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Interannual variation in habitat use by juvenile Southern Bluefin Tuna in southern Western Australia during the summers of 2005-2007: implication for recruitment index estimates

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ABSTRACT: The spatial habitat usage of juvenile southern bluefin tuna in southern Western Australia (SWA) was investigated through acoustic monitoring of tuna tagged with acoustic transmitters during three austral summers (2004/05, n=79 fish, 2005/06, n=81, 2006/07, n=84). A total of seventy receivers were deployed on three cross-shelf lines and three inshore topographic features (lumps) from December to May each summer. Temperature and salinity data from a separate CTD survey were used to determine water mass composition and the relationship to tagged fish distribution. Habitat usage by fish was divided into two groups: lump-association in 2004/05 and 2006/07, and wide distribution over the continental shelf in 2005/06. The interannual differences in fish distribution were related to the presence of sub-Antarctic water. The sub-Antarctic water was observed in the subsurface layer close to the shelf edge in 2005/06, and the area had higher chlorophyll-a concentrations than the inshore area. There was also slower warming in temperature over the summer in 2005/06 compared with 2004/05 and 2006/07. These results indicated that variation in temperatures was associated with a La Nina event (2005/06). Nutrient rich sub-Antarctic water may have a strong influence on fish distribution in 2005/06, with juvenile southern bluefin tuna attracted to the regional topographic features in 2004/05 and 2006/07 when sub-Antarctic water was absent. Environmental variability may be the major cause of the changes in habitat use observed for juvenile southern bluefin tuna in SWA.

KEY WORDS: Acoustic telemetry, Population distribution, Habitat preference, Water masses structure, Sub-Antarctic water, Chlorophyll, La Nina

要約

オーストラリア南西海域においてミナミマグロ未成魚のハビタットの空間利用を調査するために，音響タグ追跡調査をオーストラリアの夏季に 3 年間実施した（2004/05; n = 79, 2005/06; n = 81, 2006/07; n = 84）．毎年 12 月～5 月に，合計 70 台の受信機を陸棚上に 3 列のライン状に，また沿岸の地形学的特徴（小海山）にも係留した．CTD 調査によって得られた水温・塩分記録は水塊の構成を明らかにすることと，その水塊と標識魚の分布との関係を明らかにするために用いた．標識魚のハビタット利用は沿岸の小海山域に蝟集し続ける年（2004/05, 2006/07）と陸棚上を分布の中心とする年（2005/06）に明瞭に分かれた．この分布の経年変化は Sub-Antarctic water の存在が関係していた．2005/06 年，Sub-Antarctic water は陸棚斜面近くの表層付近で観察され，その場所は表層クロロフィル a 濃度が沿岸に比べて高かった．また，2005/06 年の夏季の水温上昇は 2004/05 年，2006/07 年に比べて遅れた．これらの結果から，2005/06 年の水温変動は La Niña 現象に関連していることが示唆された．栄養塩豊富な Sub-Antarctic water は 2005/06 年の標識魚の分布に強く影響を及ぼしていた可能性があるが，一方で Sub-Antarctic water が不在であり，陸棚域が貧栄養状態であった 2004/05 年と 2006/07 年の標識魚は小海山域に蝟集したものと考えられた．このような環境変動がオーストラリア南西海域におけるミナミマグロ未成魚のハビタット利用の変化を引き起こす主な原因となるであろう．

INTRODUCTION

The use of scientific survey data for assessing for the abundance of commercially important fish stocks has become a necessity in many regions. Errors and biases in estimating abundance from such surveys may thus have great economic impact.

Southern Bluefin Tuna (SBT, *Thunnus maccoyii*) spawn in the northeast Indian Ocean from August to May (Farley and Davis 1998). Young-of-the-year move down the west coast of Australia and are found as age-1 SBT in southern Western Australia. The acoustic (sonar) survey (AS) under the Recruitment Monitoring Program has been established to monitor the relative abundance of 1-year old SBT based on a line transect survey using a consistent protocol (omni scanning sonar) since 1995/96 austral-summer season. The acoustic survey area (ASA) was established in the area between Albany and Esperance, where the width of continental shelf becomes narrow, with the assumption that most 1-year old SBT (and 2-year old) will pass through along the southern western coast of Australia during summer. Acoustic estimate have been used as relative indices of the recruitment of SBT (Itoh and Tsuji, 2002).

The standard estimation procedure used in AS of SBT did not take account potential changes in the spatial and temporal distribution (STD of fish). The reliability of the surveys indices thus depends on the stability of the bias caused by STD. Evidence of differences between years in STD has been observed. Previous reports indicated that the juvenile SBT were moving inshore of the ASA, or were not moving through the area during the period of the survey (Hobday (2003), Hobday and Kawabe (2004), Hobday et al (2005), Hobday et al (2007), Hobday et al (in press)). These results suggest that there may be a tendency for this inshore bias to increase with decreased recruitment indices of SBT (Itoh 2005). Thus, there is an urgent need to investigate the main causes of decline in indices in relation to the STD (fish distribution and migratory timing) of 1-year SBT.

Transect line survey by hydroacoustics such as omni sonar and quantitative echo sounder cannot sample in the complete ASA. Fish distributed off the sonar beam on the sea surface may be sampled by the trolling and counted by visual observers but are less detectable by the sonar and echosounder. On the other hand, if STD of fish coincided with the sampling time of the AS research vessel, the survey may be reliable. Hence, variations in STD of fish over the AS research area may affect the SBT density/abundance estimates. This problem involves a complex set of factors, of which fish behavior is most important. Fish density estimates would be affected both by natural behavior such as horizontal movement patterns and migration timing.

In the 1990s, the development of archival tags was regarded as a significant advance for tracking marine organisms. These tags allow a detailed recording of light intensity that used to estimate daily position to an accuracy of about 140km (Welch and Everson 1999). The study of more localized migration patterns, such as those in coastal waters or over the continental shelf, requires that locations be estimated with much finer spatial resolution. However, many species and age classes, such as juvenile SBT, are simply too small to be equipped with large and extensive ‘pop-up’ archival tags. The alternative is small archival tags that must be recovered opportunistically, typically by fisherman, and returned to the laboratory. This means that a relatively large number of fish must be tagged to ensure reasonable numbers of tag recoveries over the desired time scale (months to one or more years). Thus, these tags may not be suitable for questions related to movements through the acoustic sonic region (e.g., 256.5km wide sonar survey box). Recent advances in acoustic tagging technology have made available low-cost, submersible receivers that can automatically detect and identify passing fish, such as cod and tuna (Klimley and Holloway 1999, Comeau et al 2002, Hobday 2002, Hobday 2003, Kawabe et al., 2003, Heupel et al 2006).

It is well known that topographic features are associated with particular oceanic conditions, and intrusion of warm or cold water masses into reef areas can affects the movements of a predator (Klimley & Butler 1988, Willis & Hobday 2007). Willis & Hobday (2007) reported that SBT (2-3 years old) detections at a reef were related to an upwelling event in the Great Australian Bight (GAB), their presence diminishing just after intrusion of upwelled cold water. This suggests that the influx of water mass that productivity will be higher into a reef may have a direct effect on habitat usage and foraging behavior of juvenile SBT. Based on broad criteria, water masses in SWA can be distinguished as three types of water: (1) Leewuin Current water (LCW: low salinity tropical water from the north of WA (typically > 20^{o}C, < 35.65psu)), (2) Sub-tropical water (STW: high salinity from the Indian Ocean (typically > 18^{o}C, > 35.7psu)), and (3) Sub-Antarctic water (SAW: low salinity from Southern Ocean (typically < 18^{o}C, < 35.5psu)). During austral autumn and winter, the Leeuwin Current, which may entrain the sub-tropical waters, flows southwards from the North West Shelf towards Cape Leeuwin against weak southerly winds (Godfrey & Ridgway 1985, Cresswell & Peterson 1993, Ridgway & Condie 2004). In summer, however, when juveniles spend more time, southerly winds are generally strong in SWA. Thus, tropical Leeuwin Current flow weakly (Godfrey & Ridgway 1985, Ridgway & Condie 2004) and the nutrient rich sub-Antarctic water seem to be flowing to the continental shelf from offshore and/or the bottom layers (Cresswell & Peterson 1993, Cresswell & Griffin 2004). As the proportion of these waters mixing varies seasonally and interannually (Rochford 1986, Godfrey & Ridgway 1985, Cresswell & Peterson 1993). An important question is how juvenile SBT distribution is modified in response to variation in water masses.

The object of this study was to identify annual fluctuations in fish positioning and aggregation as a function of spatial variation in a specific habitat in the 2004/05, 2005/06 and 2006/07 season. And, oceanographic observations of temperature and salinity together with satellite remote sensed chlorophyll-a data were used to determine the relationship between interannual variation in habitat usage and oceanographic conditions in austral summer.

MATERIALS AND METHODS

Study area. The study was conducted along the coast of southern Western Australia (SWA) between Albany (35.01^{o}S, 117.01^{o}E) and Esperance (33.52^{o}S, 121.53^{o}E) (Fig. 1). The width of the continental shelf was 30-60 km and on the shelf, the waters are mostly less than 80 m in depth. There were many lumps in this coastal area, which are known to attract tuna.

Fish tagging. Acoustic tagging was conducted in accordance with Hobday et al. (2003). In short, fish were caught by poling or trolling at the stern of the vessel and then carried to a tagging cradle. Acoustic tags were surgically implanted in the belly of each fish and two conventional tags attached posterior to the second dorsal fin. The time from capture to release was less than two minutes. The tags (VEMCO V8SC, V9, V16) transmitted a coded pulse at a frequency of 69kHz at random intervals every 20-60 seconds with a predicted lifetime of over 365 days.

Acoustic monitoring. The survey periods were from December to March in 2004/05, and from December to May in 2005/06 and 2006/07. A total of 70 listening stations were assembled and deployed on December 3-5 in 2004, and December 1-3 in 2005 and

2006. Three cross-shelf lines of 20-21 stations were established from the coast to the shelf edge near Albany (Line 1), Bremer Bay (Line 2) and Esperance (Line 3), and three stations were placed at each of three lumps between Line 1 and Line 2 (Fig. 1). Listening stations were subsurface and consisted of a mooring anchor, wire cable, VEMCO VR-2 receiver, timed electronic release, 50 meters of release rope in a PVC canister, and floats. Temperature-depth recorders (TDR VEMCO) were attached to a subset of the receivers and sampled every 30 minutes. Stations were separated by approximately 1500m, which was too large for complete acoustic coverage by the stations (Hobday & Pincock, in review). This spacing decision was based on a desire to cover the width of the shelf; a tag detection range of up to 450m (V8) and 800m (V16) were expected based on detection experiments (Hobday et al. 2005, Hobday & Pincock, unpabl. data). The electronic releases on each mooring were programmed to activate after a specified interval, and stations were recovered at the surface using an attending vessel. The data were downloaded using VEMCO software and results analyzed with Microsoft Excel and Igor Pro software 4.7J (WaveMetrics, Lake Oswego, OR, USA).

Oceanographic observation. The in situ temperature environment at the depth of the receivers was characterized using TDR data, and temperature and salinity profiles were collected as part of a CTD survey from January to February in each year. The number of CTD observations each year between Albany and Esperance was 71, 88 and 27 (Fig. 1). Temperature time series data on TDRs data used to understand the rising trend during summer. And to investigate summer temperatures in Southwest Australia over long period, sea surface temperature anomaly data from 1980 to 2007 obtained by the bureau of meteorology of the Australian government website (http://www.bom.gov.au/cgi-bin/silo/reg/cli_chg/timeseries.cgi). Southern Oscillation Index (SOI) data from 2004 to 2007 were obtained from the Environmental Protection Agency of Queensland Government in Australia (http://www.longpaddock.qld.gov.au/SeasonalClimateOutlook/SouthernOscillationIndex/SOIDataFiles/index.html).

Data analyses. To define the SBT habitat use in the survey area, the detection rate of tagged fish was estimated in each location (Line 1, Line 2, Line 3, and Lumps), as the number of tagged fish detected as a proportion of the number of resident tagged fish for the month. The number of resident tagged fish was the maximum number of detected SBT each day. To determine whether the aggregation region is specifically the lumps or inshore in general, tag detections were tallied for the three inshore stations on each line and for the three lumps.

In order to describe the water masses in summer, the temperature and salinity diagrams were visually inspected. The characteristic temperatures and salinities of potential water masses were based on data from previous studies (Rochford 1986, Cresswell & Peterson 1993). Mean temperatures and salinities from data CTD collected subsurface (15-20 m) to reduce the effects of surface heating and evaporation, and from deep depths (55-60 m) were calculated in accordance with Ridgway & Condie (2004). For the CTD data, inshore casts were defined where water depth was ≦ 200 m and offshore casts where depth was > 200 m.

Sea surface temperature were obtained from the MODIS Terra monthly 4 km and 9 km composites data, and sea surface color (chlorophyll-a) concentrations were collected from the SeaWiFS monthly 9 km of level 3 dataset (http://oceancolor.gsfc.nasa.gov/). Analysis of satellite data was conducted using Marine Explorer version 4.65 (Environmental Simulation Laboratory Co, Ltd. Japan). Fish distribution were overlaid horizontal distribution of chlorophyll-a with the GIS software, and vertical distribution of temperature and salinity by CTD were calculated using the kriging interpolator. These data were used to determine oceanographic habitat use and environmental features. The relationship between sea surface temperature and chlorophyll-a abundance on each 9 km resolution data for the period January and February for three years was also investigated to inform the habitat preferences of the SBT.

RESULTS

Station recovery and detections

The experimental period was 102, 160, 177 days for the three years, respectively. A total of 60 (86 %), 58 (83 %) and 62 (89 %) stations were retrieved each year (Table 1), and represent sufficient sites to determine habitat preference. A total of 290 (79, 81, 84 each year) SBT tagged over the three years were released at both inshore and mid-shelf in SWA in early December and early January. Tagged SBT were similar in size each year and ranged in size from 41-64 (51.8 ± 6.2), 43-73 (49.4 ± 6.4) and 44-93 (57.3 ± 5.8) cm FL, respectively. The total number of tagged SBT detected at the stations was 55 (70 %) in 2004/05, 68 (84 %) in 2005/06 and 62 (73 %) in 2006/07. There was no significant difference between the size of the tagged fish and detected fish, or the types of tag (Hobday 2003, Hobday et al. 2005).

Spatial usage of SWA by SBT

Detections were obtained from December to March in 2004/05, and from December to May in 2005/06 and 2006/07 (Fig. 2). The high use areas were defined by the percent of fish that were detected. In 2004/05, the lumps had a high and consistent SBT usage from December to March. In 2006/07, the fish location was mainly around lumps from December to February then shifted to the eastern area (Line 3) from March to May. In April and May, no fish remained at the lumps. In all three years, larger SBT were found around the lumps during summer (December-February). However, SBT were detected more at the lumps than at the inshore receivers on each line (Fig. 4). In 2005/06, the high use area shifted from west to east on the continental shelf over the period of monitoring. The high use area was to the east (Line 3) in December and west (Line 1) in January then shifted to the center (Line 2) in February. After this, tagged fish had high occurrence in the central and eastern areas of the survey region. Moreover, SBT detections were scattered the continental shelf from inshore to shelf edge during summer (Fig. 3). In contrast to 2004/05 and 2006/07, the lumps were not frequently used in 2005/06. Thus, two patterns of SBT spatial habitat were observed: a lump association was observed in 2004/05 and 2006/07, and wide spread continental shelf distribution in 2005/06 during summer (December-February).

Interannual difference in water masses

Temperature and salinity profile of the waters within the survey area presented the T-S diagrams for each year (Fig. 5). Inshore values for three years varied little and were usually found to occupy a range of 3.7 ^{o}C and 0.39 psu in 2005, 3.1 ^{o}C and 0.39 psu in 2006, 2.3 ^{o}C and 0.28 psu in 2007 between subsurface and deep depth, except for the bottom values of two deep stations in 2007. These inshore waters were within the sub-tropical range (i. e. T: 18-21 ^{o}C, S: 35.5-36.0 psu). Figure 6 shows vertical distributions of water temperature and salinity at the center line of survey region (see Fig. 1) during January-February. In 2007, there was a large influx of the SAW at the bottom depth and a thermocline was present at approximately 50 m depth. Offshore values in 2005 and 2007 were within the sub-tropical range. However, offshore water properties in 2006 were different, with a mix of both sub-tropical water and sub-Antarctic water. The sub-Antarctic intrusions were observed offshore in the vicinity of the shelf edge at both the deep and subsurface layers.

Seasonal change in temperatures during the survey period were visible in the time series data of subsurface temperatures recorded by the TDRs (Fig. 7). The inshore temperature values increased to the maximum from January to May: the maximum was 20.5 ^{o}C in 2004/05, 20.3 ^{o}C in 2005/06, and 20.5 ^{o}C in 2006/07. The time of maximum temperature varied between early February in 2005, the end of April in 2006 and the end of February in 2007. In 2006, the rise of water temperatures over the summer was slower than the other years. Horizontal temperature distribution represented by isolines of 19 ^{o}C and 20 ^{o}C were on the continental shelf in January in 2005 and 2007, and the temperatures were higher 1 ^{o}C by comparison with 2006 (Fig. 8). In fact, the 2006 summer sea surface temperature anomaly was the coldest for 25 years (Fig. 9), and this was associated with a La Nina event (Fig. 10). Therefore, the SAW may be well mixed from deep to subsurface layer in this year.

Sub-Antarctic water in relation to chlorophyll-a

Figure. 11 show the relationship between satellite-based sea surface temperature and chlorophyll-a concentration during January-February. In 2005 and 2007, high chlorophyll-a values were observed together with high temperature values when the subsurface SAW was absent. In 2006, the SAW was present in the subsurface layer, and the correlation between SST and chlorophyll-a was flat in January and negatively correlated in February. Lower SST and high chlorophyll-a levels indicate strong upwelling in the GAB, and are followed by relatively high zooplankton density, then high densities of eggs and larvae of sardine and anchovy (Ward et al. 2007). Our result suggest that the influx of SAW plays an important role in raising the inshore productivity, and subsequently an abundance of zooplankton and pelagic fish for as prey for juvenile SBT.

Spatial habitat usage by SBT in relation to chlorophyll-a

Primary productivity, as represented by chlorophyll-a concentration during each summer showed that chlorophyll-a inshore areas including the lumps was higher (> 0.2 mg m^{-3}) than offshore areas (< 0.15 mg m^{-3}) in 2004/05 and 2006/07. The chlorophyll-a isolines extended in the east-west direction on the shelf, and offshore values were less variable (Fig. 3). In contrast, offshore chlorophyll values (> 0.2 mg m^{-3}) in 2005/06 were higher than inshore regions (< 0.15 mg m^{-3}). The isolines indicated patches in the area in January, and the frontal zone of high chlorophyll-a values formed a circular pattern in the vicinity of the shelf edge in February. The large number of detected SBT occurred in wide area from inshore to shelf edge in 2005/06, and vice versa in 2004/05 and 2006/07 (Fig. 3). The habitat use of juvenile SBT in all years was similar, in that the locations with a high number of detections overlapped regions with high chlorophyll-a values.

DISCUSSION

Interannual variation in SBT habitat use

We successfully tagged large number of fish (79, 81, 84) every summer, monitored continuous behavior for individuals, and found interannual variation in population distribution across the three years. Juvenile SBT habitat usage in SWA is divided into two types (i) high frequency of detection around lumps (e.g. 2004/05 and 2006/07), and (ii) occurrence over much of the continental shelf (i.e. 2005/06) (Fig. 2). This result is consistent with historical records of SBT distribution in SWA based on analysis of SBT catch data (Nishida et al. 1997). Juvenile SBT stayed continuously around lumps from December to February. The high frequency of SBT presence around lumps (ranging from 72 % to 89 % by month in 2004/05, from 50 % to 89 % by month in 2006/07) indicated that they spent more time within the detection range (450-800 m) of each station at lumps than in other areas. This emphasizes the importance of these regional topographic features for juvenile SBT over summer in some years. On the other hand, infrequent presence at lumps in 2005/06 (ranging from 0 % to 41 % by month) and widespread occurrence of juvenile SBT across the continental shelf (Fig. 2), suggest that lumps do not attract juveniles SBT every year.

Interannual variation in water masses

Cold temperature and low salinity were observed at offshore regions in 2006 and at inshore regions in 2007 which indicate a mix of sub-tropical water and sub-Antarctic water, although most other waters spanned the characteristics of sub-tropical water (Fig. 5). The Leeuwin Current water mass is absent at this time every year. These results agree with previous studies for water mass characteristics during summer in SWA

(Rochford 1986, Cresswell & Peterson 1993). Fig. 6 shows vertical distributions of water temperature and salinity for inshore to offshore stations. The SAW (< 18^{o}C, < 35.5psu) remain offshore and confined to the bottom layer (>80 m depth) in 2005. In 2006, the water presented subsurface layer around shelf edge. In 2007, a thermocline was present at 50 m depth and the sub-Antarctic water formed the bottom layer on the continental shelf. Thus, comparison of the vertical structures during January-February showed they differed every summer. The sub-Antarctic water was absent from the subsurface layer in 2006, in common with both in 2005 and 2007. Thus, cool waters were associated with high chlorophyll-a concentrations only in 2006, when the sub-Antarctic water was present in the subsurface layer (Fig. 11).

Habitat usage in relation to oceanography

Ward et al. (2006) showed that levels of primary, secondary and fish production in the GAB increased due to the coastal upwelling cold waters, with prey for juvenile SBT such as sardine and anchovy larvae being abundant. It is known that easterly wind facilitate coastal upwelling and Ekman Drift during summer and autumn in the GAB. This vertical temperature structure appears to be similar to our results in 2007 in that cold waters remained in the bottom layer on the shelf in SWA (Fig. 6). However, surface water temperatures in inshore areas were not cooler than the surrounding waters (Fig. 8). This implies that the high detection rate of SBT on the inshore lumps in 2005 and 2007 may not be linked to increased productivity in these areas due to upwelling. Generally, relatively high production occurs in inshore waters of SWA where pelagic schooling fish species such as pilchard (Fletcher et al. 1994). Fig. 3 also showed that wide areas of the inshore region had higher chlorophyll-a concentrations than offshore regions in 2005 and 2007. As a result, the inshore lumps were more attractive to SBT. Juvenile SBT spent most time around lumps when the sub-Antarctic water was absent from the sub-surface layer in summer. In other words, juveniles SBT tended to concentrate around topographic features with relatively high prey density when there was low productivity on the edge of the continental shelf.

In 2005/06, cool sub-Antarctic water was observed in the offshore subsurface layer which also had higher chlorophyll-a concentrations than inshore and lumps areas (Fig. 6), and chlorophyll-a fronts were present along the shelf edge in February (Fig. 3). In SWA, a cyclonic eddy associated with the sub-Antarctic water often forms close to the shelf edge from February to April (Cresswell & Griffin 2004). In eastern Tasmania, Young et al. (1996) found that the high biomass of zooplankton on the shelf is the result of increased nutrients derived from a mixture of sub-Antarctic water and upwelling. Thus, chlorophyll-a fronts in the vicinity of the shelf edge may be evidence of upwelling and increased productivity, which may spill over to the shelf. The high zooplankton biomass indicated that the physical and biological conditions had been sufficiently persistent for a localized food chain to develop. In such years, wide areas of the continental shelf may be important habitats for SBT juveniles during summer. Previous work during summers between 1998-2000 on the diet of 1-year old SBT in SWA concluded that juveniles were opportunistic feeders (Kemps et al. 2003). The diet of 1-year old fish consisted largely of teleosts (> 95%) which were mostly pelagic species (e.g. sardine (*Sardinops sagax*), anchovy (*Engraulis australis*)) and meso-pelagic species (e.g. silver trevally (*Pseudoccaranx dentex*), jack mackerel (*Trachurus declivis*)), with some interannual variation. The dominat region of habitat use by juvenile SBT in all years coincided with the each high chlorophyll-a areas. Our results suggested that temporally varying environmental characters such as the presence of nutrient rich sub-Antarctic water may have a stronger influence on SBT distribution in 2005/06 than did the topographic features.

These interannual habitat differences and water mass presence may be related to the El Nino-Southern Oscillation phenomena, as has been shown in other regions (Kitagawa et al. 2006). La Nina conditions occurred during the summer of 2005/06, while the summer seasons of 2004/05 and 2006/07 showed normal meterological patterns in SWA (Fig. 10). In fact, 2005/06 was the coldest year in terms of water temperature anomaly in SWA during summer: sea surface temperatures in SWA during summer were the coldest recorded in 25 years (Fig. 9). Supporting this, was our sub-surface TDR data which indicated that temperatures warmed slowed to the maximum of ~20.5 ^{o}C by the end of April in 2006, in comparison to 2005 and 2007 where the same temperature was reached in early February (Fig. 7). In 2006, offshore temperature and salinity may have been influenced by the intrusion of cold, low salinity sub-Antarctic water. Therefore, in 2005/06 when sub-Antarctic water was present in SWA, tagged SBT were showed a wide distribution; but in 2004/05 and 2006/07 when sub-Antarctic water was absent from SWA, tagged SBT occurred more frequently at lumps. This analysis shows that variation in SBT may be related to water mass distribution, which in turn influence productivity and the development of forage at either inshore or offshore locations

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REFERENCES

Comeau LA, Campana SE and Castonguay M (2002) Automated monitoring of a large-scale cod (*Gadus morhua*) migration in the open sea. Can J Fish Aquat Sci 59: 1845-1850

Cresswell GR, Griffin DA (2004) The Leeuwin Current, eddies and sub-Antarctic waters off south-western Australia. Mar Freshw Res 55: 267-276

Cresswell GR, Peterson JL (1993) The LC south of Western Australia. Aust J Mar Freshw Res 44: 285-303

Farley JH, Davis TLO (1998) Reproductive dynamics of southern bluefin tuna, *Thunnus macccoyii*. Fish Bull 96: 223-236

Fletcher WJ, Tregonning RJ, Sant GJ (1994) Interseasonal variation in the transport of pilchard eggs and larvae off southern Western Australia. Mar Ecol Prog Ser 111: 209-224

Fonteneau A (1991) Seamounts and tuna in the tropical Atlantic. Aquat Living Resour 4: 13-25

Godfrey JS, Ridgway KR (1985) The large-scale environment of the poleward-flowing LC, Western Australia: Longshore steric height gradients, wind stresses and geostrophic flow. J Phys Oceanogr 15: 481-495

Heupel MR, Semmens JM and Hobday AJ (2006) Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. Marine and Freshwater Research 57(1): 1-13.

Hobday AJ (2002) Acoustic monitoring of SBT within the GAB; exchange rates and residence times at topographic features (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/02/03). CSIRO Marine Research, Hobart, Australia.

Hobday AJ (2003) Nearshore migration of juvenile Southern Bluefin Tuna in Southern Western Australia. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS 03/15). CSIRO Marine Research, Hobart, Australia

Hobday AJ and Kawabe R (2004) Movements of juvenile southern bluefin tuna in southern Western Australia. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/04/09). National Research Institute of Fisheries Science in Yokohama

Hobday AJ, Kawabe R, Takao Y, Miyashita K (2005) Movements of juvenile southern bluefin tuna in southern Western Australia: lines and hotspots. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS 05/13). CSIRO Marine Research, Hobart, Australia

Hobday AJ, Kawabe R, Takao Y, Miyashita K, Itoh T (in press) Correction factors derived from acoustic tag data for a juvenile southern bluefin tuna abundance index in southern Western Australia. In J. Nielsen (ed). Electronic Tagging and Tracking in Marine Fisheries II. Reviews: Methods and Technologies in Fish Biology and Fisheries.

Itoh T, Tsuji S (1996) Age and growth of juvenile southern bluefin tuna *Thunnus maccoyii* based on otolith microstructure. Fish Sci 62: 2, 892-896

Itoh T and Tsuji S (2002) Comparison of the results during 1995-2002 in the acoustic survey. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS02/05). CSIRO Marine Research, Hobart, Australia.

Itoh T, Tsuji S (2004) Review of acoustic monitoring survey – analyses of data for eight years. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No.

RMWS 04/03). CSIRO Marine Research, Hobart, Australia

Itoh T (2005) Acoustic Index of age one southern bluefin tuna obtained from the 2004/2005 survey. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS05/04). CSIRO Marine Research, Hobart, Australia.

Kawabe R, Hobday A, Takao Y and Miyashita K (2003) Horizontal movements of juvenile SBT and implication for the design of Sonar survey in WA (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS/03/16). CSIRO Marine Research, Hobart, Australia.

Kemps HA, Totterdell J, Gill HS, Hutchins B, Tsuji S (2003) The diet and feeding ecology of migrating one-year old southern bluefin tuna (*Thunnus maccoyii*) off southern Western Australia (1997-2003). (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS 03/09). CSIRO Marine Research, Hobart, Australia

Kitagawa T, Sartimbul A, Nakata H, Kimura S, Yamada H, Nitta A (2006) The effect of water temperature on habitat use of young Pacific bluefin tuna *thunnus orientalis* in the East China Sea. Fish Sci 72: 1166-1176

Klimley AP, Butler SB (1988) Immigration and emigration of a pelagic fish assemblage to seamounts in the Gulf of California related to water mass movements using satellite imagery. Mar Ecol Prog Ser 49: 11-20

Klimley AP and Holloway CF (1999) School fidelity and homing synchronicity of Yellowfin tuna, *Thunnus albacares*. Mar Biol 133: 307-317

Kimley AP, Jorgensen SJ, Melo AM, Beavers SC (2003) The occurrence yellowfin tuna (*Thunnus albacares*) at Espiritu Santo Seamount in the Gulf California. Fish Bull 101: 684-692

Leigh GM, Hearn WS (2000) Changes in growth of juvenile southern bluefin tuna (*Thunnus maccoyii*): an analysis of length-frequency data from the Australian fishery. Aust J Mar Freshw Res 51: 143-154

Nishida T, Lyne V, Scott R, Itoh K (1997) Preliminary spatial analyses on juvenile southern bluefin tuna (*Thunnus maccoyii*) in the acoustic survey area off Esperance in West Australia. (Southern Bluefin Tuna Recruitment Monitoring Workshop Report No. RMWS 97/23). CSIRO Marine Research, Hobart, Australia

Ridgway KR, Condie SA (2004) The 5500-km-long boundary flow off western and southern Australia. J Geophys Res 109(C4): C04017

Rochford DJ (1986) Seasonal changes in the distribution of Leeuwin Current waters off Southern Australia. Aust J Mar Freshw Res 37: 1-10

Ward TM, Mcleay LJ, Dimmlich WF, Rogers PJ, Mcclatchie S, Matthews R, Manpf J, Ruth PDV (2006) Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (*Sardinops sagax*), anchovy (*Engraulis australis*) and southern bluefin tuna (*Thunnus maccoyii*) in the GAB. Fish Oceanogr 15: 3, 191-207

Welch DW and Eveson JP (1999) An assessment of light-based geoposition estimates from archival tags. Can J Fish Aquat Sci 56: 1317-1327

Willis J, Hobday AJ (2007) Influence of upwelling on movement of southern bluefin tuna (*Thunnus maccoyii*) in the Great Australian Bight. Mar Freshw Res 58: 699-708

Worm B, Lotze HK, Myers RA (2003) Predator diversity hotspots in the blue ocean. PNAS 100: 17, 9884-9888

Young JW, Bradford RW, Lamb TD, Lyne VD (1996) Biomass of zooplankton and micronekton in the southern bluefin tuna fishing grounds off eastern Tasmania, Australia. Mar Ecol Prog Ser 138: 1-14

Table 1. Recovery information of acoustic receivers by location for the three years (2004/05, 2005/06, 2006/07).

Location	No. of deployed stations	2004/05 No. of recovered Receiver	TDR	2005/06 Receiver	TDR	2006/07 Reciever	TDR
Line 1	20	19	4	16	2	19	5
Line 2	20	15	4	18	2	19	4
Line 3	21	18	5	15	3	16	5
Lumps	9	8	2	9	3	8	1
Total	70	60 (86%)	15 (83%)	58 (83%)	10 (71%)	62 (89%)	15 (83%)

Table 2. Summary of the number of tagged juvenile southern bluefin tuna in three years (2004/05, 2005/06, 2006/07).

Tagging date	No. of	FL cm	Mean tagging location		No. of
	tagged fish	(Mean ± SD)	Latitude	Longitude	detected (%)
7-Dec-2004	22	56.0 ± 6.0	-34.58	118.99	86
3-Jan-2005	1	45.0	-35.20	117.95	0
4-Jan-2005	7	46.6 ± 5.6	-35.18	118.04	14
5-Jan-2005	15	53.4 ± 6.6	-34.76	118.70	73
6-Jan-2005	10	50.0 ± 5.2	-34.66	118.83	80
7-Jan-2005	6	54.2 ± 5.4	-34.65	118.82	83
8-Jan-2005	13	47.8 ± 2.0	-34.92	119.08	54
9-Jan-2005	5	48.6 ± 1.3	-34.49	119.42	80
4-Dec-2005	1	45.0	-34.54	119.26	100
5-Dec-2005	1	45.0	-34.68	118.75	100
7-Dec-2005	1	67.0	-34.69	118.76	100
8-Dec-2005	5	44.4 ± 1.1	-35.19	118.00	80
6-Jan-2006	21	46.0 ± 1.0	-34.85	119.04	86
7-Jan-2006	2	45.5 ± 0.7	-34.93	118.72	50
8-Jan-2006	13	46.0 ± 1.2	-34.74	118.83	69
9-Jan-2006	7	62.3 ± 10.8	-34.63	118.88	86
10-Jan-2006	30	51.2 ± 3.7	-34.65	118.84	90
4-Dec-2006	17	57.6 ± 2.7	-34.57	118.97	100
5-Dec-2005	15	58.1 ± 4.2	-34.57	118.97	93
7-Dec-2006	2	62.0 ± 8.5	-34.66	118.84	100
8-Dec-2006	1	49.0	-35.17	117.94	0
9-Dec-2006	18	53.1 ± 3.4	-35.11	116.60	39
10-Dec-2006	1	54.0	-34.52	115.29	0
8-Jan-2007	7	57.9 ± 1.8	-34.94	116.08	29
9-Jan-2007	7	58.6 ± 15.7	-35.20	117.97	57
11-Jan-2007	1	63.0	-34.57	118.97	100
12-Jan-2007	15	59.9 ± 2.3	-34.57	118.98	93

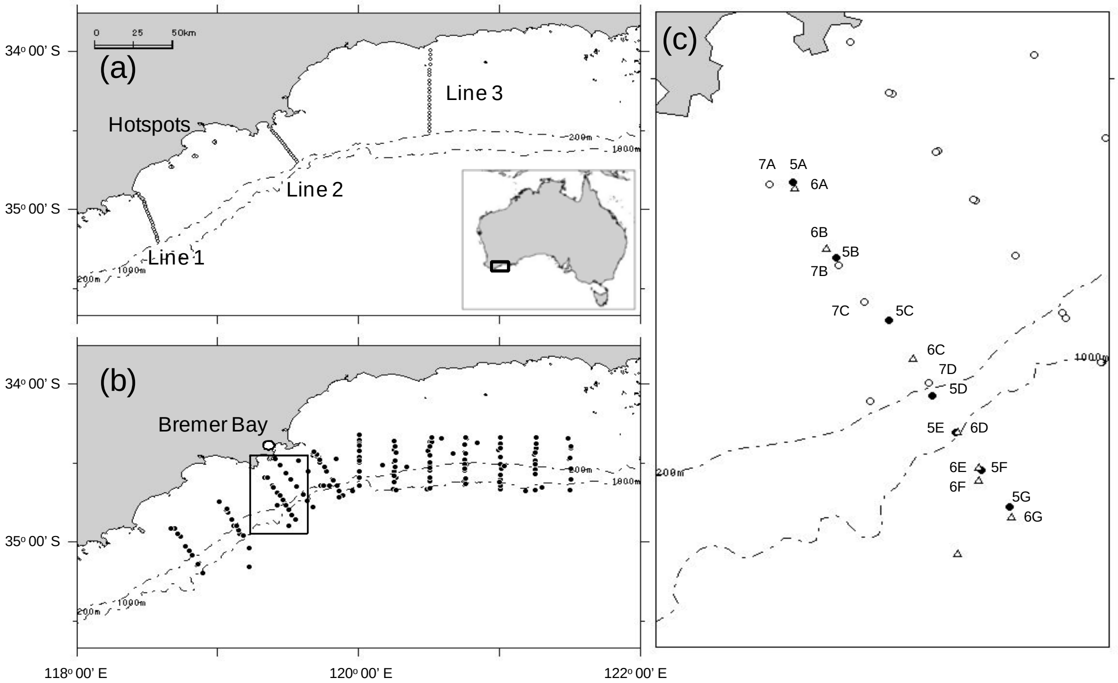


Figure 1. (a) Survey area in southern Western Australia. The map shows the location of acoustic receivers (represented by white circles). (b) Distribution of CTD observations conducted for three summers (2005-2007) from January to February. (c) Sections of the inner side of black line on (b). CTD observations measured along cross shelf lines 5A-5G (black circles in 2005), 6A-6G (triangle in 2006), 7A-7D (white circles in 2007).

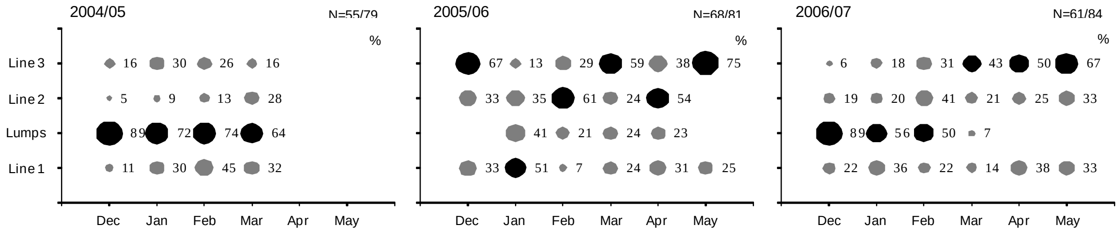


Figure 2. Detection rate in each location, indicated by appearance of southern bluefin tuna (SBT) in proportion to the number of resident SBT in a month. Black circles show maximum values for the month.

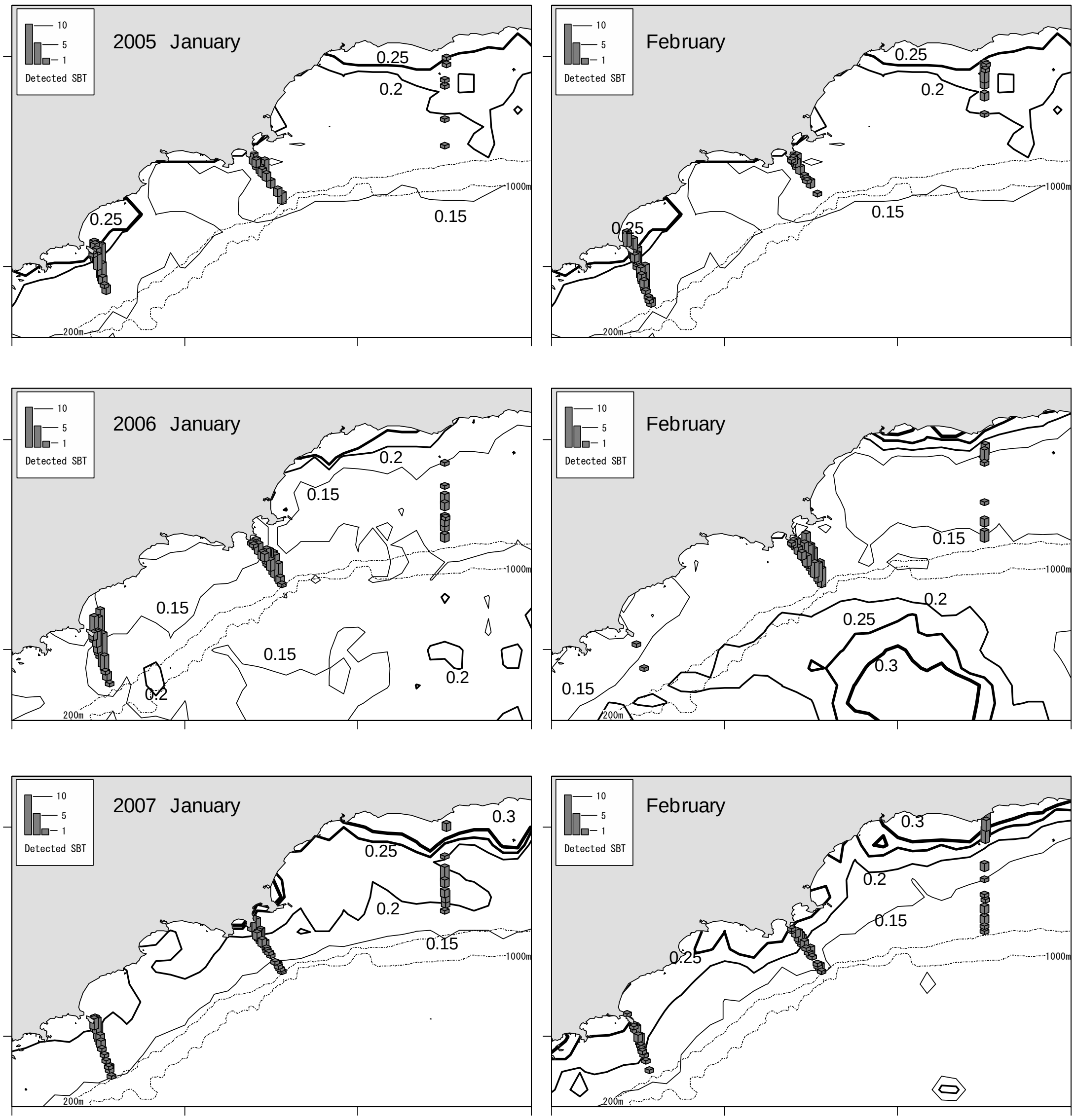


Figure 3. Yearly distribution of tagged southern bluefin tuna in relation to chlorophyll concentration in southern Western Australia from January to February in 2005, 2006, 2007. The bars shows the number of detected fish at each acoustic station.

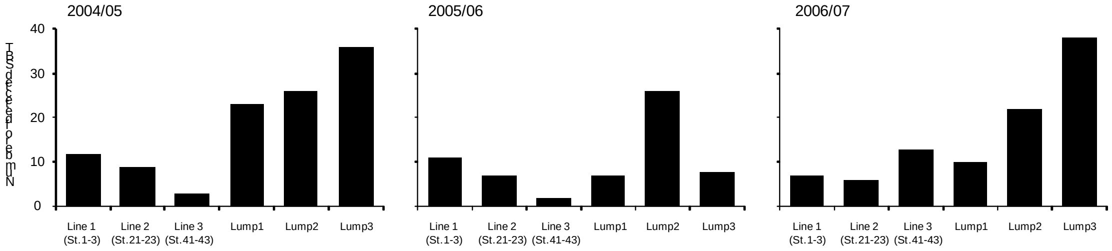


Figure 4. Total southern bluefin tuna tags detected at each inshore station during the survey period.

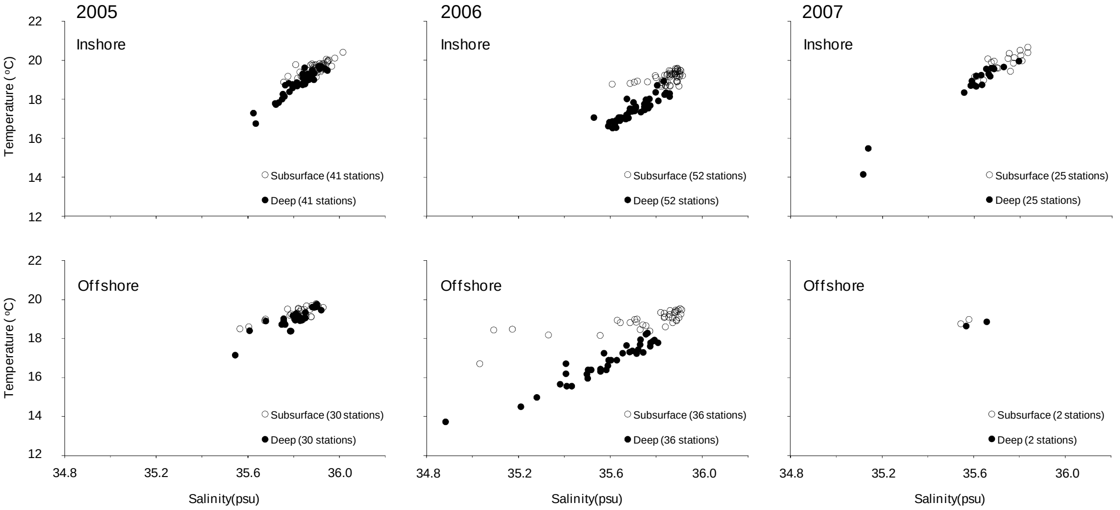


Figure 5. Temperature-salinity plots for all CTD stations (2005-2007) inshore (≦200m: above panel) and offshore (> 200m: below panel) in January and February represented by subsurface (from 15 to 20m depth) and deep (from 55 to 60m depth).

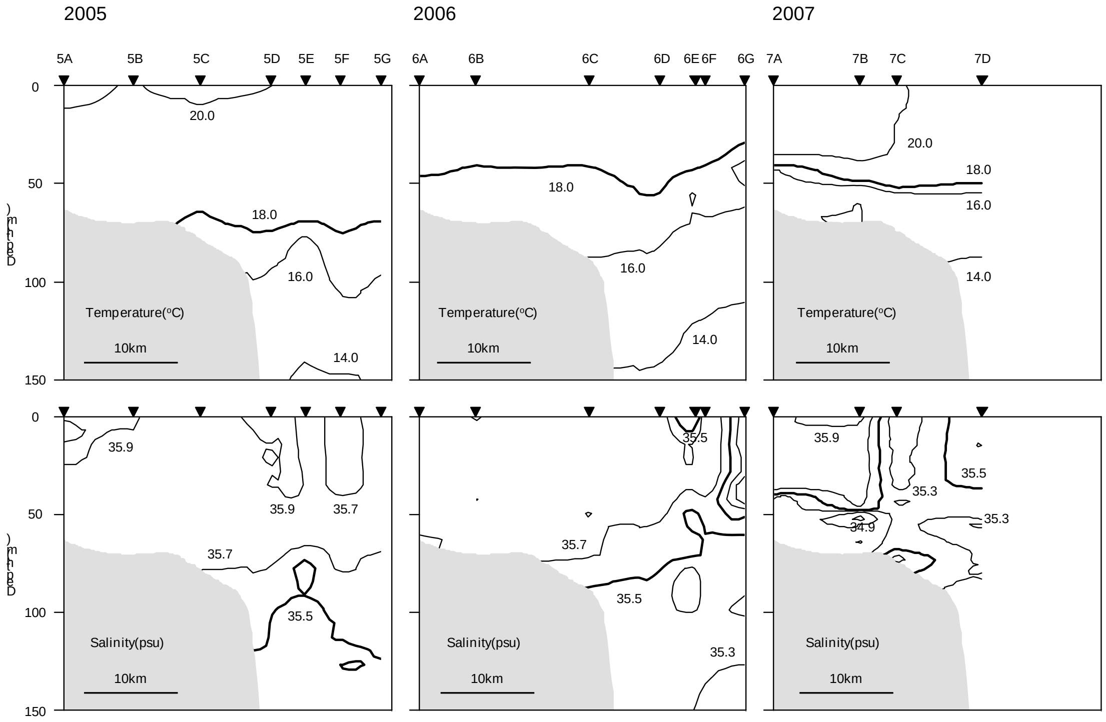


Figure 6. Vertical distributions of water temperature and salinity from coast towards offshore in January and February over 2005-2007. Ticks on the top of each figure represent the CTD stations A-G (see Fig. 1).

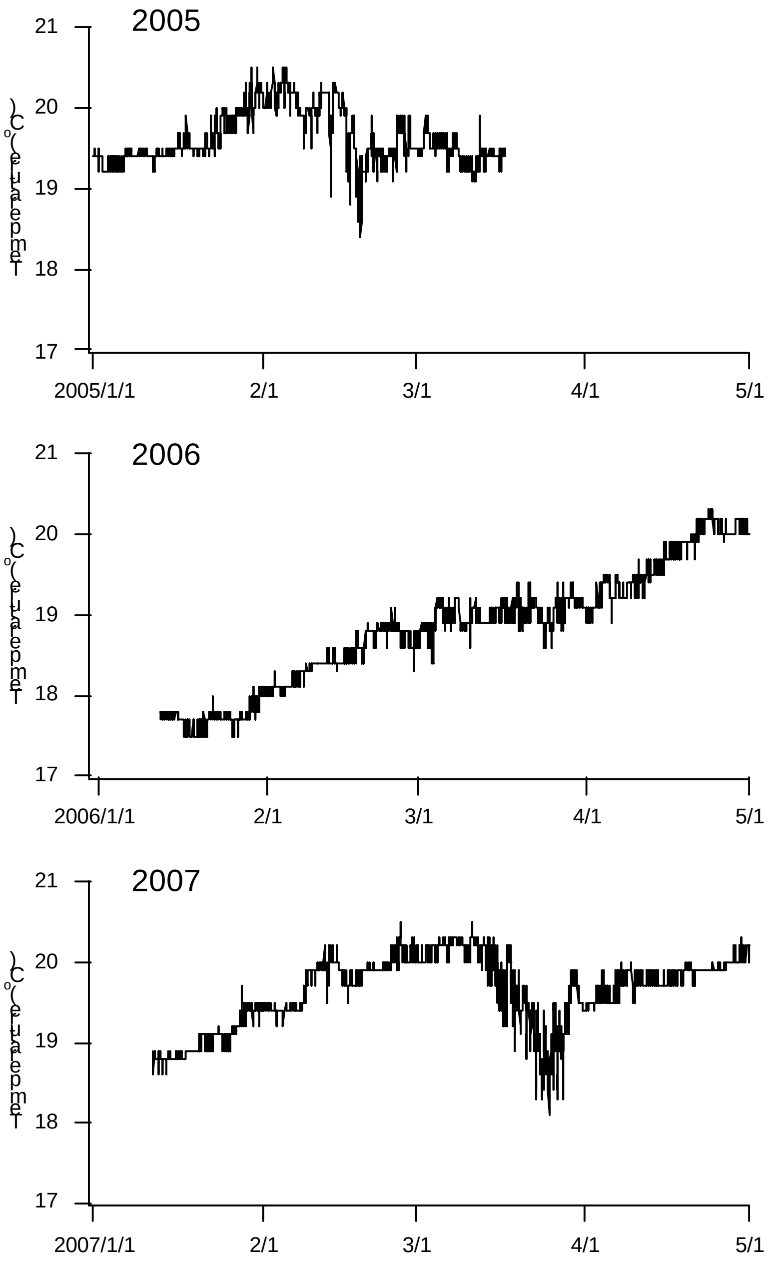
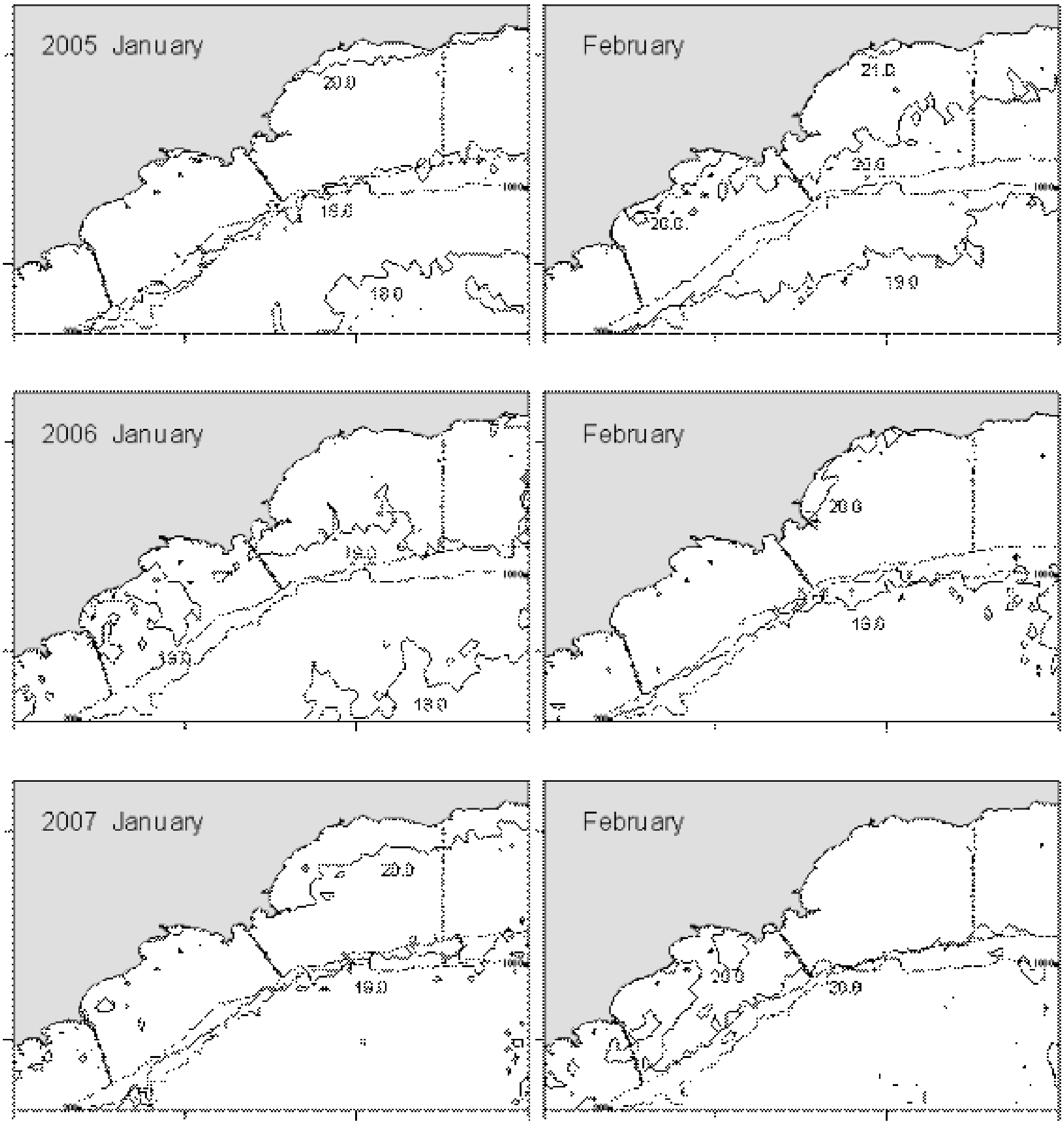


Figure 7. Pattern in subsurface temperature at coastal stations of Line 1 as recorded by subsurface TDRs for three years.



2005 January

February

2006 January

February

2007 January

February

Figure 8. Temperature isotherms (^{o}C) during January-February for 2005, 2006, 2007.

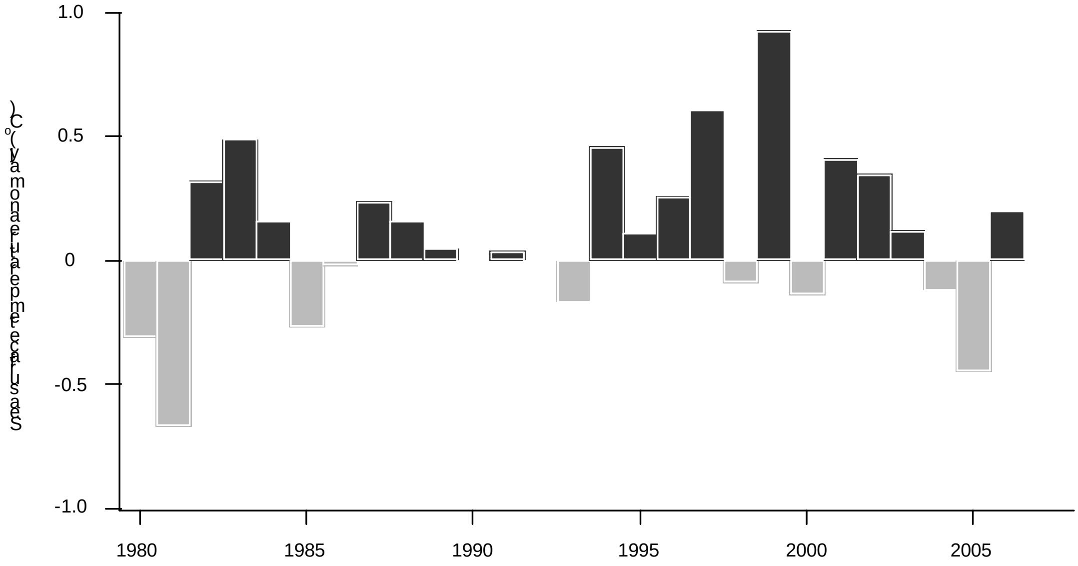


Figure 9. Time series data of sea surface temperature during summer from 1980 to 2007 in the southwest region of Australia.

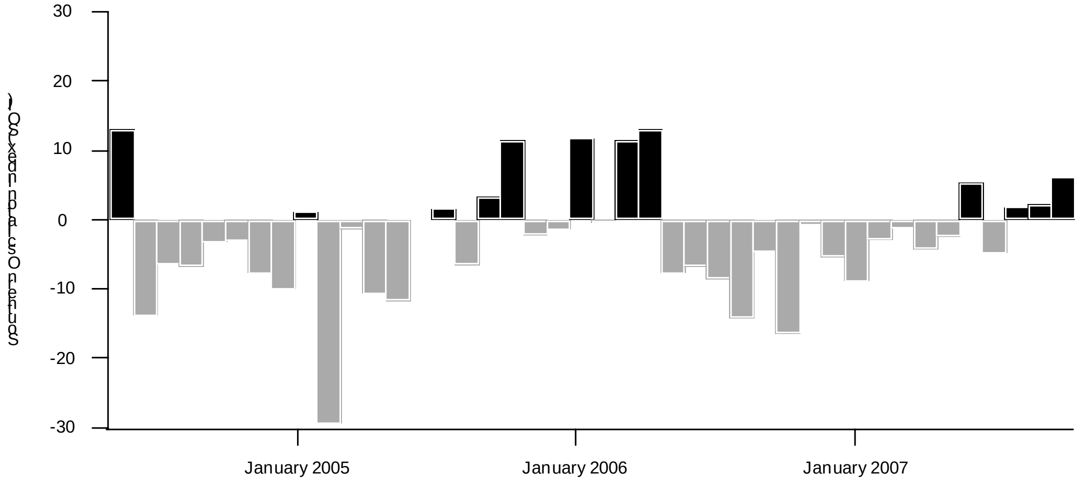


Figure 10. Southern Oscillation Index (SOI) from 2004 to 2007.

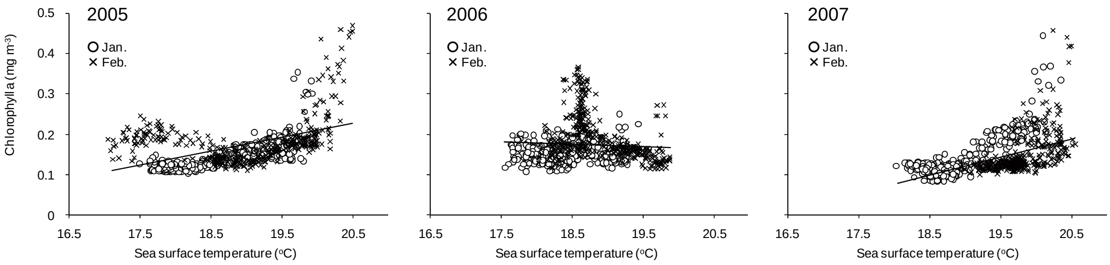


Figure 11. Relationship between sea surface water temperature and sea surface chlorophyll concentration for three years in January and February. The data collected SeaWIFS in 9×9 km grid in SWA (latitude range: 34.0-36.0^{o}S, longitude range: 118.5-120.5^{o}E).