line).

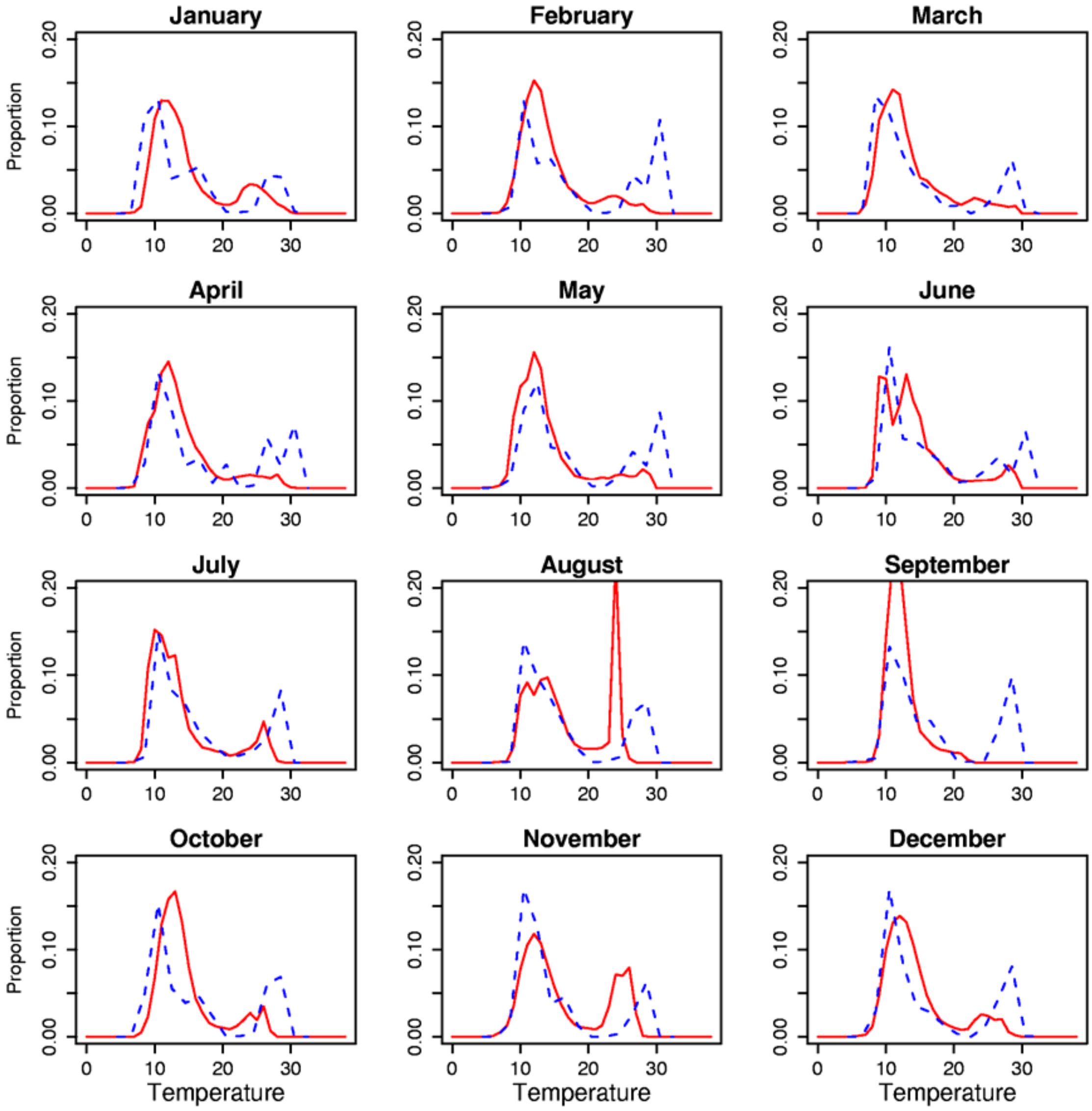


Figure 7.4.25. Estimated time-at-temperature for bigeye tuna in stratum 2 from archival tags during the day (solid line) and fitted estimates with a statistical habitat- based model (dashed line).

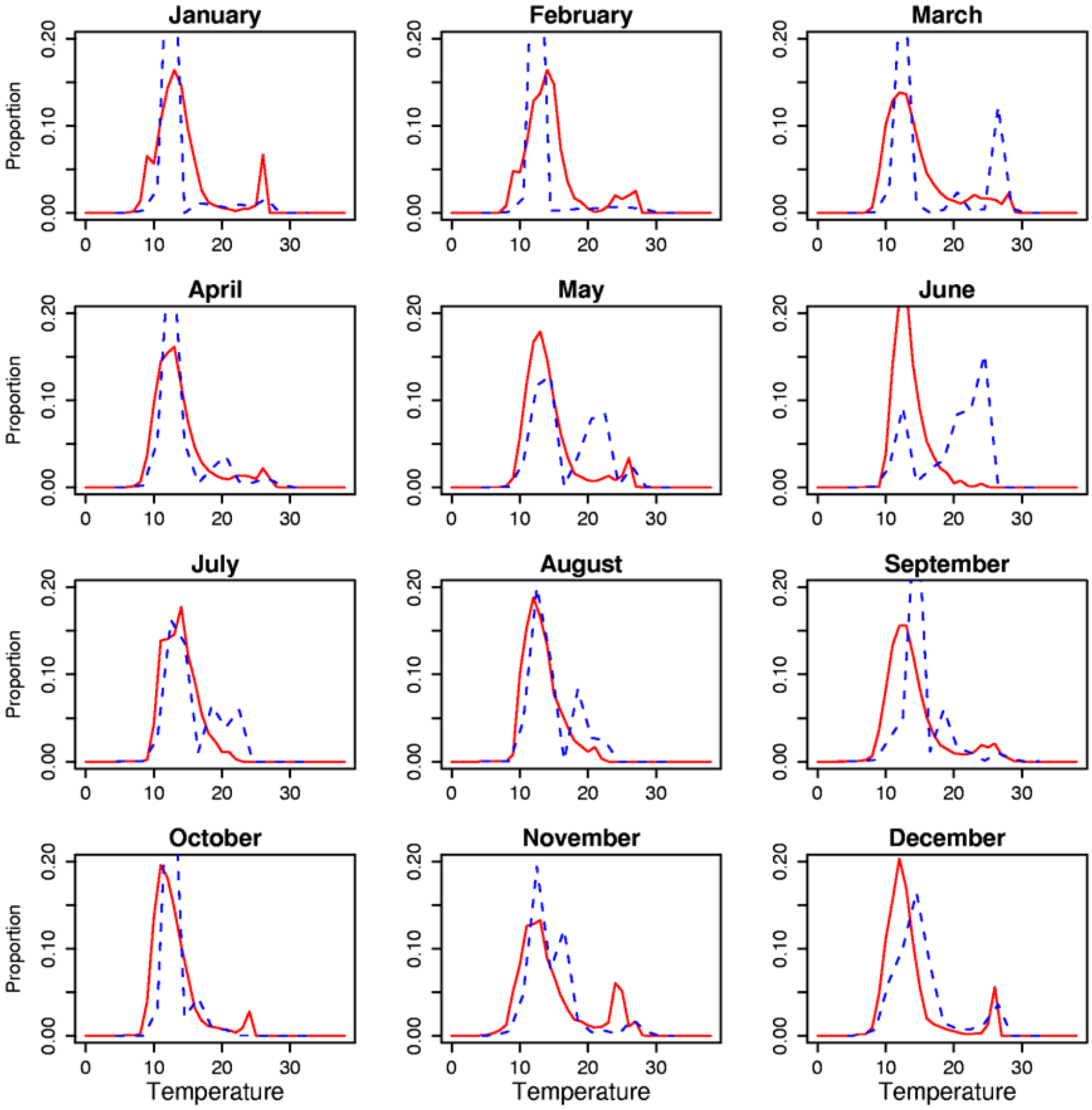


Figure 7.4.26. Estimated time-at-temperature for bigeye tuna in stratum 3 from archival tags during the day (solid line) and fitted estimates with a statistical habitat- based model (dashed line).

Ambient temperatures estimated by the statHBS consisted of a single mode typically between 10-18°C or were bimodal with an additional peak at temperatures warmer than 23°C (Figures 7.4.24. to 7.4.26.). The fitted values are indicative of day and night behavior representing a composite of ambient temperatures experienced throughout the longline set. The poor performance of the HBS models may be related to the assumption of a vertical distribution of fish at temperatures associated with the day and a lack of incorporation of night-associated temperatures. Fitted temperatures corresponded well with daytime temperature profiles for the cooler mode, although at warmer temperatures the fitted temperatures differed from the archival tag data for some months and areas. In strata 1 and 2, the bimodal daytime temperature distribution was evident from October to January, but fitted values indicated a warmer mode from January to June in stratum 1 and during all months in stratum 2. The warmer mode was less pronounced in stratum 3 similar to that demonstrated by the tag data, although the statHBS demonstrated a warm mode during March and June.

Inter-annual variability in standardized trends varied between strata (Figure 7.4.27) with stratum 1 (which had the lowest fishing effort) demonstrating the largest inter-annual variability. Year effects were similar between standardisation models, although nominal trends were more optimistic than statHBS trends for strata 2 and 3. There was some coherence in trends between areas as year effects for each model were high from 1984 to 1988 and relatively low from 1990 to 1997.

Due to differing spatial areas and numbers of observations and parameters, a comparison between results of the 1° and 5° standardisation analyses is not straightforward (see section 7.4.1). In general, the monthly statHBS approach applied to the 1° data explained 9 to 13 % of the deviance, a similar amount of deviance as explained by the model fit to the 5° data in MFCL Area 4 (Table 7.4.6.). One approach to evaluate modeling results on different spatial scales is to qualitatively compare the distribution of residuals in a spatial context. A median residual (observed catch-predicted catch) was estimated for each 5° square from the equator to 35°S and from 130° to 170°E. This area represents MFCL Area 4 but also includes strata from MFCL areas 2, 3 and 5. Residuals for the 1° data are closer to zero compared to the 5° data (Figure 7.4.28.), which indicate a potential benefit of using finer-scale oceanographic data to vertically distribute bigeye tuna and standardise effort.

7.4.2.4. Discussion

Bigeye behaviour, in general, appears to be predictable, with depths during the day largely spent between 300 and -600 m and surface oriented behaviour occurring at night. However, it must be noted that this study (see Chapter 7.2.) has shown that there are spatio-temporal differences in the behaviour of bigeye which may not be adequately understood or predicted. This variability may introduce significant uncertainty into the CPUE standardisation process.

7.4.2.4.1. Spatial uncertainty

Characterising uncertainty regarding the factors driving behavioural differences is further complicated by the limitations of current geoposition estimation methods. Obtaining robust, light-based geoposition estimates for pelagic fish, particularly bigeye tuna, has been particularly problematic and SST- based latitude estimation and statistical filtering methods have also been found to be limited (see Chapter 7.1.). The potential impact of such uncertainties on any analyses that use behavioural data is immediately apparent given that spatial strata are determined using the geoposition data and the behavioural data (depth and temperature data) are aggregated based on these strata. Any bias in position estimates results in the allocation of biased behavioural preference data to any given strata. Consequently, uncertainty in geoposition estimates therefore adds to behavioural uncertainty in a multiplicative fashion. Although mean absolute errors in light-based latitude estimates from ATs have been reported to range between 0.8 to 3.5° (Musyl et al. 2001), it must be noted that these are mean errors and such light- based geoposition estimates can contain much greater errors. Methods using SST data have been found to improve the accuracy of latitude estimates (Teo et al. 2004) and estimation of latitude using non-light- based methods [such as SST matching, processing algorithms or Kalman Filter (Sibert et al. 2003) methods] offer some prospect of progress in estimating position. However, as evident in these analyses, methods utilising SST matching were hampered by the coarse resolution of the available SST data.

There are several possible implications that may arise from this uncertainty. In several instances the CPUE models were found to predict much cooler temperatures than observed in the archival tag data. It is possible that this is a result of geolocation error leading to mis-specified temperature preferences within strata. The fitting of the model to the HBF data may then reflect actual depth and temperature preferences.

However, statHBS models with monthly temperature data were found to fit the temperature distributions more closely and also demonstrated improved AIC values. To some extent, this contradicts the possibility of geolocation error causing errant temperature and depth distributions and suggests that the spatial stratification coupled with more detailed oceanographic data facilitates better model predictions. However, including monthly temperature parameters in a model increases the degrees of freedom and could result in an over-fit of the data. However, the AIC is designed to indicate the most parsimonious model and allows for an evaluation of the tradeoff between a higher number parameters and a better fit, thereby reducing the likelihood of an over-fitting of the data. Without more data or improved geolocation estimates it is impossible to say which of these options is the most likely.

Another caveat in this analysis derives from the likelihood that most of bigeye tagged by CSIRO/SPC appeared to be largely restricted to the north western Coral Sea thereby remaining resident in one spatial stratum. Some eastward movements were estimated, but definite confirmation of these movements was limited to only a few fish. Therefore, the extent of behavioural changes in the other strata of MFCL Area 4 were inferred from small numbers of fish. If gear configuration is related to the vertical distribution of fish, then the HBF data has the possibility of reflecting spatial differences in depth preference. However, spatial differences in gear configuration shown in the JPL may also be driven more by fishery dependent factors or targeting of other species and may not be a robust indicator of the depth distributions of bigeye alone. Gear configuration was observed to change over the three decades spanned by the dataset, however, it is unknown what factors caused this and if they are related to any real shifts in oceanography or the vertical distribution of bigeye tuna. It is also known that the pre-1975 fishery targeted mostly yellowfin tuna progressively shifting toward a targeting of bigeye in later years. This is likely to have influenced the HBF signal.

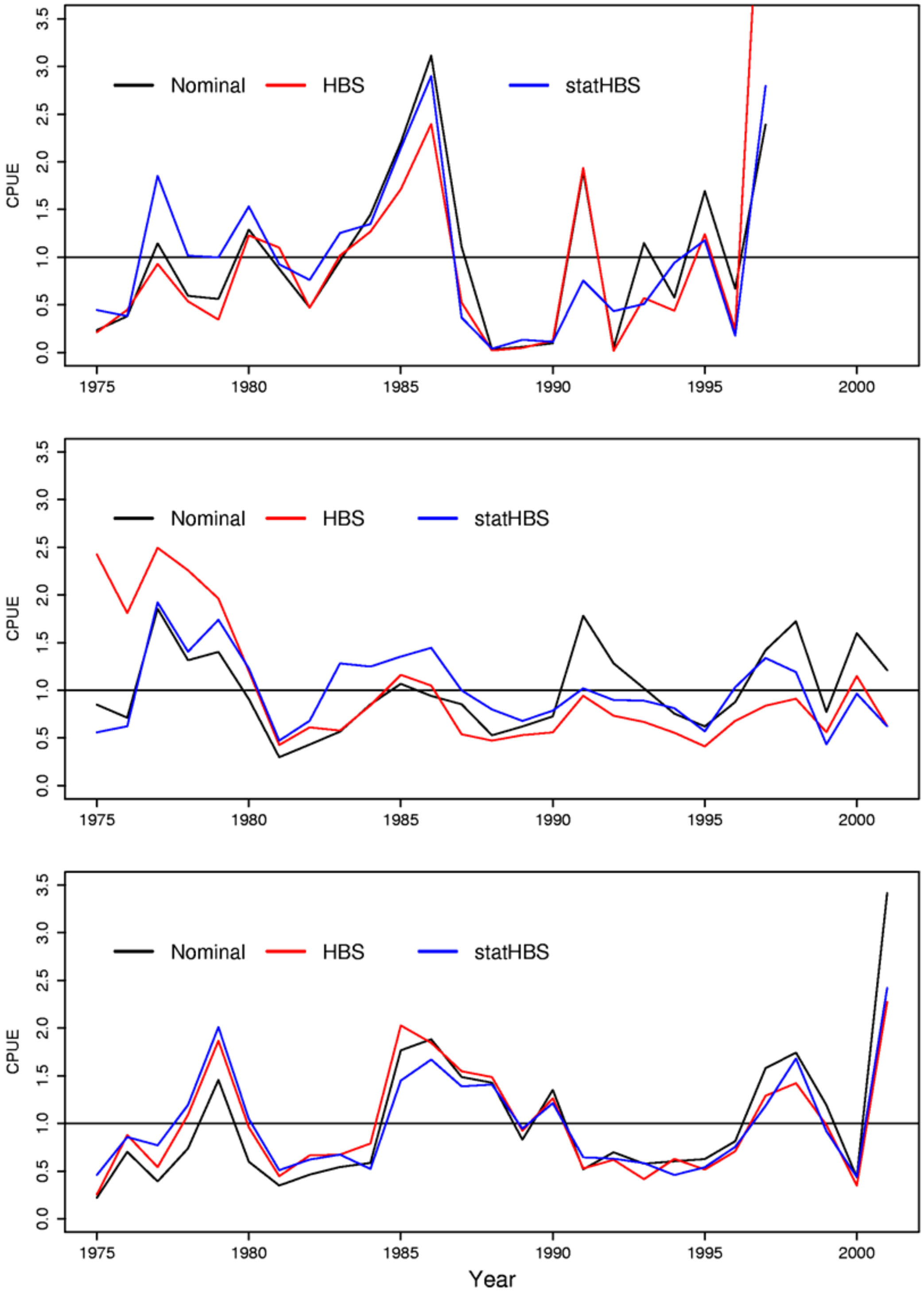


Figure 7.4.27. Normalised trends in relative abundance for stratum 1 (top), 2 (middle) and 3 (bottom). Trends were estimated for nominal CPUE and standardised with habitat-based and statistical habitat-based models.

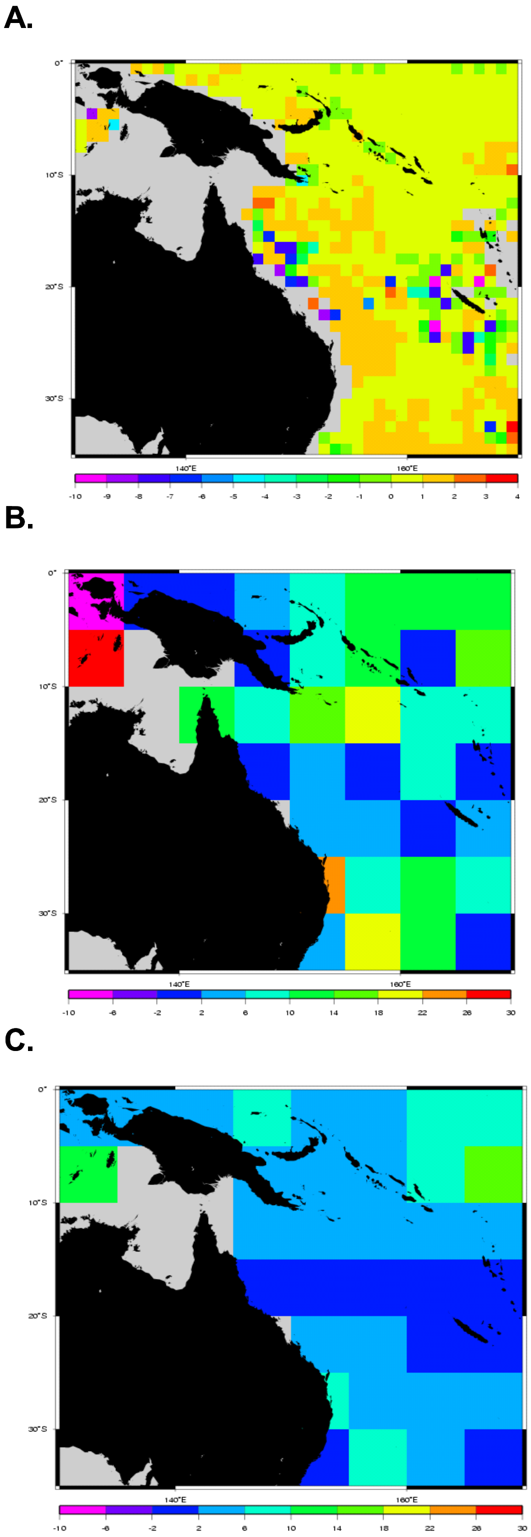


Figure 7.4.28. (a.) Median residual (observed-estimated) catch from 1975 to 2002 based on a 1° analysis and 5° analysis for each 1° square from 1975 to 2002 using (a) 1° data (b) 5° data and (c) 1° data aggregated to 5° for comparison with the 5° analysis.

7.4.2.4.2. Inter-annual variation in data sources and model predictions

The year effects predicted by the HBS and statHBS models were observed to be moderately variable, with the stratum with the lowest fishing effort (stratum 1) displaying the most variability by year. All models displayed a similar amount of variability and predicted peaks in the CPUE series at similar times. Overall the models indicate that the CPUE from each stratum has varied around a more or less constant average since 1975.

Significant intra- and inter-annual variation was observed in the setting behaviour (e.g. gear configuration) and catch rates in the domestic fishery (see Chapter 7.3.) and gear configuration changed over time in the JPL. Additionally, both individual and spatio-temporal differences in the behaviour of bigeye were observed in the AT data (see Chapter 7.2). Variability between individual tags was found to be comparable to that demonstrated by tags across time. This raises the question of whether data can be validly aggregated together from fish that may be behaving differently with respect to ocean conditions. However, determining if fish are actually behaving in a significantly different manner can, in itself, be a complicated process given the lengthy time series of complex data returned from ATs. The results of Chapter 7.3. observed that catch rates were highest during the night around the full moon and gave some examples of particular fish that spent more time within 1-50 m depth during a full moon. ot all fish tagged were observed to behave in this way, suggesting that the extent of the influence of the full moon is still unclear.

Intuitively, it seems most likely that covariates operating over a localised time scale (for example daily or monthly) drive the behaviour observed in the archival tags. In other words, bigeye in general, respond to variables that affect their immediate environment and foraging success. This does not mean that variables such as temperature collected from XBT data will not reflect changes in the oceanography that will in fact, influence behaviour at a local level. However, some behavioural differences may be reflected in data aggregated over a long term (e.g. response to regional warming/cooling in temperature), while others are likely to be transient (e.g. depth preference in response to moonphase). Currently the HBS and StatHBS methods do not utilise data from covariates that are not physical oceanographic variables. To use such information would require further work and, more importantly, a better understanding of the factors driving behavioural data.

While this analysis has concentrated on the JPL dataset, it would be possible to extend this approach to the Australian domestic fishery given sufficient gear configuration data. However, presently, too few gear configuration data are available for the Australian domestic fishery (see Chapter 7.3.) for use in the HBS and statHBS methods. Furthermore, the Japanese data are also influenced by varying fishing methods for bigeye in the Coral Sea which are absent from the Australian fishery data. Handlining and pole and line methods have been used to target surface aggregations of bigeye tuna by the Japanese fishery in the past (Ward 1996) and would need to be accounted for in similar analyses on the Australian fishery data.

7.4.2.4.3. *Which method is most appropriate for standardising relative abundance data?*

This chapter aimed to determine appropriate methods for standardising relative abundance data for bigeye tuna. Here we have examined the question of whether increasing the spatial and temporal resolution of the models allows for better prediction of catch and effort data using HBS and statHBS models.

StatHBS methods at a 1° spatial scale and GLM methods at a 5° spatial scale were found to give the best fit to the data and predict the catches most accurately. The statHBS method has the advantage of being able to incorporate behavioural data directly. A fine scale analysis found that considering 1° CPUE data improved the model fit although more work is required to determine whether greater model flexibility or "over-fitting" is occurring. In the limited analysis conducted here the AIC values suggested that this was not the case. The residuals for the 1° data as compared to the 5° data (Figure 7.4.29.) additionally suggest there is a potential benefit of using finer-scale oceanographic data to vertically distribute bigeye tuna and standardise effort. However, GLM methods were not used in the finer-scale analyses and as such it is difficult to determine the effectiveness of GLM methods in standardizing catches across both scales.

7.4.2.4.4. *Further work*

- The fine scale analysis of bigeye tuna catch and effort data in the Coral Sea and W/CPO has identified several areas that require more research. In summary:
- The Japanese longline fishery is currently the only available dataset for this type of analysis. Further gear configuration data are required from the Australian domestic fishery to extend these analyses to the Australian fishery.
- The degree of uncertainty in geolocation estimates places a limit on the spatial resolution of HBS and statHBS CPUE standardisation methods. As a result, application of these methods at finer spatial scales depend on improvements to estimate geolocation and associated errors.
- Temporal changes in bigeye behaviour will affect the outcome of HBS modeling. Determining the factors that directly and indirectly drive behaviour are likely to be helpful in refining the HBS and statHBS methods.
- The majority of fish incorporated into these analyses were estimated to be largely located in the north-western Coral Sea, resulting in the placement of the majority of behavioural data into the spatial strata containing the least amount of effort from the Japanese longline fishery. Expansion of archival tag deployment to increase the extent of behavioural data from these areas is required.
- Variability in the behaviour of bigeye both temporally and spatially implies that spatio-temporal variation in behaviour in the model may not be accounted for. Better characterisation of depth and temperature preference (i.e. habitat models) may be required.
- This study is unable to disassociate geolocation errors from behavioural variability. Simulation studies and sensitivity analysis of the HBS and StatHBS method would be

useful here in determining the effect of various sources of uncertainty on the final estimates of CPUE.

- A better understanding of the relationship between HBF and actual depth would also help to reduce uncertainty in habitat based standardisation. Currently an assessment of the depth distribution of gear involving the collection of time-depth records is underway in the Coral Sea (R. Campbell[2] personal communication) and he results of these analyses will be useful in parameterising habitat standardisation models.

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[2] Robert Campbell, CSIRO Marine Research

8. BENEFITS AND ADOPTION

This project, the first major investigation into the habits of bigeye tuna in the Coral Sea has substantially increased our understanding of the horizontal and vertical distribution of this species in this region. It has provided new insights into the interactions of individuals within their marine environment both from an ecological and a physiological point of view and has forwarded our understanding of the interactions of this species with the Australian fishery. The substantial data provided by this project on the habitat preferences of bigeye tuna in the Coral Sea has enabled a more comprehensive integration of these aspects of the behaviour of this species into stock assessment models and has highlighted the vulnerability of these models to variability in the habitat preferences of bigeye both temporally and spatially. The greater understanding of the habits of bigeye provided by this study has enabled new insights into those factors driving variability in the Australian fishery and has provided insights into the relationship between targeting practices and the behaviour of this species. The potential for the retainment of bigeye tuna within the Coral Sea (both through resident fish and those that undertake cyclical migrations) is an important consideration for the sustainable management of this species and the limited data this study provides on movements within the ET&BF are also important for the management of this species within Australian waters.

The outputs produced by this project have played an important role in informing AFMA's process of developing Total Allowable Effort (TAE) options for the ET&BF. An important consideration in this process has been the degree of connectivity between bigeye populations in the broader WPO and those exploited by Australian domestic fisheries. In this context, the patterns of residency in Coral Sea bigeye suggest that AFMA's management of bigeye in the eastern AFZ (as distinct from RFMO efforts to control effort and/or catches throughout the Central/WPO) will have a direct impact on local populations and on the sustainable development of the ET&BF.

The demonstration of high levels of retainment of bigeye within the WPO follows similar findings for bigeye in other parts of the world, and for yellowfin in the WPO and Coral Sea. The growing evidence for restricted movement of Pacific Ocean tunas, particularly in sub-equatorial regions, raises the issue for the newly established Western and Central Pacific Fisheries Commission of how best to manage across the broad range of these fisheries for the sustainability of regional/localised populations. Localised depletions have the potential to significant affect the viability of island and coastal state fisheries, yet fishery-wide controls of effort or catch will be unlikely to prevent localized depletions of these stocks.

In addition to increasing our knowledge of bigeye tuna and the fishery that operates on this species within the Coral Sea from an ecological, physiological and management perspective, this study has also contributed to advances into the methodology involved in processing and analyzing these data. Obtaining position estimates from geolocation derived data is not an exact process. The analyses presented here have contributed to a greater understanding of the biases and errors involved in generating position estimates and have additionally contributed to developing methodologies attempting to address these biases and errors.

9. FURTHER DEVELOPMENT

This project has largely confirmed the hypothesis Hampton & Gunn (1998) put forward that while there is some dispersal of bigeye tuna out of the north-western Coral Sea, a large proportion are retained within the area. However, there is a substantial degree of uncertainty surrounding the position estimates generated by geolocation analyses which limit the spatial scale at which movement patterns can be investigated. Further development of analyses capable of refining geolocation estimates is required at two levels: (i) in the generation of light attenuation curves to address issues with light collected at depth during dawn and dusk and (ii) in the post-processing refinement of position estimates, for example by integrating statistical models such as Kalman Filters with sea surface temperature matching techniques. Use of other telemetry techniques such as pop-up archival transmitting tags (PSATs) which collect light data both while on the fish and post release may provide those data required to develop more accurate light attenuation curves required for refinement of position estimates.

The majority of bigeye tagged as part of this project were caught and released in the north-western Coral Sea. While there is some suggestion of spatial variability in the habitat preferences of this species, assessments were limited by confounding factors such as individual variability, temporal variability and small sample sizes. Further tagging of larger numbers of fish from the southern part of the fishery may provide insights into the presence of spatial variability in habitat preferences within this species as well as providing further information on the links between bigeye throughout the ET&BF. Further, collaborations with other institutions involved in the collection of location and habitat preference data from bigeye throughout the broader Pacific Ocean should be encouraged in an effort to address broader scale spatial variability in the movement patterns and habitat preferences of this species.

Integration of data collected from archival tag (AT) deployments with data on the longline fishery within the Coral Sea were limited by a number of factors. Because longline gear configuration data were not available for the Australian domestic longline fleet, those analyses relating to catch per unit effort (CPUE) models were limited to those data collected from Japanese longline fleets. Information on depth distributions and water temperature preferences of bigeye in the main part of the fishery south of 20°S were sparse, thereby restricting detailed analyses on this part of the fishery. Further to these, uncertainties surrounding position estimates and the high level of individual variability in depth and water temperature preferences demonstrated by bigeye resulted in only limited interpretation of relative abundance trends and relationships observed between bigeye behaviour and the fishery. Further broad-scale collection of data relating to gear configuration including hooks per float and data on the vertical distribution of hooks (such as those collected via the use of time-depth recorders) would facilitate broadening assessments of CPUE models to include data specific to the Australian domestic longline fleets and would strengthen those analyses investigating relationships between the behaviour of bigeye and the Australian domestic longline fishery. Further collection of depth and water temperature data on fish from those areas of the fishery south of 20°S, refining geolocation derived position estimates (as detailed above) and increasing temporal and spatial assessments of bigeye behaviour (as detailed above and below) would also serve to provide data essential for a more comprehensive assessment of the relative abundance of bigeye within Australian waters and the relationships of these stocks with the distribution of the fishery.

While there was little evidence of ontogenetic shifts in habitat preferences or movement patterns demonstrated by bigeye tagged as part of this study, assessments were limited. Further investigations should involve the development of means by which robust indicators of physiological change are identified and quantified. Further data collected either via the tagging of larger size ranges of individuals or via collaborations with other institutions collecting such data would serve to increase the power by which such indicators could be identified and quantified.

This project constitutes the most continuous recording of the behaviour and habitat preferences of this species to date. However, because information on the diet, predator-prey relationships, and interactions between predator-prey relationships and the environment of bigeye tuna in the western Pacific Ocean is sparse, interpretation of those data collected is limited. We now have a better understanding of what bigeye tuna do in the western Coral Sea, but not why bigeye behave as they do or what drives the variability observed in their behaviour. Investigations into the diet, predator-prey relationships and the relationships these have with the environment would provide greater insights into the foraging behaviour and the influence of environmental determinants on foraging behaviour in this species.

10. PLANNED OUTCOMES

The planned outcomes of this project were to (i) increase our understanding of the link between bigeye in the Coral Sea and the larger Pacific Ocean; (ii) provide data that will allow an objective analysis of bigeye catch per unit effort (CPUE) trends and the variability in these and (iii) provide more information on the links between bigeye in the Coral Sea and those targeted in the rapidly expanding south-east Queensland/northern NSW fisheries.

This study has demonstrated that bigeye tuna are in general, residential animals suggesting only low levels of dispersal and mixing between populations both within ET&BF and with populations outside the ET&BF. Integration of detailed data on the habitat preferences of bigeye tuna into CPUE models has provided key insights into the suitability of these models in standardizing CPUE and has highlighted key limitations of the data for such standardisations. This study has provided essential data for the development and testing of models of a more robust nature, enabling more accurate and objective analyses of bigeye CPUE trends.

Most important of the planned outcomes achieved is the realisation that the results of this project have been reviewed and adopted by the ET&BF Resource Assessment Group (RAG) and used in the RAG’s provision of advice to the ET&BF Management Advisory Committee (MAC) and AFMA Board on risk weighted options for setting a Total Allowable Effort for the ET&BF.

The results from the project have also been presented at the Standing Committee on Tunas and Billfish (SCTB), and consideration of the findings of localised movements has contributed to advice from this committee to the Preparatory Conference for the Western and Central Pacific Fishery Commission. Stock assessment models for bigeye have incorporated the new information provided by the study on availability, movements and depth preferences of bigeye.

11. CONCLUSION

The objectives of this study used archival tag (AT) technology to ascertain the movement patterns of bigeye tuna within the Coral Sea region and from this, the relationship between populations of bigeye tuna both within the area off the east coast of Australia and with the broader western Pacific Ocean (WPO). New insights into the habitat preferences of bigeye within this region were established and progress was made toward understanding the effect of spatial and temporal behavioural differences of bigeye tuna on standardised relative abundance time-series and the relationship of these behavioural differences with the fishery.

Geolocation derived position estimates, on a coarse-scale, revealed that in general, bigeye tuna appear to be resident within the north-western Coral Sea area. Only three of the 17 fish on which ATs were recaptured made large scale movements, moving east and into the greater Coral Sea before either being recaptured or returning to waters close to their release position. Two CTs of the 66 returned were recaptured in areas east and north of the Coral Sea. These data suggest that the east coast of Australia largely comprises localised populations of bigeye tuna, a proportion of which are transitory, either making cyclical large-scale movements east and into the broader WPO before returning to the Coral Sea or dispersing into areas outside of the Coral Sea (Objectives one and three). Limitations in the accuracy of geolocation derived position estimates confounded the establishment of finer-scale movements, although comparisons with post-processing filtering techniques (SST-matched position estimates and Kalman filtered position estimates) suggest there may be some limited movements in a north-south direction. However, those data collected as part of this project are not substantive enough to ascertain the extent of movement in this direction (Objective two).

Return rates for conventional tags were more than twice (24.5%) that for archival tags (10.6%), differing from other programs where conventional (CT) and ATs have been released simultaneously (e.g. bigeye in Hawaiian waters where returns were similar, southern bluefin tuna off southern Australia where returns of ATs were higher than those for CTs). The differences in return rates may be a result of a number of factors including (1) higher rates of mortality in bigeye tuna in this study as a result of the methodology used to deploy ATs; (2) a higher rate of post-tagging infection in the bigeye tuna released with ATs in this study (3) higher compliancy rates of reporting and returning of ATs throughout the Hawai'ian and SBT fishery or (4) differences in sample sizes and sampling effort. Ascertaining the factors resulting in these differences in return rates is difficult, however precautions maximising the survivorship of fish released, including running water over the gills and skin and reducing the maximum time that the fish is out of water should be encouraged.

The depth and water temperature preferences of individual bigeye tuna were established and, as observed in other parts of the Pacific Ocean, demonstrated distinct diurnal variability (Objective four). Seasonal shifts in the depth and water temperature preferences of bigeye tuna were evident and appeared to be closely related to seasonal shifts in the thermal structure of their oceanic environment. While some spatial variation in the depth and water temperature preferences of bigeye was observed, it is difficult to determine if this variability is directly associated with the movements of individuals or a factor of seasonal shifts in habitat preferences or individual variability in habitat preferences. Comparisons with those habitat and behaviour data collected from bigeye in other parts of the Pacific Ocean suggest some broad-scale regional differences, possibly associated with regional differences in the thermal structure of the oceanic environment. Dissolved oxygen tolerance of bigeye tuna in the Coral Sea appears to be similar to that observed elsewhere with individuals routinely inhabiting waters with dissolved oxygen levels as low as 1-2ml/L^{-1}. The effect of temperature on blood oxygen affinity and the variability in vertical distribution individuals appear to demonstrate with oceanic thermal structure, suggest water temperature is possibly the major determinant of habitat frequented by bigeye tuna. Individuals additionally demonstrated considerable variability in diving behaviour in association with the lunar cycle, often shifting preferred depths on those nights around the full moon to those slightly deeper than those throughout the rest of the lunar cycle. However, changes in depth distributions were not consistent across lunar cycles, nor were they consistent between individuals. Considerable individual variation was evident both in depth and water temperature preferences, suggesting a flexibility in the foraging strategies and physiology of individuals.

Trends in the gear configuration, fishing behaviour and effort of fishing operations demonstrated clear relationships with the behaviour of bigeye tuna, shifting to reflect diurnal shifts in depth distributions and also those shifts in depth distributions associated with lunar phase. These trends have clearly increased the efficiency of longline fishing effort with respect to targeting bigeye, enhancing the catchability of this species (Objective five). Seasonal variability in catches appeared to demonstrate relationships with seasonal variability observed in habitat preferences, however, these were not always clear, reflecting the high individual variability observed in bigeye behaviour. Such variability also suggests that those factors influencing the relative catchability of bigeye are complex. There are likely to be range of other environmental, behavioural, and operational factors than those covered in this study that also influence the catchability of bigeye; for example, seasonal differences of the feeding behaviour or differences in fishing gear configuration/deployment; data for which are limited. Spatial assessments of the interaction between bigeye and the longline fishery (*i.e.* the availability of fish to the fishery) were limited due to the uncertainty associated with geolocation derived position estimates, small sample sizes and biases associated with the fishery itself.

During the course of this study, a total of 269 bigeye tuna were tagged with CTs and of these 189 were injected with 5 ml of strontium chloride (Objective six). Otoliths collected from those fish recaptured have already been included in analyses validating age estimates and establishing the formation of annual increments in the otoliths of bigeye (Farley et al. 2003).

In addition to the above objectives, habitat preferences were combined with gear configuration data from the Japanese longline fishery and modeled oceanographic data and incorporated into three models used to standardise nominal catch per unit effort (CPUE) at two spatial scales (1° and 5°). Models were then compared on the basis of how well they then adjusted nominal CPUE given the preferences of individuals through space (both horizontal and vertical) and time for a particular area of the western Pacific fishery. Of the three models, the HBS performed poorly relative to the stat-HBS and GLM approaches in standardising CPUE and is not recommended for CPUE standardisation (Objective four). Although the stat-HBS and GLM approaches appeared to adjust nominal CPUE in a more accurate manner, the results from all models were biased by limitations of the AT data. These limitations include data availability within some of the spatial strata (e.g. the area of highest catch contained the least amount of AT derived data), uncertainties associated with position estimates generated via geolocation and individual variability in the habitat preferences of bigeye. Poor performance could also be associated with poor characterisation of habitat through space and time by the oceanographic models or a poor understanding of the factors driving variability in bigeye behaviour.

The incorporation of the results of the project into ET&BF research advisory group (RAG) and advice to the ET&BF management advisory committee (MAC) and AFMA Board on risk weighted options for setting a Total Allowable Effort for the ET&BF demonstrates an important return on investment in this integrated form of research. The study incorporated use of innovative observation tools developed by CSIRO and collaborators over the last decade, refinement of methods to analyse AT data, use of statistical models to integrate observations collected at various levels of detail - from the behaviour of individual fish to the behaviour of fishers. The result is a powerful insight into the factors driving variability in fishery CPUE data, which should inform future analyses and use of such data in stock assessment.

The results from the project have been presented at the Standing Committee on Tuna and Billfish (SCTB), and consideration of the findings of localised movements has contributed to advice from this committee to the Preparatory Conference for the Western and Central Pacific Fishery Commission. Stock assessment models for bigeye have incorporated the new information provided by the study on availability, movements and depth preference of bigeye.

The demonstration of high levels of retainment of bigeye in WPO follows similar findings for bigeye in other parts of the world, and for yellowfin in the WPO and Coral Sea. The growing evidence for restricted movement of Pacific Ocean tunas, particularly in sub-equatorial regions, raises the issue for the newly established Western and Central Pacific Fisheries Commission of how best to manage across the broad range of these fisheries for the sustainability of regional/localised populations. Localised depletions have the potential to significant affect the viability of island and coastal state fisheries, yet fishery-wide controls of effort or catch will be unlikely to prevent localised depletions of these stocks.

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13. INTELLECTUAL PROPERTY

No intellectual property is claimed.

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15. APPENDICES

Appendix A. Release and recapture information for conventional tags deployed on bigeye tuna in the Coral Sea.

Tag Number	Release		Recapture			DAL	Displacement	
	FL (cm)	Location	Date	FL (cm)	Location		nmi	km
7 October 1999								
CO0153/55^	77	17°34'S 147°17'E	06/11/00	111	16°19'S 146°48'E	397	80.0	148.2
CO0171/12^	75	17°34'S 147°17'E	01/11/00	102	16°48'S 146°56'E	392	50.5	93.5
9 October 1999								
CO0177/78^	87	17°34'S 147°17'E	18/04/03	155	17°53'S 147°28'E	1290	21.6	40.0
CO0191	78	17°34'S 147°17'E	16/04/03	130	17°51'S 147°28'E	1288	20.0	37.1
13 October 2001								
CO1005/06^	102	16°04'S 146°31'E	26/09/02	117	16°15'S 146°28'E	348	11.2	20.7
CO1063/64^	86	16°03'S 146°33'E	24/09/02	106	16°12'S 146°19E	347	16.1	29.7
CO1077/78^	80	16°03'S 146°33'E	29/09/02	104	16°20'S 146°16'E	351	23.3	43.2
CO1076^	84	16°03'S 146°33'E	–	–	–	–	–	–
CO1079/80^	85	16°03'S 146°33'E	–	103	16°17'S 146°31'E	–	13.9	25.8
CO1084^	83	16°03'S 146°33'E	22/04/02	97	18°02'S 148°01'E	192	145.9	270.3
CO1085/86^	95	16°03'S 146°33'E	23/09/02	113	16°11'S 146°24'E	346	11.7	21.6
CO1091/92^	95	16°03'S 146°33'E	27/09/02	113	16°33'S 146°42E	350	31.3	57.9
CO1103/04^	81	16°03'S 146°33'E	24/09/02	103	16°12'S 146°22'E	347	13.8	25.5
CO1109/10^	92	16°02'S 146°31'E	23/09/02	110	16°10'S 146°22'E	346	12.1	22.4
CO1123/24^	81	16°02'S 146°31'E	23/09/02	102	16°10'S 146°22'E	346	12.1	22.4
CO1129/30^	82	16°02'S 146°31'E	29/09/02	104	16°20'S 146°16'E	352	23.1	42.8
CO1133/34^	84	16°02'S 146°31'E	25/06/02	95	–	256	–	–
CO1141/42^	84	16°02'S 146°31'E	15/06/02	94	–	246	–	–
CO1159/60^	91	16°02'S 146°31'E	22/12/02	122	17°04'S 147°18'E	435	78.2	144.7
CO1165/66^	93	16°02'S 146°31'E	29/09/02	116	16°08'S 146°18E	351	14.1	26.0
CO1175/76^	76	16°02'S 146°31'E	25/09/02	102	16°17'S 146°30'E	347	15.1	27.9
CO1177/78^	76	16°02'S 146°31'E	04/10/02	–	16°05'S 146°18E	356	12.1	22.4
CO1187/88^	80	16°02'S 146°31'E	30/06/02	101	16°31'S 146°51'E	260	29.5	54.5
CO1189/90	80	16°02'S 146°31'E	09/11/01	80	15°05'S 146°08'E	27	61.4	113.7

Tag Number	**Release**		**Recapture**			**DAL**	**Displacement**	
	FL (cm)	**Location**	**Date**	**FL (cm)**	**Location**		**nmi**	**km**
CO1197/98^	80	16°02'S 146°31'E	22/09/02	104	16°10'S 146°22'E	344	12.1	22.4
CO1355/56^	85	16°01'S 146°41'E	–	–	–	–	–	–
14 October 2001								
CO1001/02	78	16°04'S 146°31'E	09/11/01	77	15°05'S 146°08'E	27	63.7	117.9
CO1007/08^	78	16°04'S 146°31'E	29/09/02	102	16°11'S 146°24'E	351	9.6	17.7
CO1009/10^	82	16°04.'S 146°31'E	15/12/02	109	17°03'S 147°22'E	428	76.6	141.9
CO1015/16^	81	16°04'S 146°31'E	29/09/02	104	16°20'S 146°16'E	351	21.3	39.4
CO1021/22^	89	16°04'S 146°31'E	04/10/02	–	16°05'S 146°18E	356	12.7	23.6
CO1027/28^	76	16°04'S 146°31'E	25/09/02	102	16°17'S 146°30'E	347	12.7	23.5
CO1031/32^	77	16°04'S 146°31'E	29/10/01	83	15°12'S 146°10'E	16	56.1	103.9
CO1033/34^	86	16°04'S 146°31.E	24/08/03	127	16°27'S 147°13'E	679	46.4	85.9
CO1035/36^	78	16°04'S 146°31'E	09/11/01	80	15°05'S 146°08'E	27	63.7	117.9
CO1039/40^	93	16°04'S 146°31'E	17/02/03	118	16°31'S 146°57E	492	36.7	68.0
CO1045/46^	77	16°04'S 146°31'E	02/11/01	–	15°17'S 146°29'E	20	47.5	88.0
CO1049/50^	84	16°04'S 146°31'E	24/08/03	129	16°29'S 147°20'E	679	52.8	97.9
CO1201/02^	77	16°04'S 146°31 'E	15/12/02	112	17°05'S 147°18'E	427	75.5	139.9
CO1213/14^	94	16°04'S 146°31'E	27/04/02	102	18°01'S 148°02'E	196	145.8	270.1
CO1227/28^	78	16°05'S 146°30'E	15/12/02	98	17°03'S 147°22'E	427	76.9	142.4
CO1229/30^	85	16°05'S 146°30'E	04/10/02	–	16°05'S 146°18E	355	11.6	21.4
16 October 2001								
CO1281/82^	91	16°01'S 146°41'E	25/05/02	101	17°47'S 147°42'E	221	121.0	224.0
CO1289/90^	80	16°01'S 146°41'E	16/09/03	129	16°37'S 147°24'E	700	55.0	101.8
CO1291/92	79	16°01'S 146°41 'E	15/12/02	106	17°03'S 147°22'E	425	74.0	137.0
CO1293/94	70	16°01'S 146°41'E	09/11/01	70	15°05'S 146°08'E	24	64.9	120.1
CO1295	82	16°01'S 146°41'E	28/04/03	110	15°40'S 146°06'E	559	40.0	74.0
CO1345/46^	81	16°05'S 146°30'E	27/04/02	88	14°15'S 146°30'E	195	110.0	203.7
CO1347/48^	82	16°05'S 146°30'E	–	–	–	–	–	–
CO1359/60^	82	16°01'S 146°41'E	15/12/02	116	17°03'S 147°18'E	425	72.0	133.3
CO1363/64^	98	16°01'S 146°41'E	23/09/02	116	16°10'S 146°22'E	342	20.1	37.1
CO1371/72^	78	16°01'S 146°41'E	25/09/02	101	16°17'S 146°30'E	344	18.8	34.8

Tag Number	Release		Recapture			DAL	Displacement	
	FL (cm)	Location	Date	FL (cm)	Location		nmi	km
CO1377/78^	82	16°01'S 146°41'E	15/12/02	110	17°03'S 147°22'E	425	74.0	137.0
CO1379^	101	16°01'S 146°41'E	22/09/02	113	16°10'S 146°22'E	341	20.1	37.1
CO1383/84^	88	16°01'S 146°41'E	15/12/02	116	17°05'S 147°18'E	425	72.0	133.3
CO1385/86^	80	16°01'S 146°41'E	29/09/02	107	16°08'S 146°18E	348	22.9	42.5
CO1387^	77	16°01'S 146°41'E	09/11/01	80	15°05'S 146°08'E	24	64.9	120.1
CO1405/06^	86	16°03'S 146°43'E	15/08/03	129	16°52'S 147°22'E	668	62.6	116.0
CO1407/08^	88	16°03'S 146°43'E	09/11/01	86	15°05'S 146°08'E	24	67.6	124.2
CO1409/10^	80	16°03'S 146°43'E	09/11/01	80	15°05'S 146°08'E	24	67.6	124.2
CO1413/14^	80	16°03'S 146°43'E	23/09/02	105	16°10'S 146°22'E	342	21.5	39.7
CO1433/34^	83	16°03'S 146°43'E	24/02/03	117	15°29'S 146°38'E	496	34.5	63.9
CO1437/38^	86	16°03'S 146°43'E	06/11/03	129	2°30'N 147°18'E	751	1116.0	2066.8
CO1439/40	89	16°03'S 146°43'E	20/04/03	–	14°15'S 165°15'E	551	1081.3	2002.5
CO1447/48^	78	16°03'S 146°43'E	15/12/02	107	17°03'S 147°22'E	425	71.4	132.3
CO1467/68	82	16°03'S 146°43'E	22/09/02	107	16°10'S 146°22'E	341	21.5	39.7

FL: fork length; DAL: days at liberty; ^ injected with SrCl.

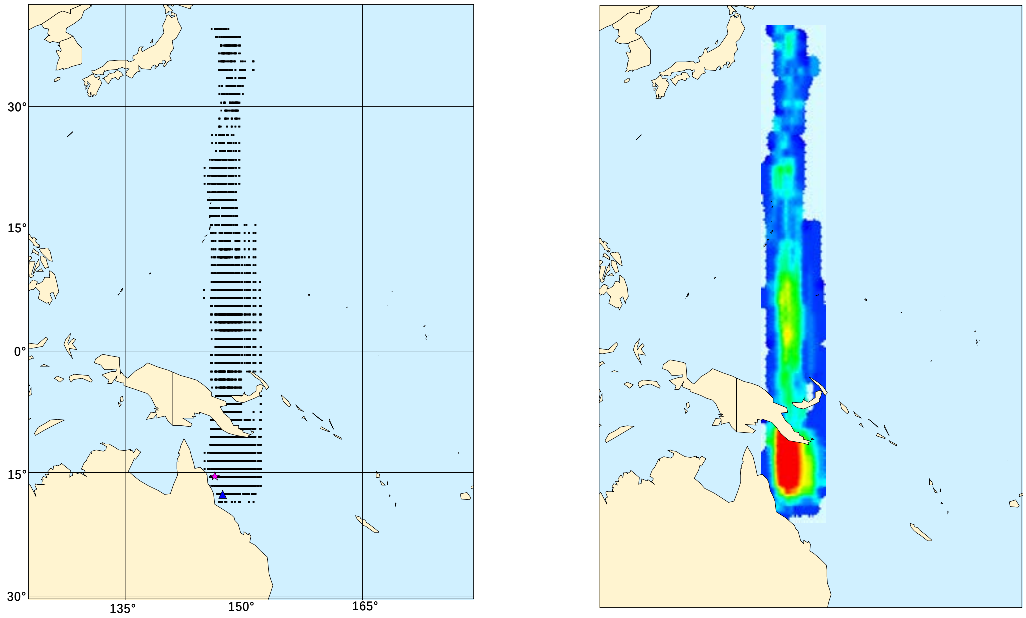
Appendix B. Release and recapture information for archival tags deployed on bigeye tuna in the Coral Sea.

Tag Number	Release		Recapture			DAL	Displacement	
	FL (cm)	Location	Date	FL (cm)	Location		nmi	km
6 October 1999								
98-347	82	17°38'S 147°20'E	27/04/02	141	17°59'S 148°01'E	934	44.7	82.9
98-353	84	17°38'S 147°20'E	26/02/02		17°30'S 164°00'E	874	7873.2	14580.9
98-357	84	17°34'S 147°17'E	16/09/03		4°31'S 178°01'E	1441	1971.1	3650.3
98-361	77	17°38'S 147°20'E	05/05/01		22°05'S 154°41'E	577	494.0	914.9
98-372	81	17°38'S 147°20'E	01/06/02		18°19'S 149°55'E	969	153.8	284.8
98-455	83	17°38'S 147°20'E	05/09/01	130	16°23'S 146°22'E	700	93.2	172.6
98-479	81	17°42'S 147°24'E	21/09/99		18°36'S 150°51'E	47	203.2	376.4
7 October 1999								
98-363	81	17°34'S 147°17'E	02/11/02	133	15°20'S 146°19'E	758	145.6	269.6
98-463	80	17°34'S 147°17'E	13/07/00	99	17°56'S 147°50'E	281	38.2	70.8
27 May 2000								
99-190	89	24°17'S 154°08'E	08/06/01	95	24°12'S 154°03'E	378	12.8	23.7
13 October 2001								
99-213	86	16°03'S 146°33'E	10/09/03	121	17°05'S 147°08'E	697	72.0	133.3
99-216	91	16°03'S 146°33'E	28/09/02	109	16°05'S 146°20'E	351	11.9	22.1
99-224	81	16°03'S 146°33'E	22/06/02	101	17°42'S 147°40'E	254	119.1	220.5
99-237	79	16°03'S 146°33'E	11/07/03		16°20'S 146°32'E	636	19.2	35.6
99-243	83	16°03'S 146°33'E	26/05/02	91	16°55'S 146°50'E	224	55.5	102.7
99-262	81	16°03'S 146°33'E	27/09/02	101	16°10'S 146°22'E	350	12.1	22.4
00-112	82	16°03'S 146°33'E	29/09/02	102	16°05'S 146°18'E	352	13.6	25.2

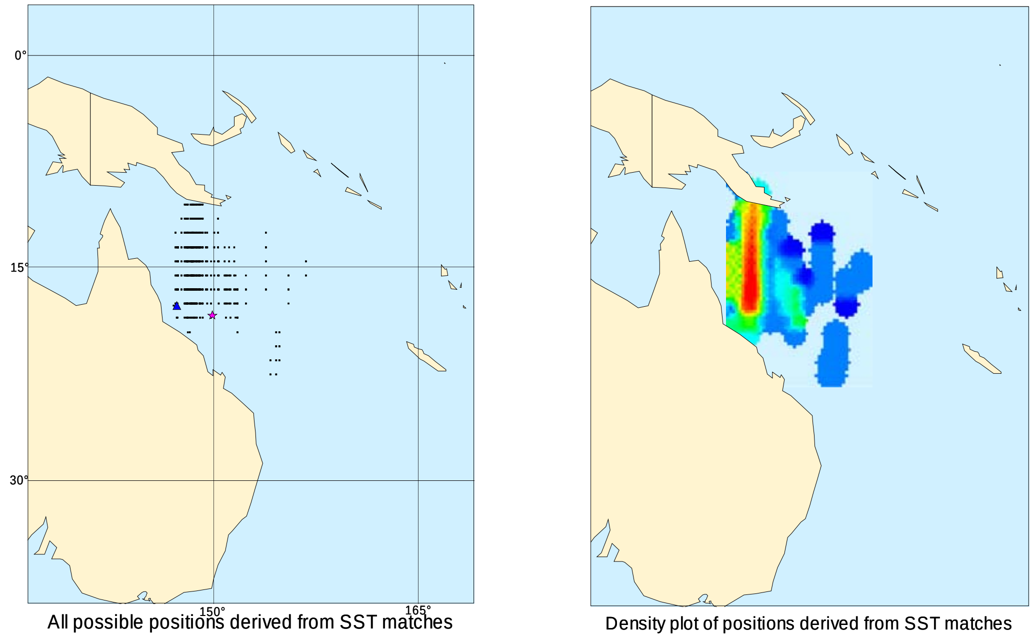
FL: fork length; DAL: days at liberty

Appendix C. Position estimates and densities of position estimates for archival tags released in the western Coral Sea 1999-2001.

A.



B.



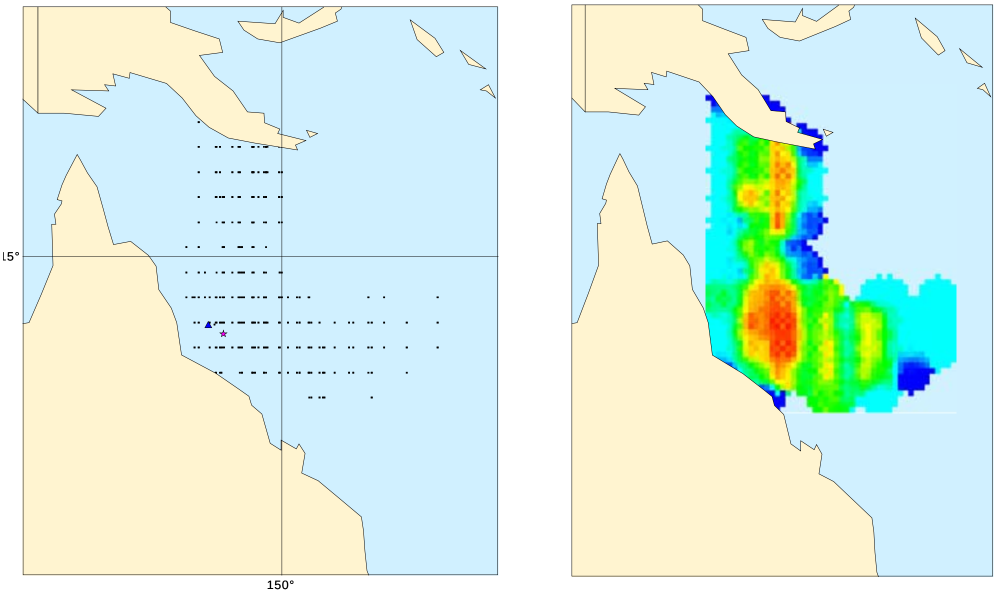
All possible positions derived from SST matches

▲ release
★ recapture
· estimated positions

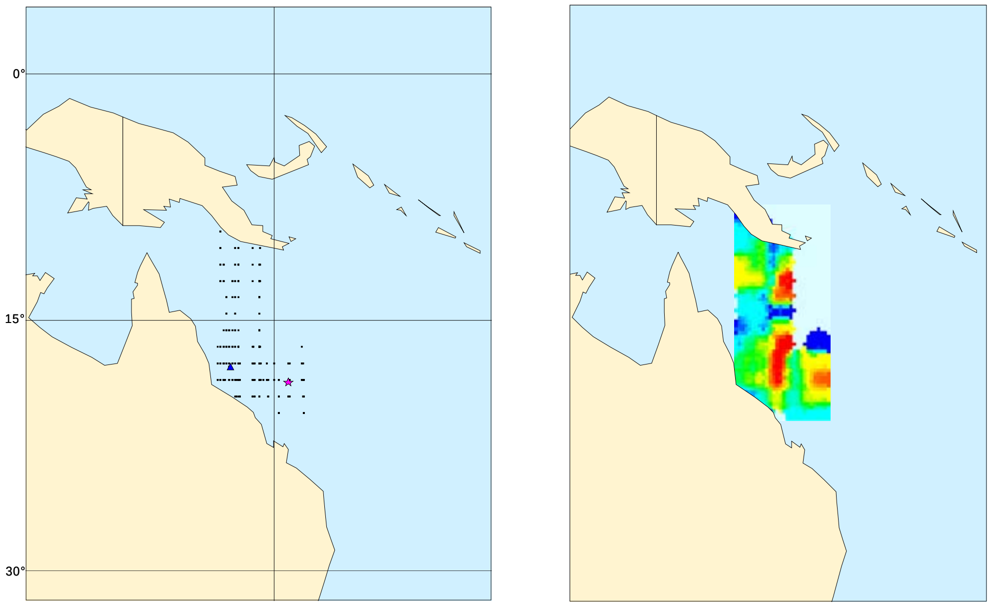
Density plot of positions derived from SST matches

🟥 highest no. matches
🟧
🟧
🟨
🟩
🟦
🟦 lowest no. matches

C.



D.



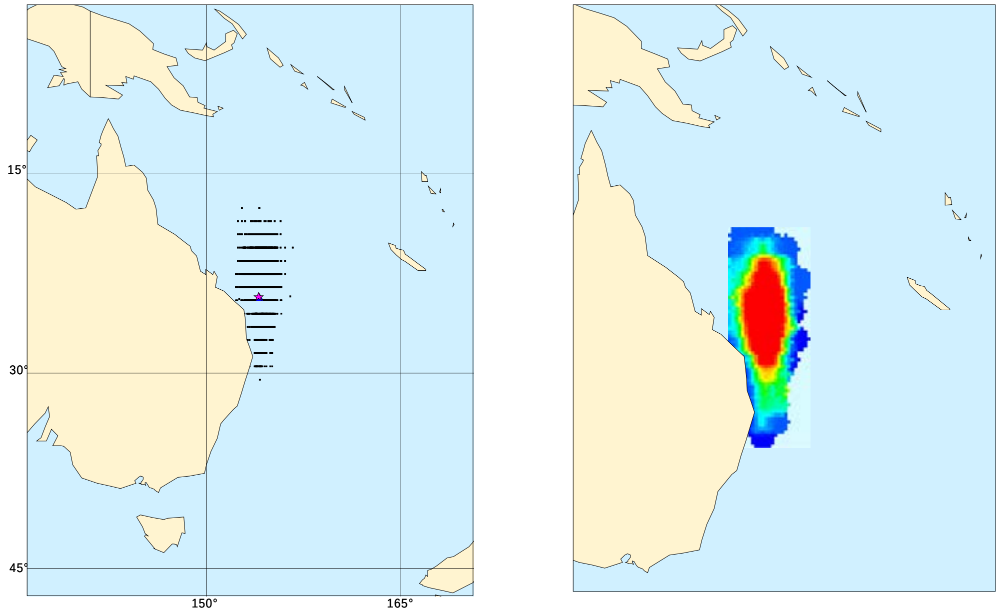
All possible positions derived from SST matches

- ▲ release
- ★ recapture
- · estimated positions

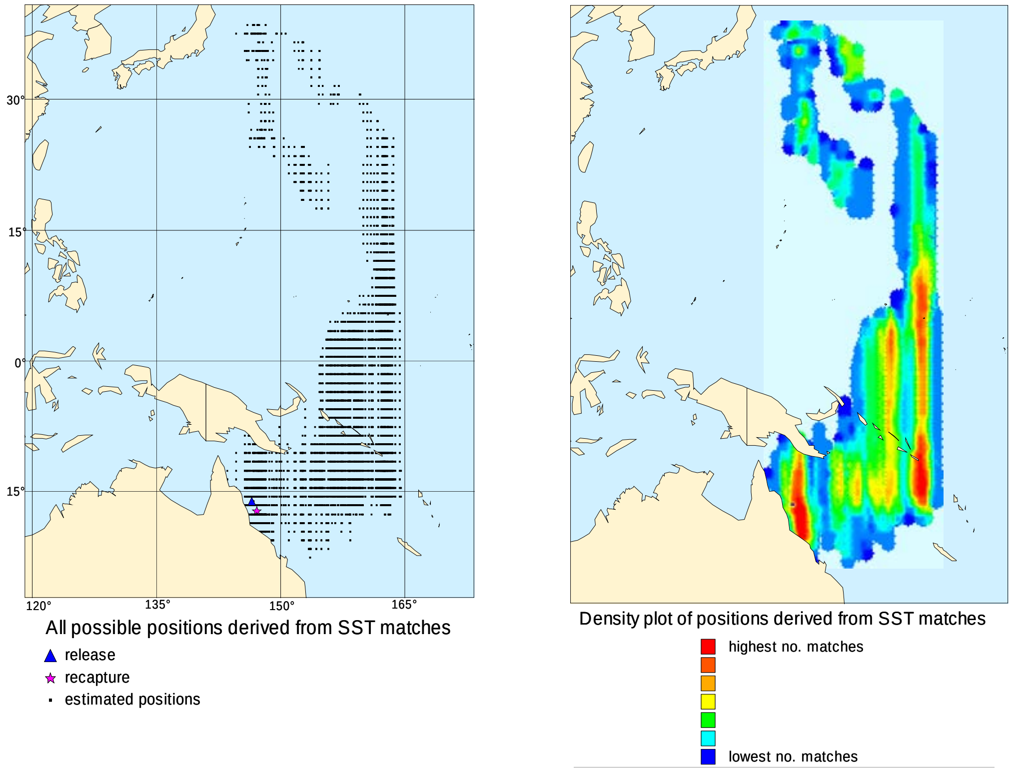
Density plot of positions derived from SST matches

- 🟥 highest no. matches
- 🟧
- 🟧
- 🟨
- 🟩
- 🟦
- 🟦 lowest no. matches

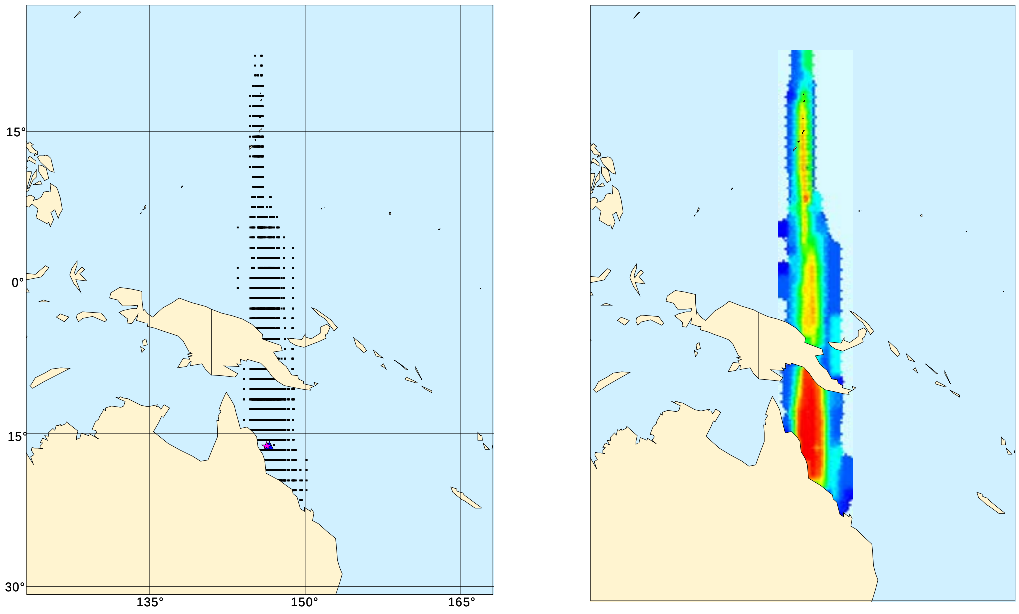
E.


15°
30°
45°
150°
165°

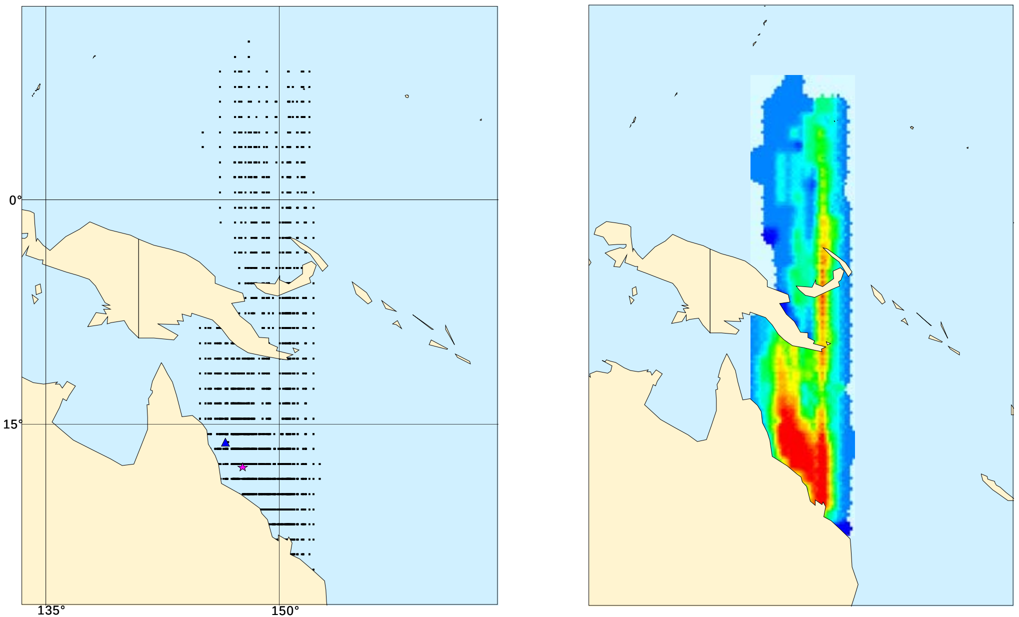
F.


30°
15°
0°
15°
120°
135°
150°
165°
All possible positions derived from SST matches
▲ release
★ recapture
▪ estimated positions
Density plot of positions derived from SST matches
🟥 highest no. matches
🟦 lowest no. matches

G.



H.



All possible positions derived from SST matches

▲ release
★ recapture
· estimated positions

Density plot of positions derived from SST matches

🟥 highest no. matches
🟧
🟧
🟨
🟩
🟦
🟦 lowest no. matches

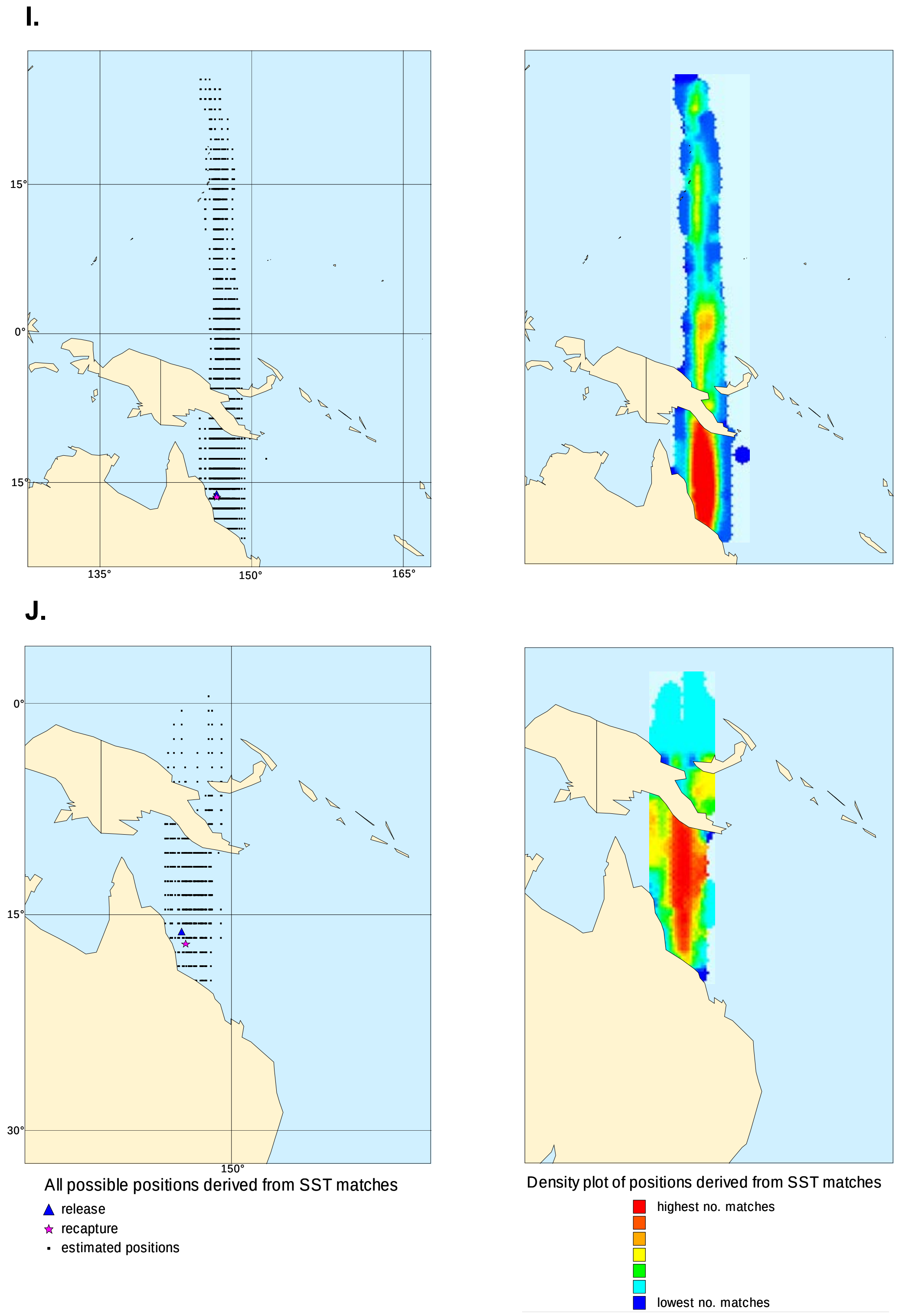


Figure C1. Position estimates and densities of position estimates for (a) 98-363; (b) 98-372; (c) 98-463; (d) 98-479; (e) 99-190; (f) 99-213; (g) 99-216; (h) 99-224; (i) 99-237 and (j) 99-243.

Appendix D. Additional methodological descriptions associated with the analyses of the behaviour and habitat preferences of bigeye tuna.

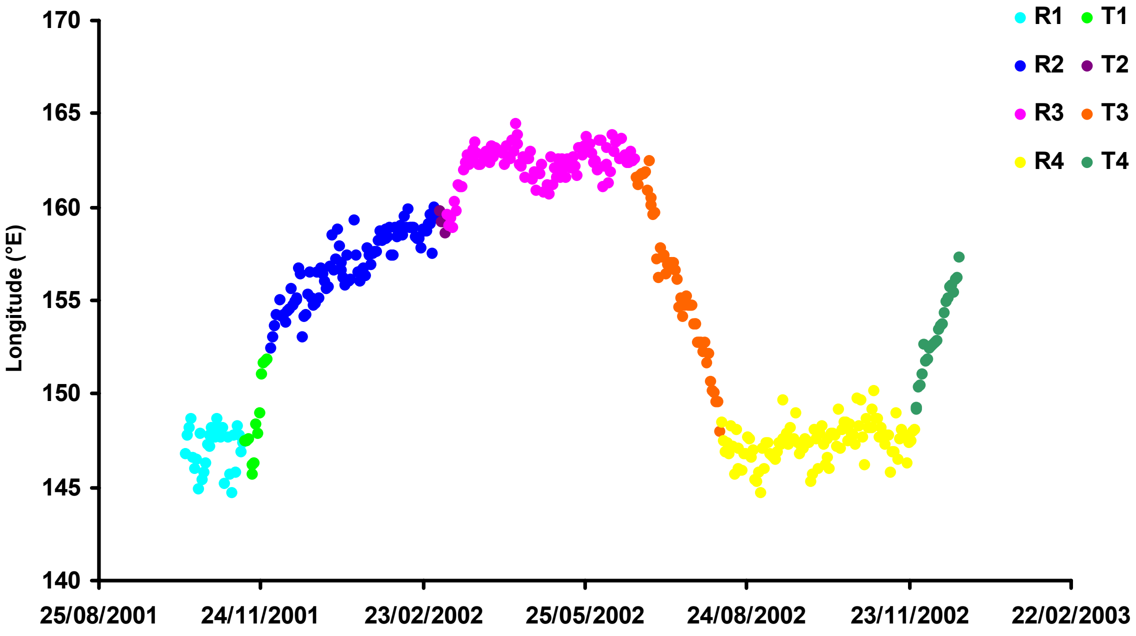


Figure D1. Longitudinal plot of position estimates from the archival tag 99-213, describing areas of residency (R) and transit (T) used in an assessment of spatial variability in habitat preferences.

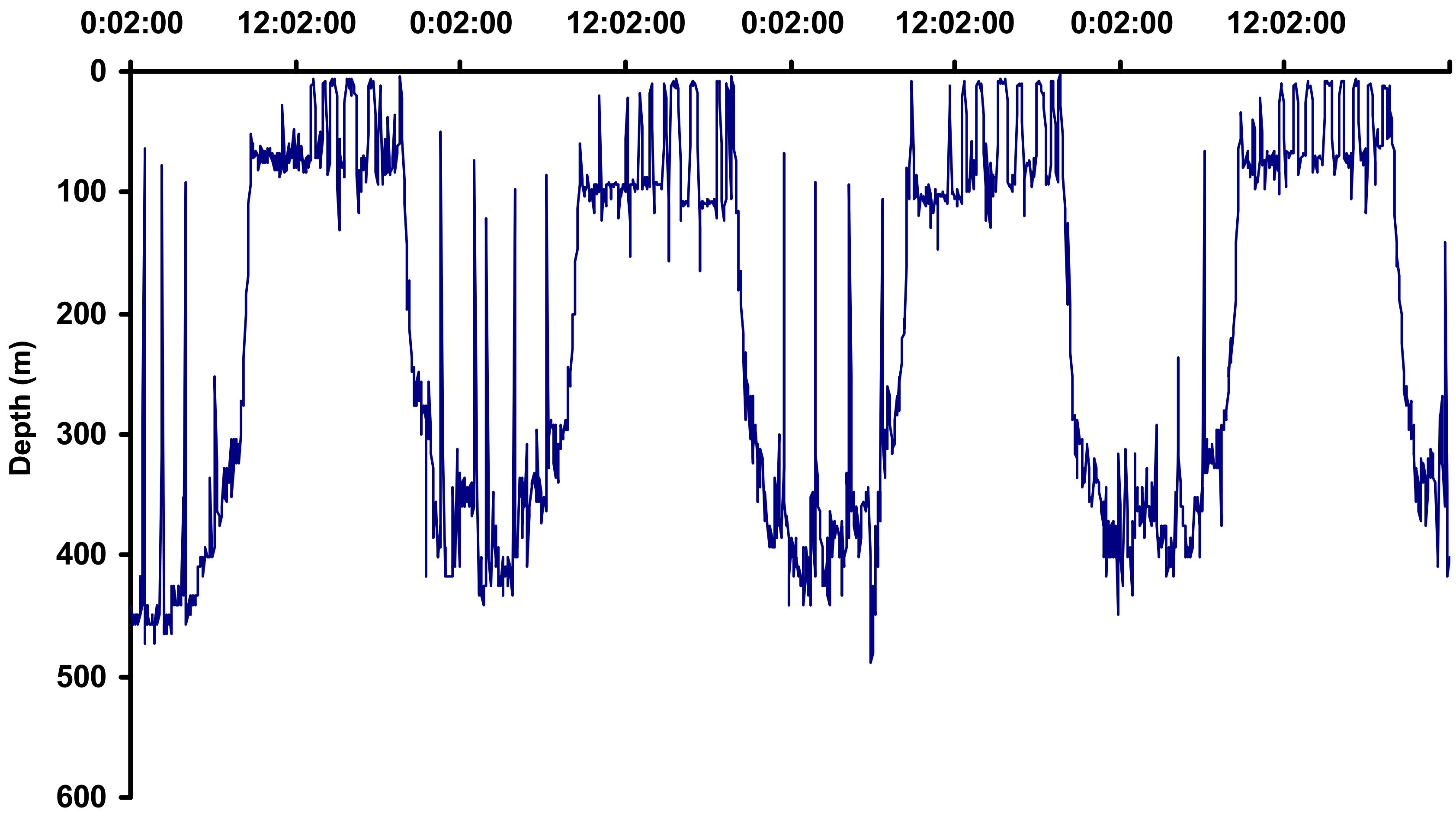


Figure D2. “Classic” diving behaviour in bigeye tuna as recorded by the archival tag 00-112 during the period 12-15 April 2004.

Appendix E. Time at depth and water temperature across seasons for archival tags at liberty 1999-2001 within the Coral Sea region.

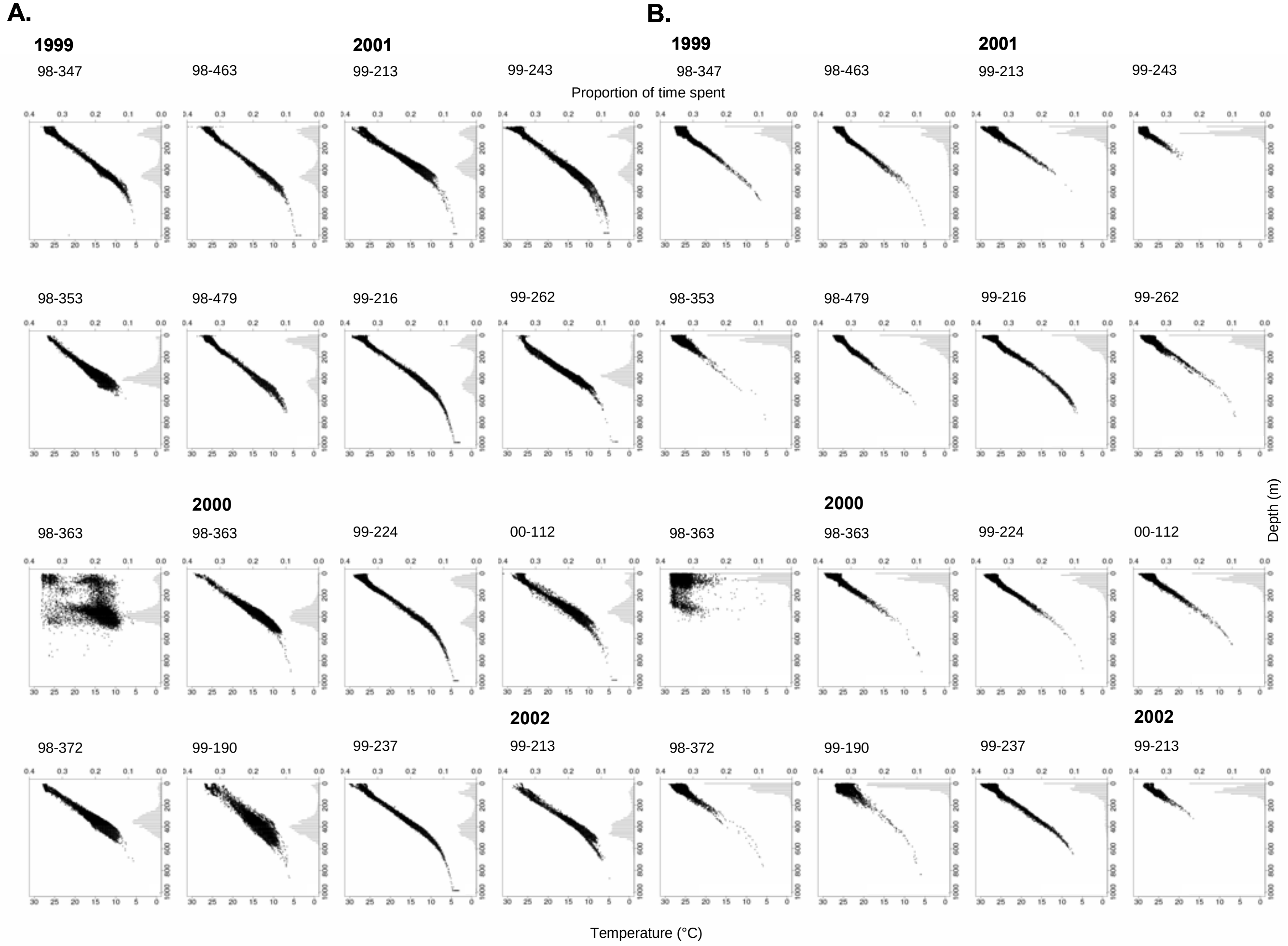


Figure E1. Time spent at depth by bigeye tuna during the (a) day and (b) at night during spring.

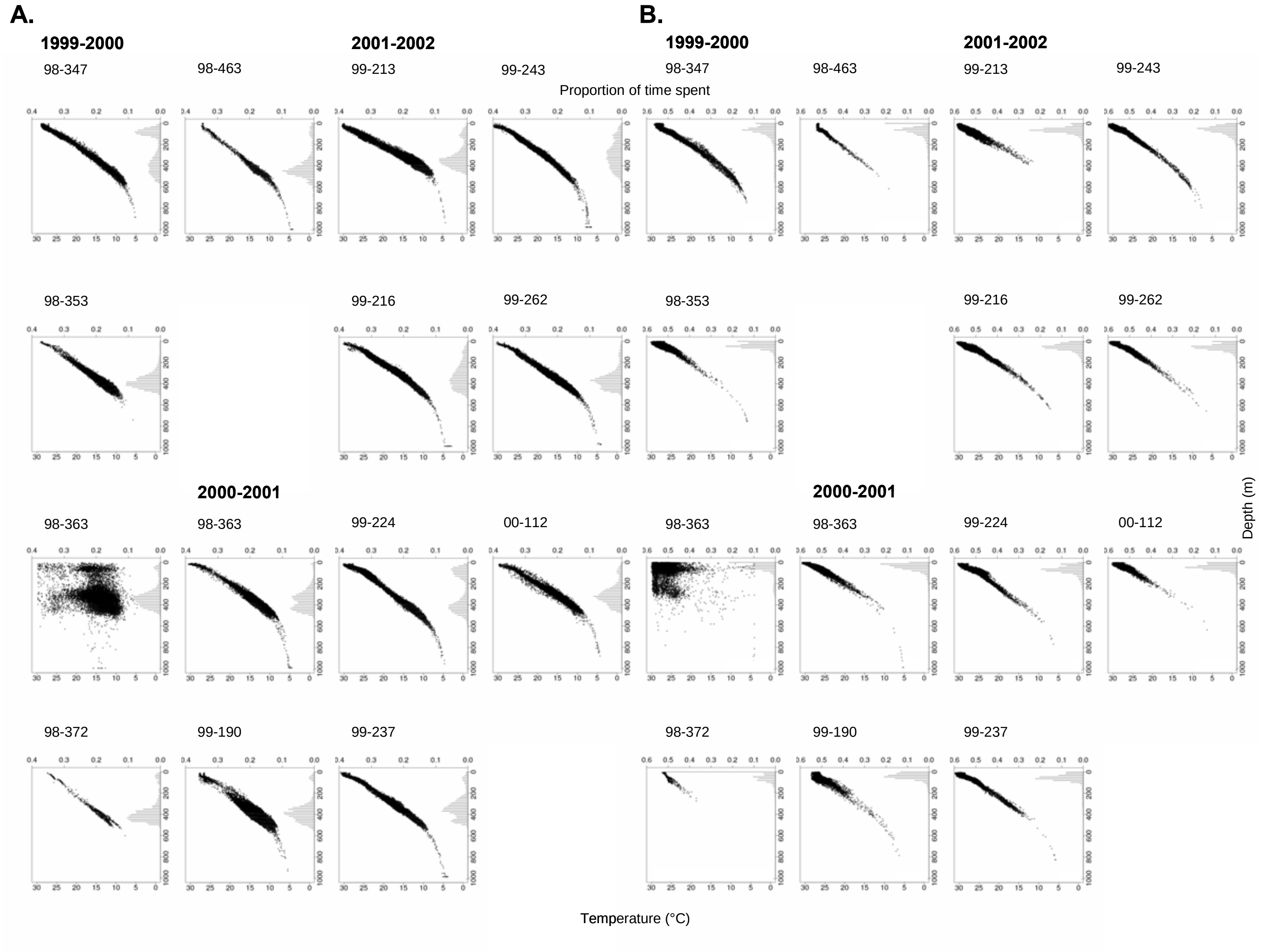


Figure E2. Time spent at depth by bigeye tuna during the (a) day and (b) at night during summer

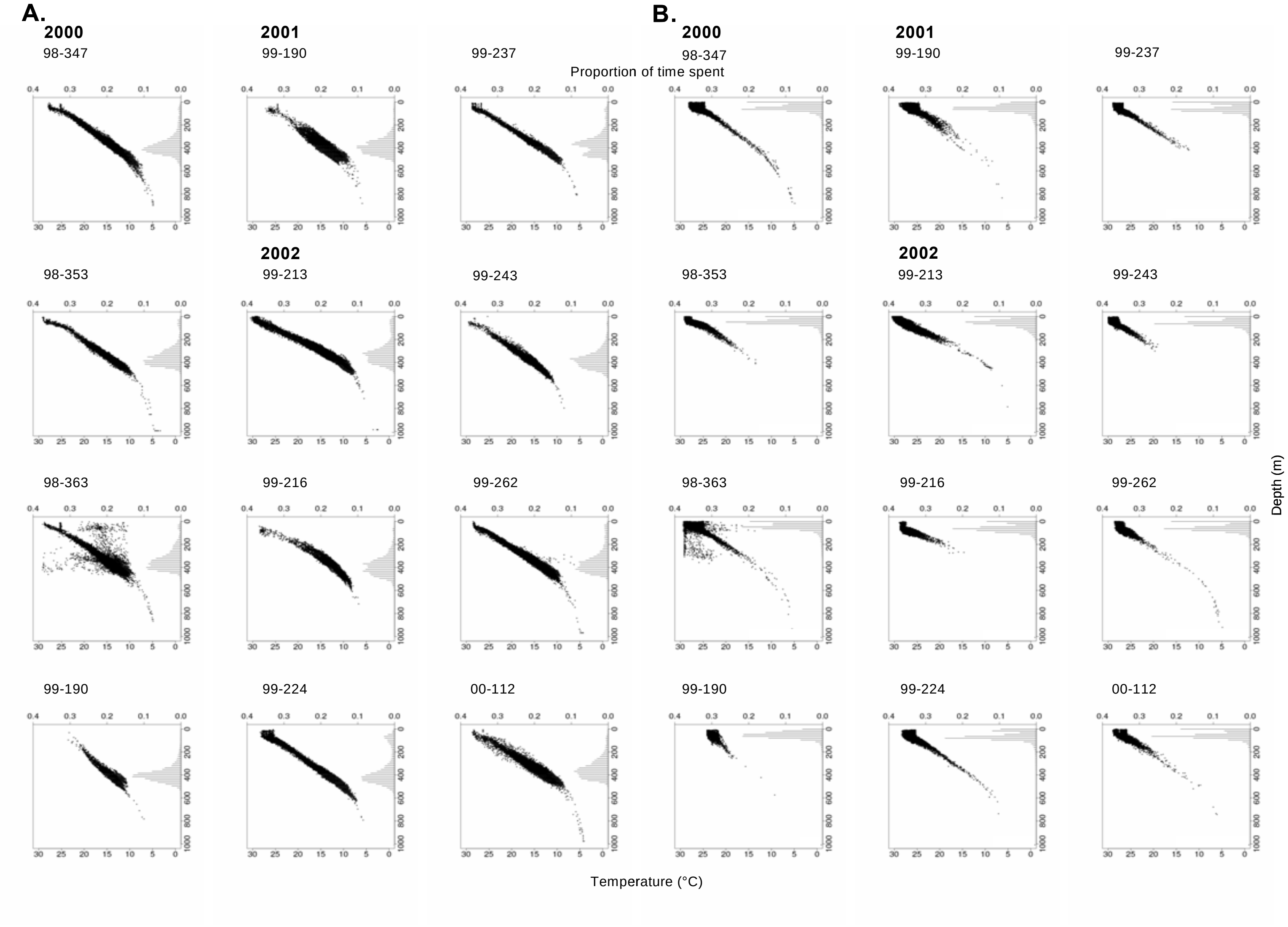


Figure E3. Time spent at depth by bigeye tuna during the (a) day and (b) at night during autumn.

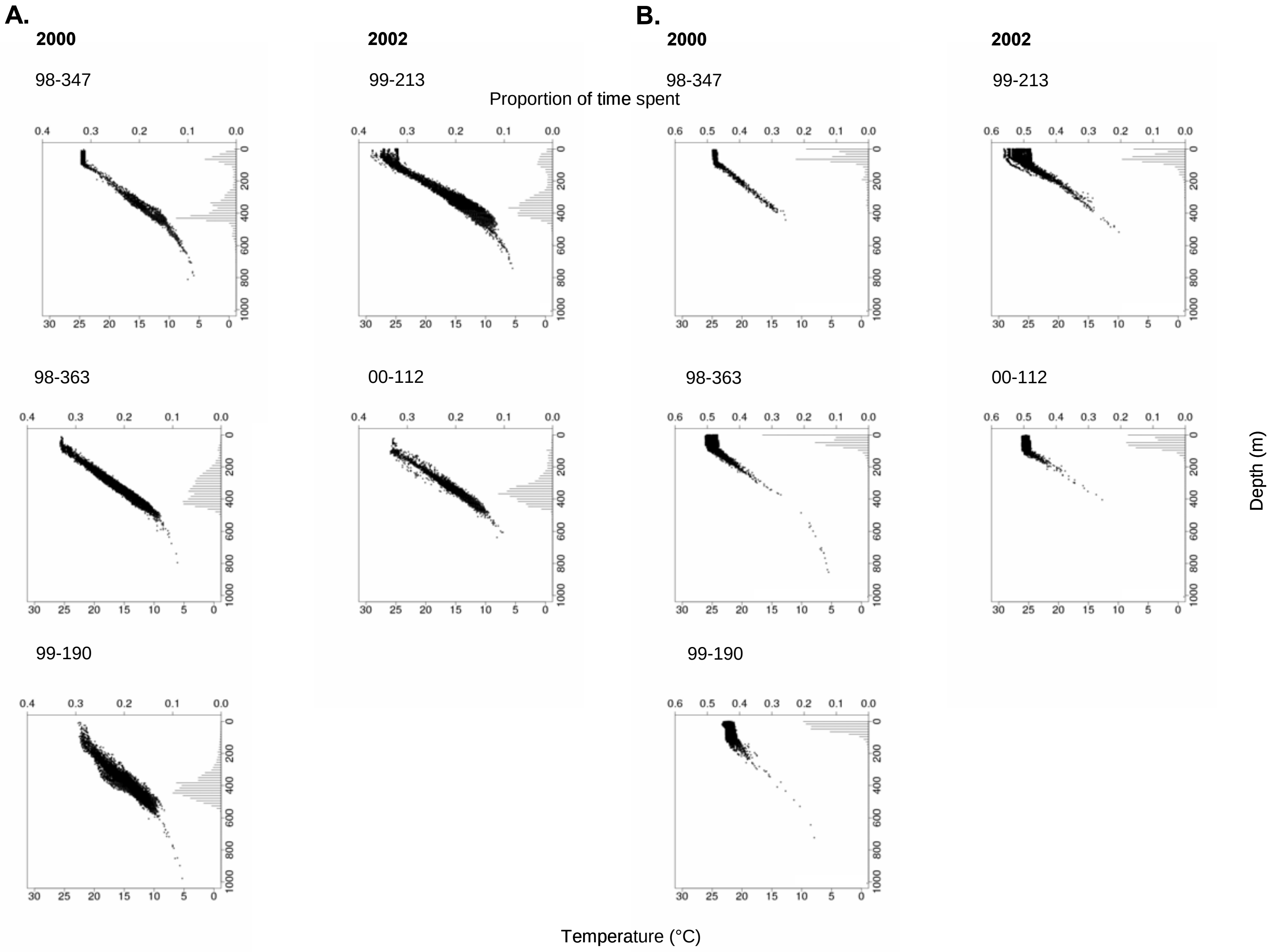


Figure E4. Time spent at depth by bigeye tuna during the (a) day and (b) at night during winter.

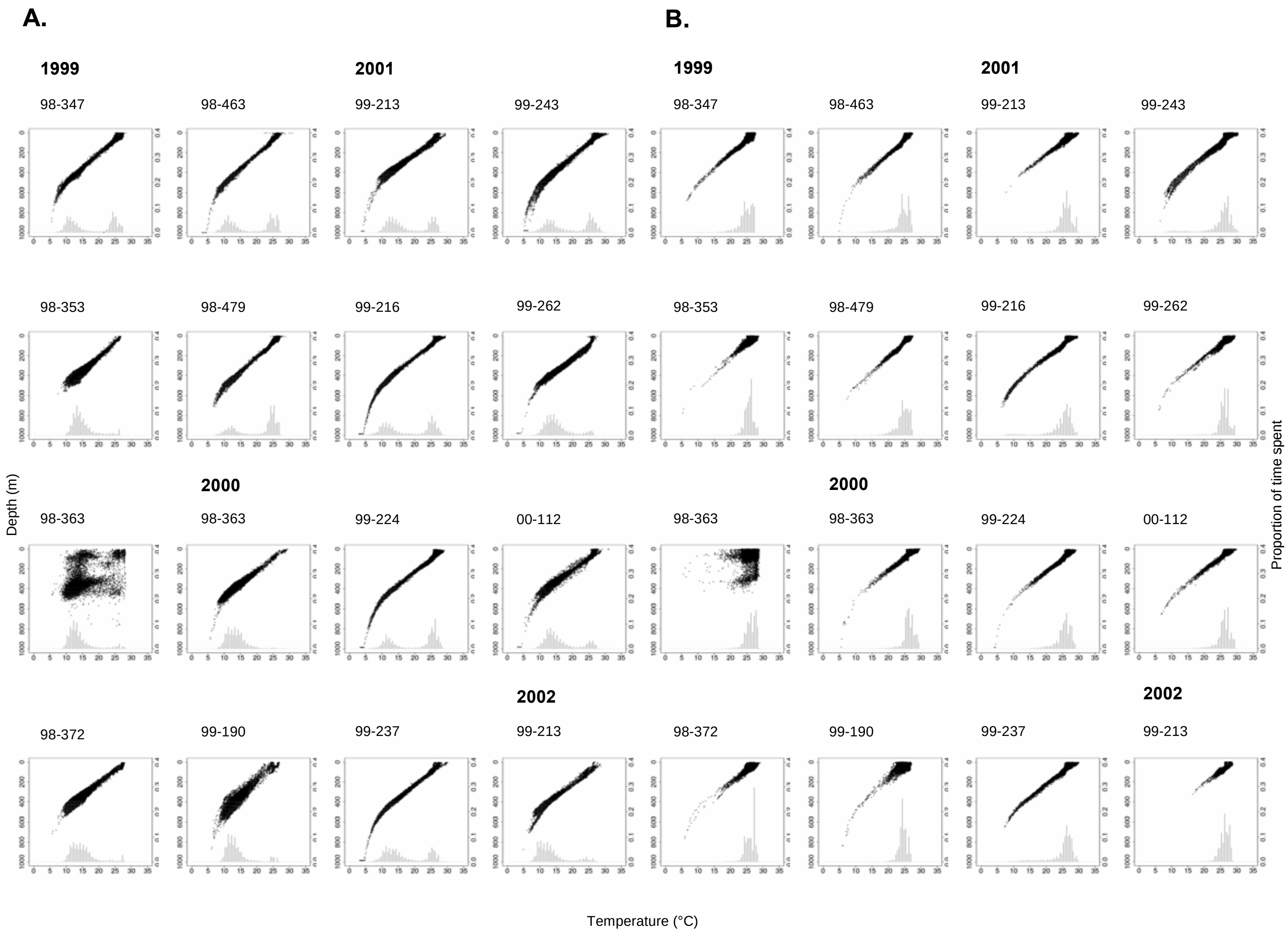


Figure E5. Time spent at water temperature by bigeye tuna during the (a) day and (b) at night during spring.

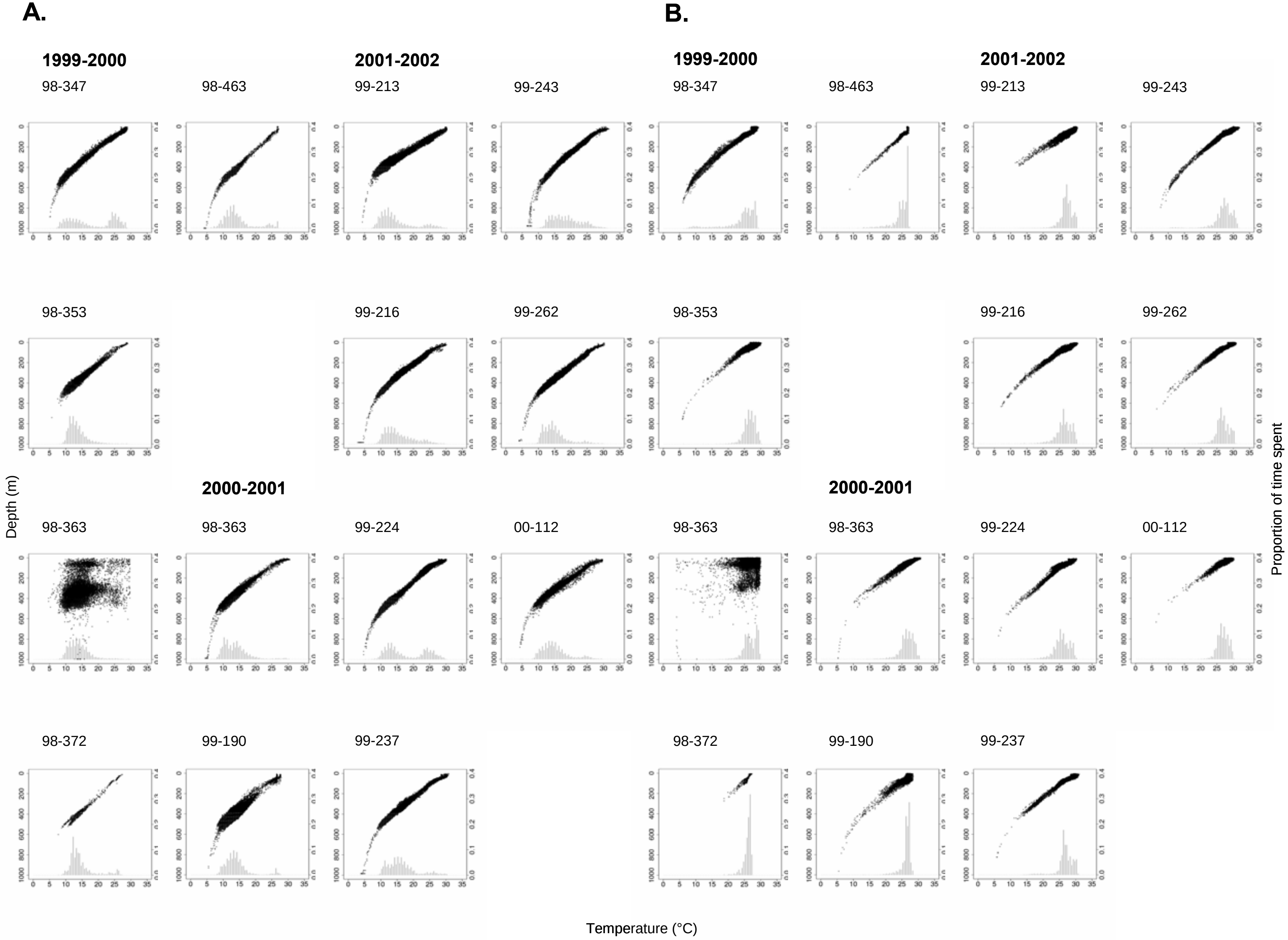


Figure E6. Time spent at water temperature by bigeye tuna during the (a) day and (b) at night during summer.

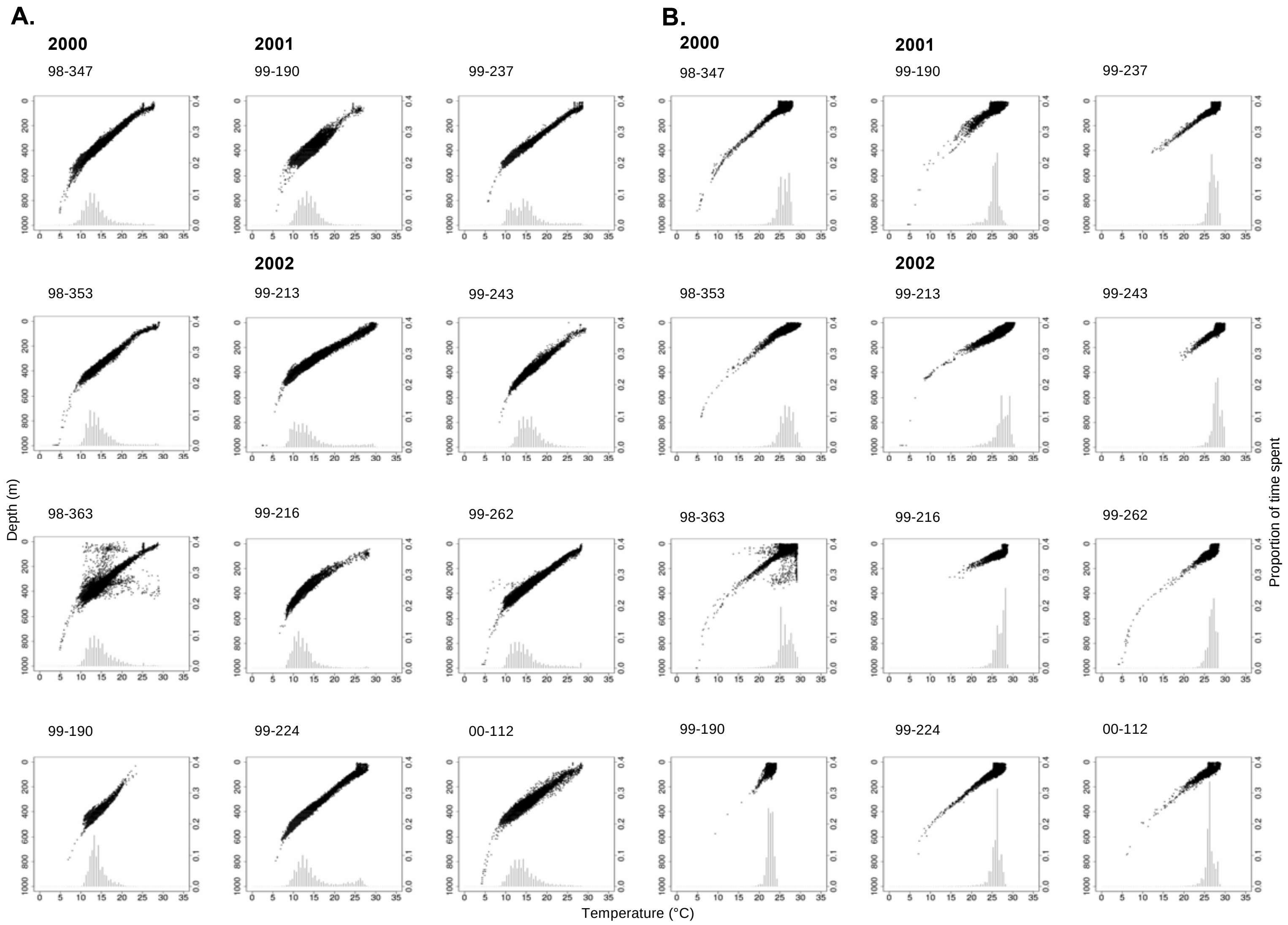


Figure E7. Time spent at water temperature by bigeye tuna during the (a) day and (b) at night during autumn.

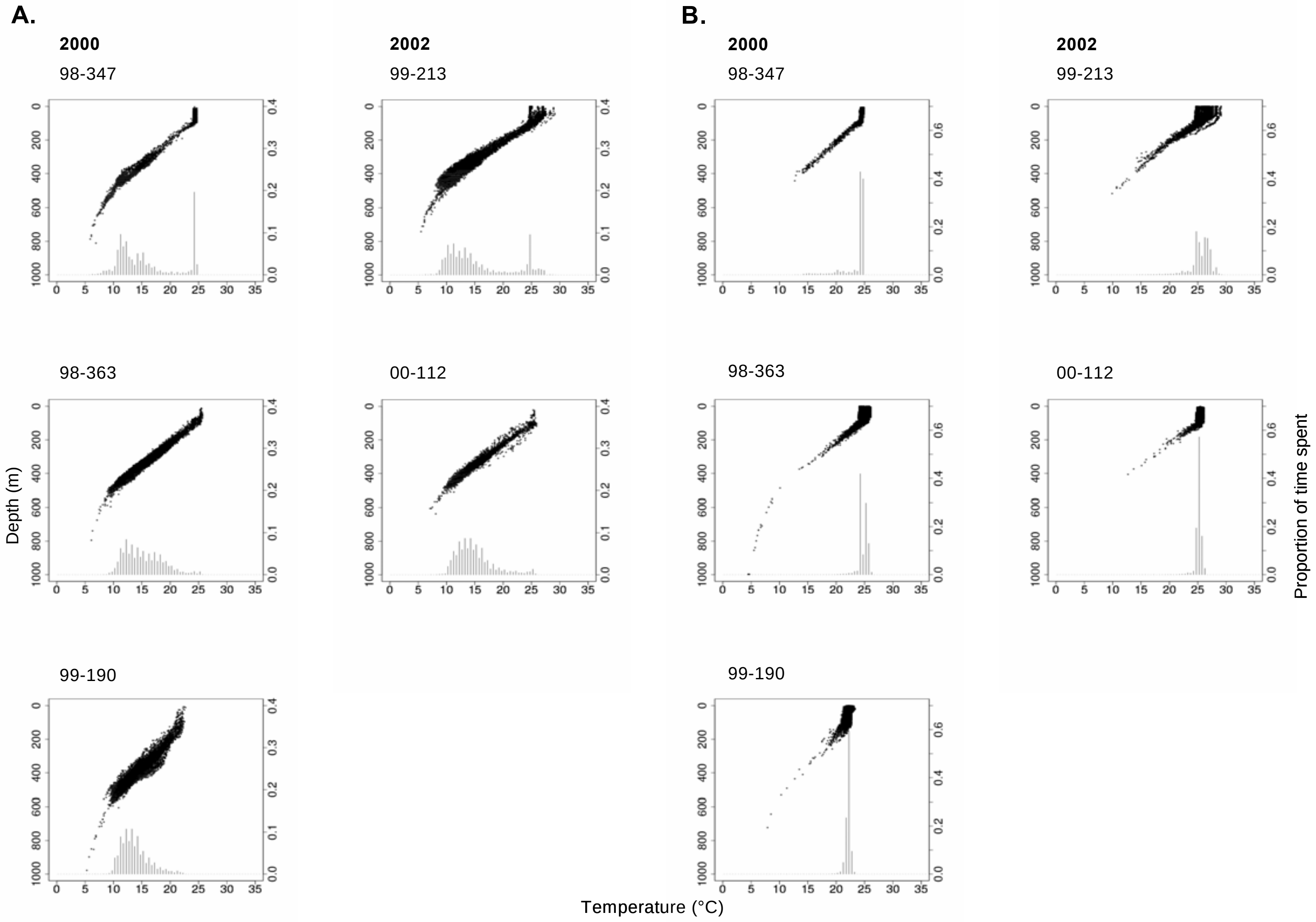


Figure E8. Time spent at water temperature by bigeye tuna during the (a) day and (b) at night during winter.

Appendix F. Spatial variability in the time at depth and water temperature for the archival tag 99-213 at liberty 2001-2002.

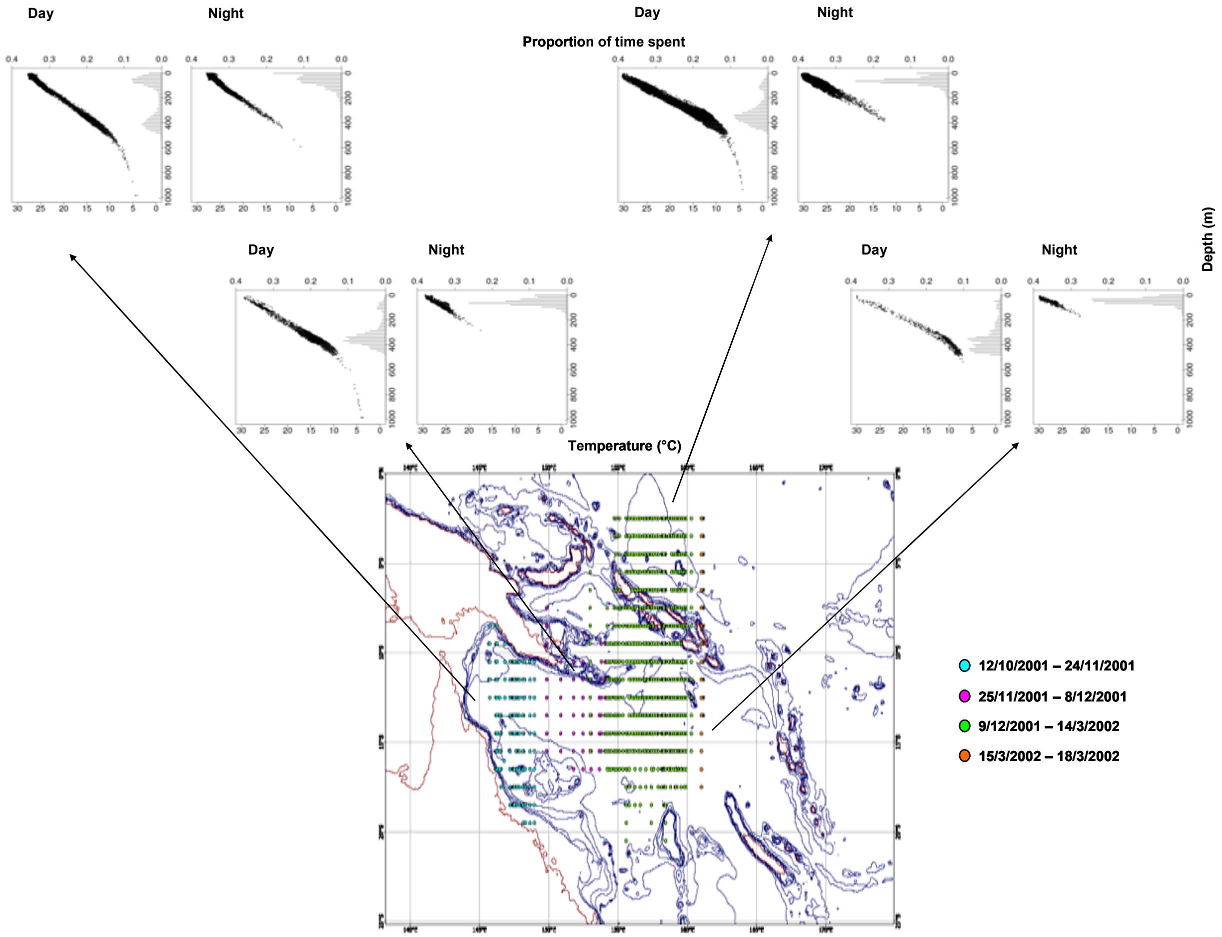


Figure F1. Spatial variability in the time spent at depth by the archival tag 99-213 during the period 12/10/2001 to 18/3/2002.

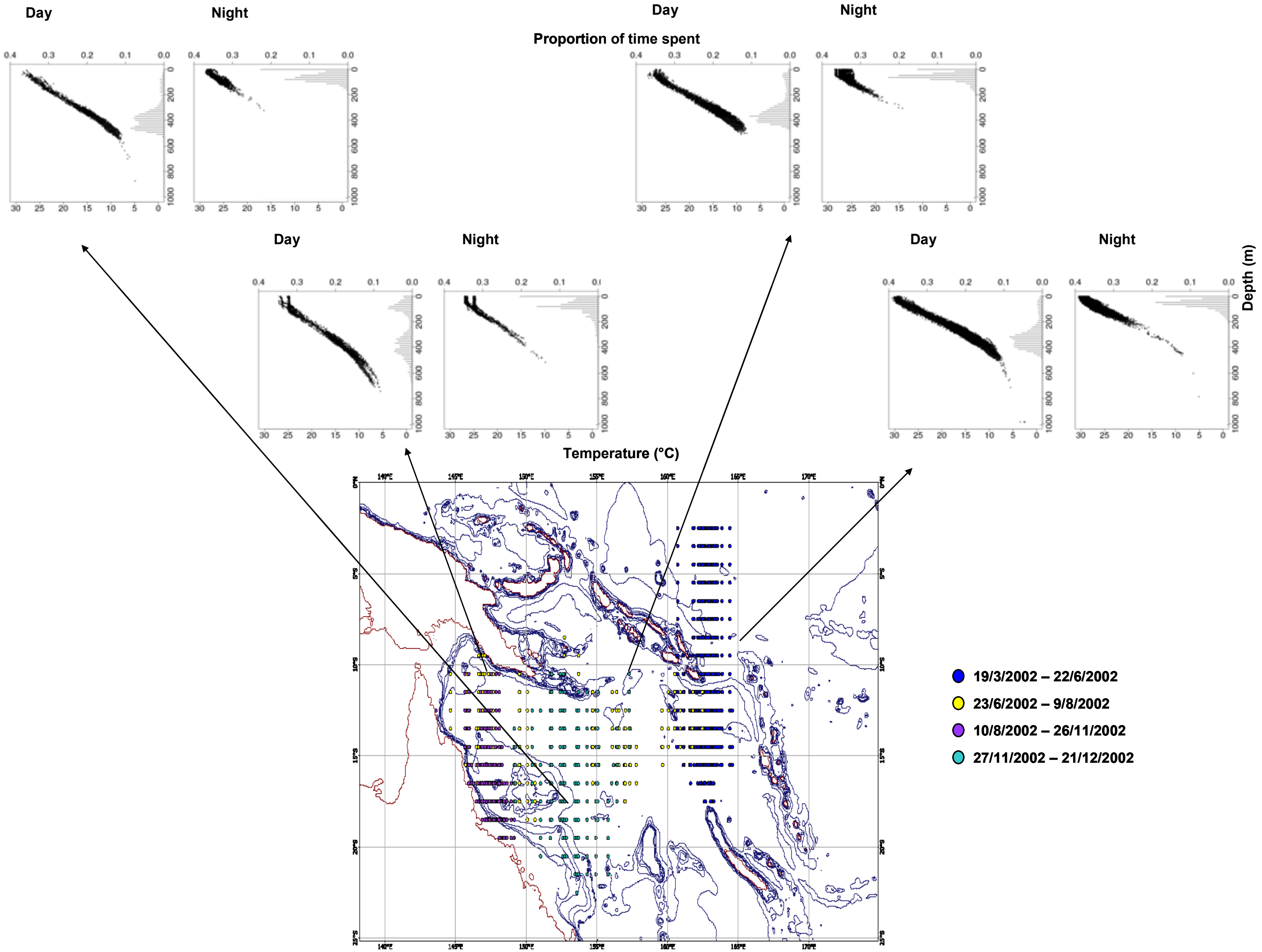


Figure F2. Spatial variability in the time spent at depth by the archival tag 99-213 during the period 19/3/2002 to 21/12/2002.

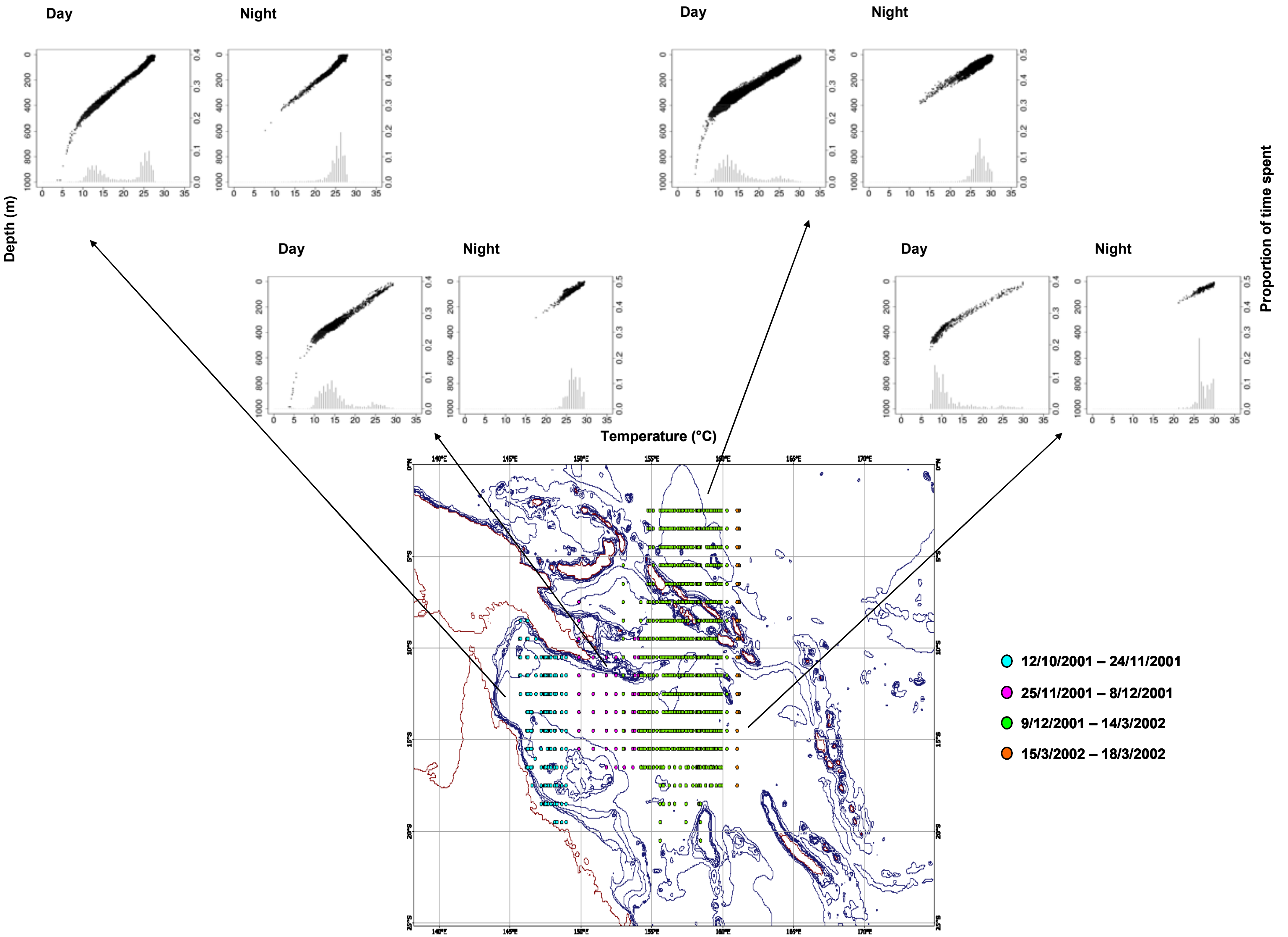


Figure F3. Spatial variability in the time spent at water temperature by the archival tag 99-213 during the period 12/10/2001 to 18/3/2002.

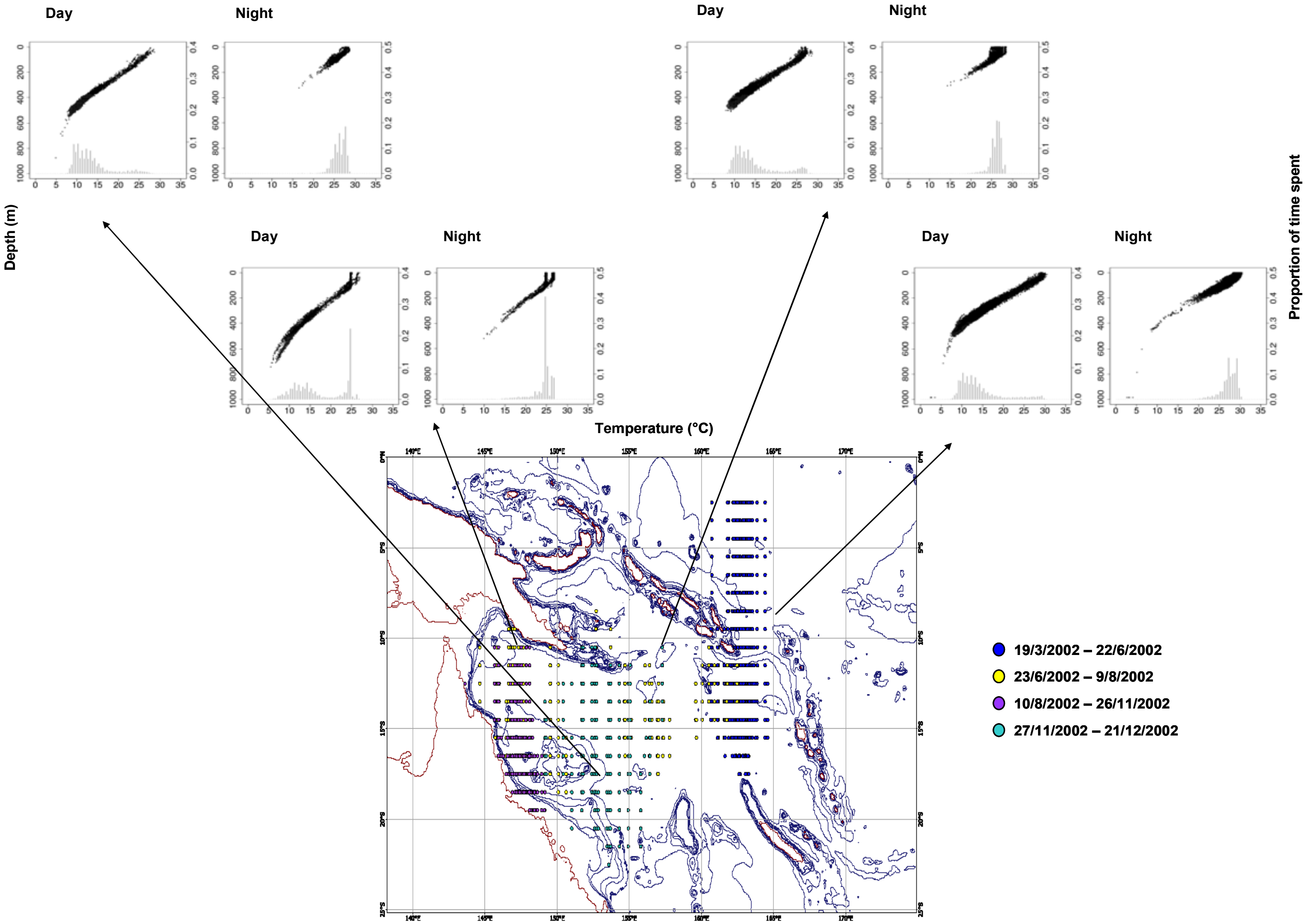
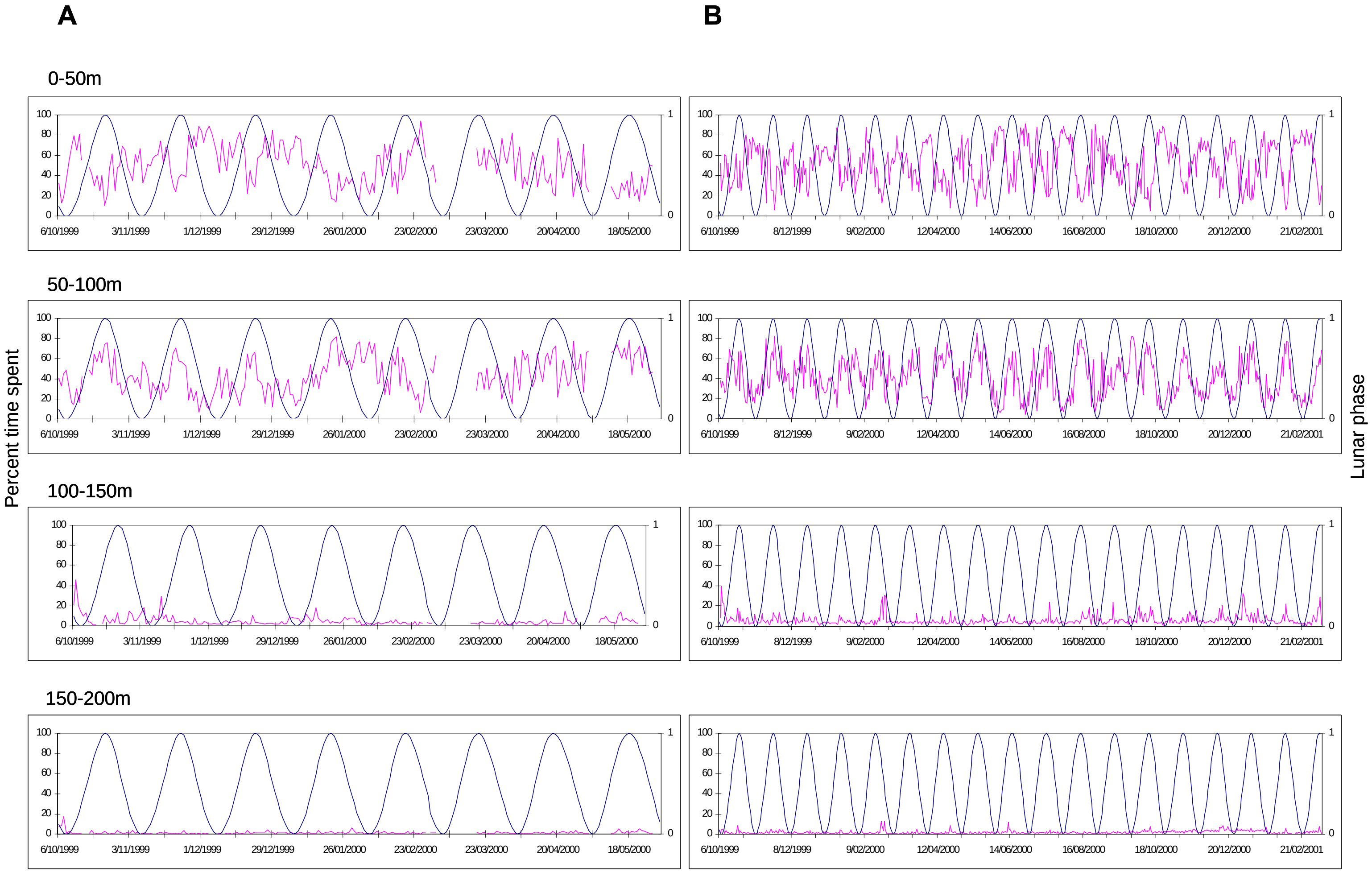
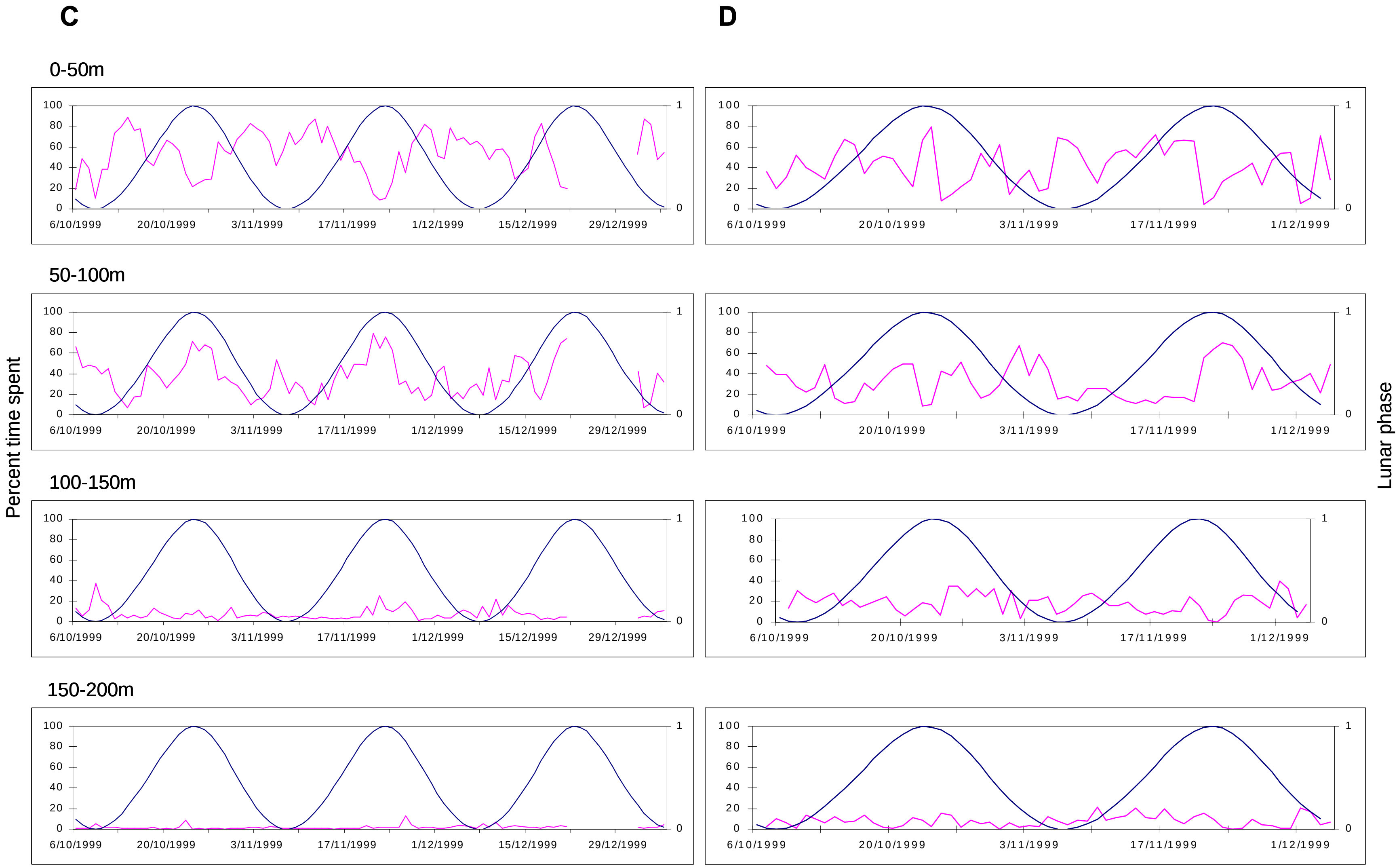
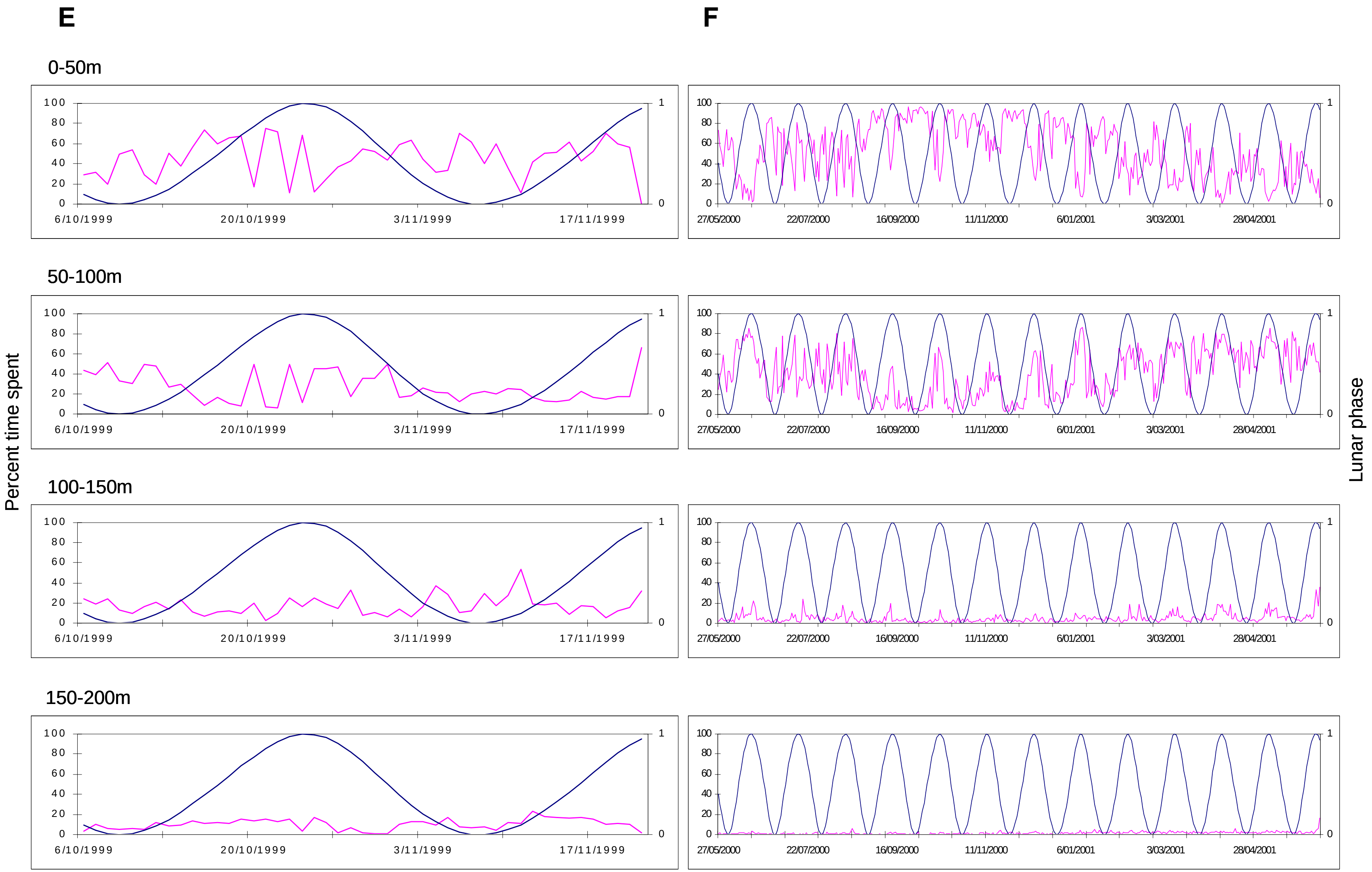


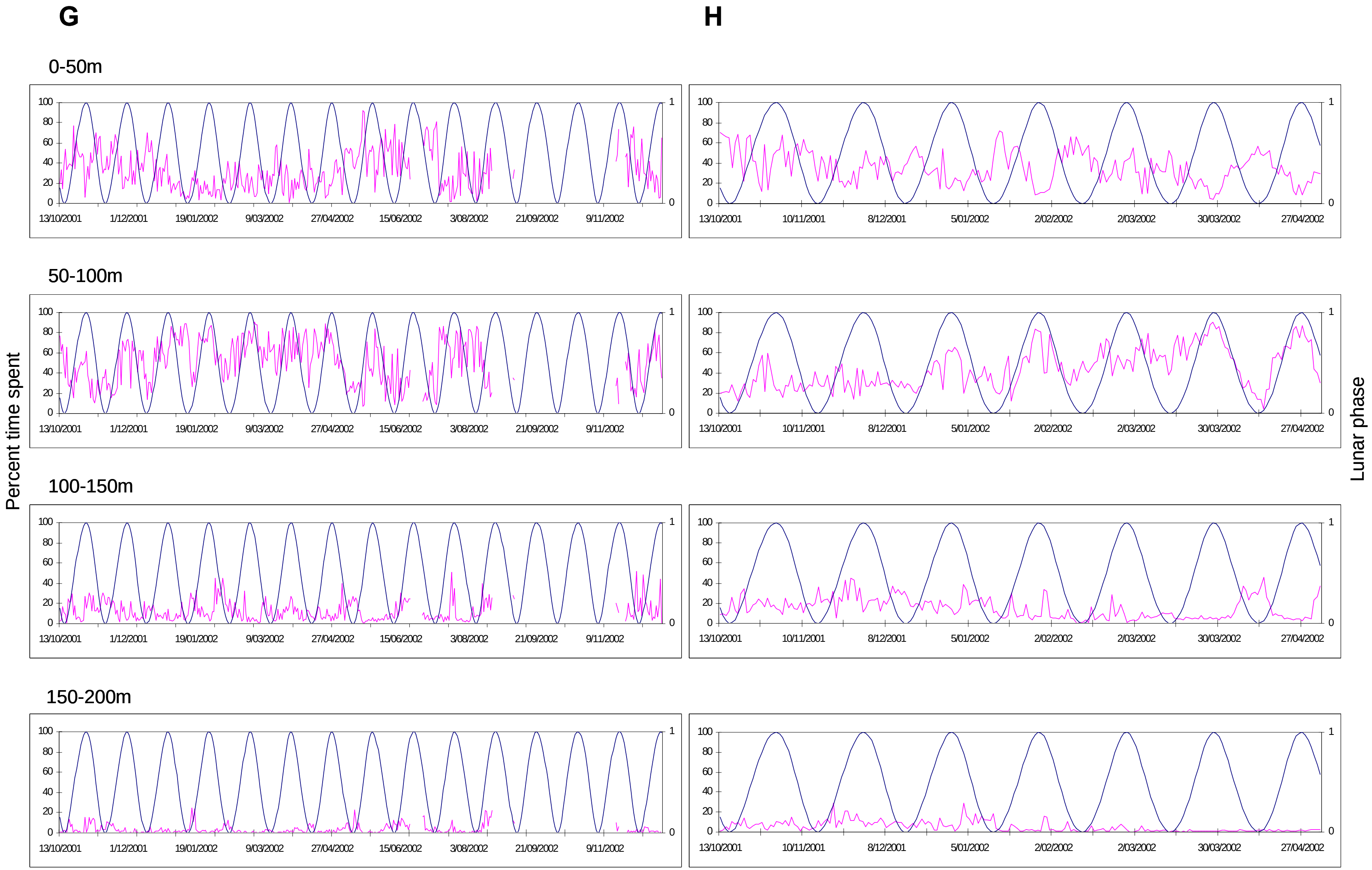
Figure F4. Spatial variability in the time spent at water temperature by the archival tag 99-213 during the period 19/3/2002 to 21/12/2002.

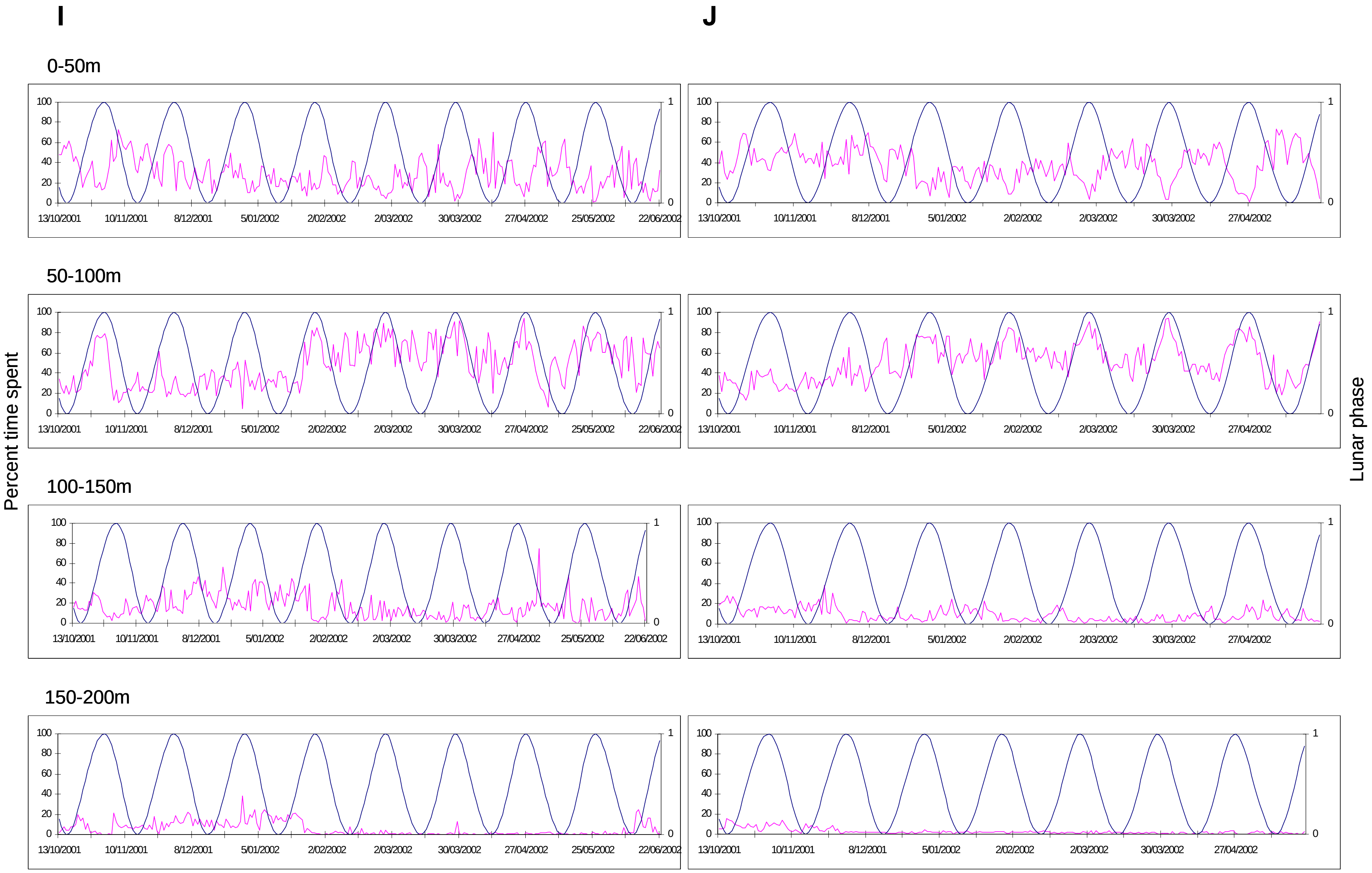
Appendix G. Time spent across 0-200m at night by archival tags at liberty 1999-2002 in relation to lunar phase.




C
D
0-50m
50-100m
100-150m
150-200m
Percent time spent
Lunar phase
100
80
60
40
20
0
1
0
6/10/1999
20/10/1999
3/11/1999
17/11/1999
1/12/1999
15/12/1999
29/12/1999


E
F
0-50m
50-100m
100-150m
150-200m
Percent time spent
Lunar phase
100
80
60
40
20
0
1
0
6/10/1999
20/10/1999
3/11/1999
17/11/1999
27/05/2000
22/07/2000
16/09/2000
11/11/2000
6/01/2001
3/03/2001
28/04/2001


G
H
0-50m
50-100m
100-150m
150-200m
Percent time spent
Lunar phase
100
80
60
40
20
0
1
0
13/10/2001
1/12/2001
19/01/2002
9/03/2002
27/04/2002
15/06/2002
3/08/2002
21/09/2002
9/11/2002
13/10/2001
10/11/2001
8/12/2001
5/01/2002
2/02/2002
2/03/2002
30/03/2002
27/04/2002


I
J
0-50m
50-100m
100-150m
150-200m
Percent time spent
Lunar phase
100
80
60
40
20
0
1
0
13/10/2001
10/11/2001
8/12/2001
5/01/2002
2/02/2002
2/03/2002
30/03/2002
27/04/2002
25/05/2002
22/06/2002

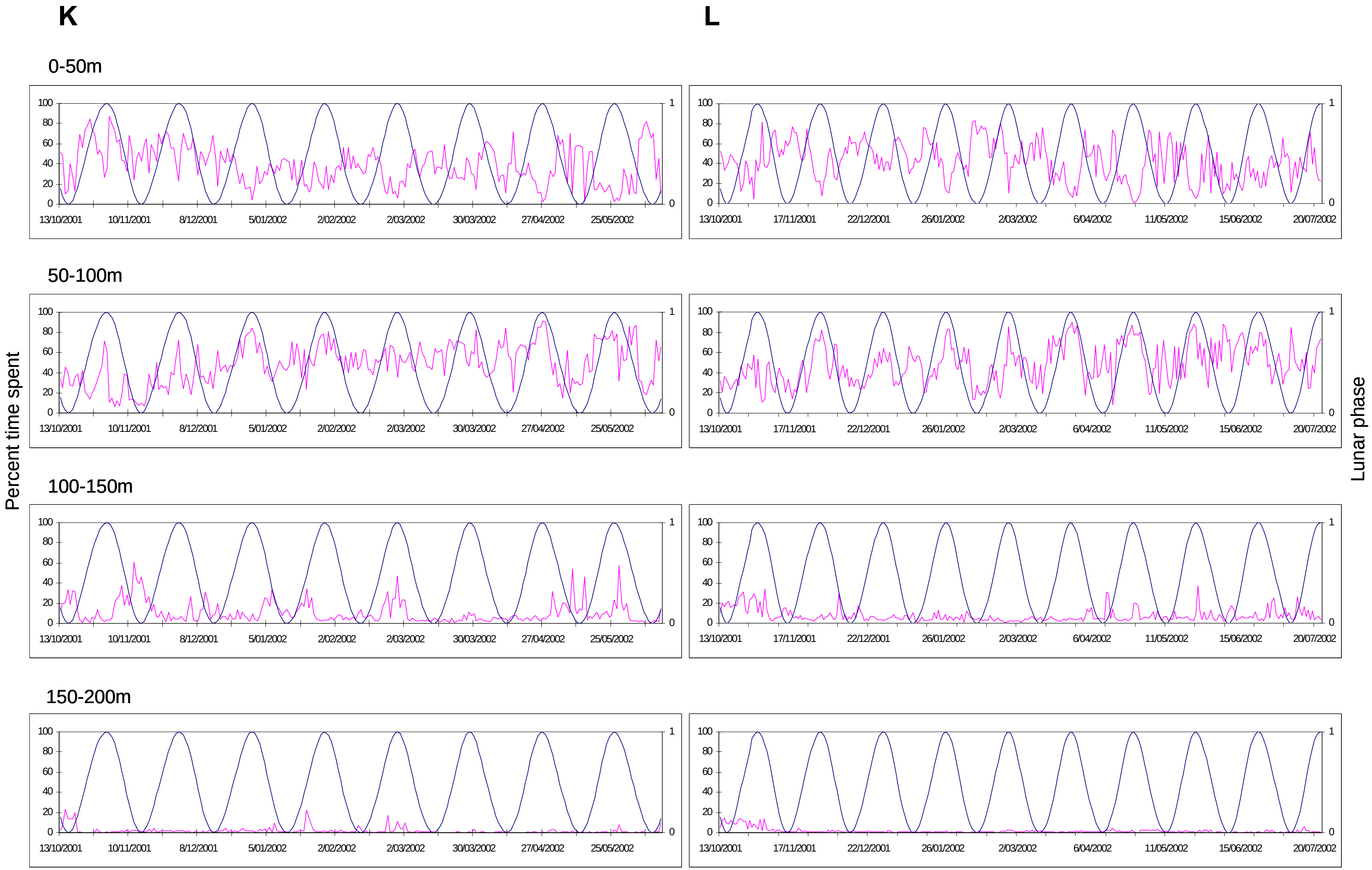


Figure G.1. Time spent across 0-200m at night (in pink) by the archival tags (a) 98-353; (b) 98-363; (c) 98-372; (d) 98-463; (e) 98-479; (f) 99-190; (g) 99-213; (h) 99-216; (i) 99-224; (j) 99-237; (k) 99-262 and (l) 00-112 in relation to lunar phase (in blue; 0: new moon, 1: full moon)