

**Ecological importance of small pelagic fishes in
the Flinders Current System**

Final Report

to

Department of the Environment, Water, Heritage and the Arts

by

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Executive Summary

1. This report builds on information collated in the '*South-West Marine Region (SWMR): Key Species Report*' and summarises available information on the ecological roles of small pelagic fishes in waters off South Australia (SA).
2. To assess the ecological importance of small pelagic fishes in the ecosystems off SA we: describe the physical and biological characteristics of SA's marine ecosystems; summarise available information on the distribution and abundance of pelagic fishes; present preliminary dietary and foraging data for key predatory species; and provide preliminary results of a trophodynamic modelling study.
3. Three distinct pelagic ecosystems occur within SA: the gulfs, Spencer Gulf and Gulf St Vincent; the Flinders Current System, which comprises shelf waters of the Bonney Coast and eastern Great Australian Bight (GAB); and the western GAB. The two gulfs are managed by the SA Government separately from the SWMR. Relatively little information is available on the small pelagic fishes of the western GAB. Hence, this report focuses mainly on the small pelagic fishes and large marine predators of the Flinders Current System.
4. The dominant oceanographic feature of the Flinders Current System is the coastal upwelling that occurs during summer and autumn off the Bonney Coast and in the eastern GAB. Eleven species of small pelagic fishes belonging six families (Clupeidae, Engraulidae, Scombridae, Carangidae, Emmelichthyidae and Scomberesocidae) occur in the region.
5. Significant biological and ecological information has been published for sardine (pilchard, *Sardinops sagax*), Australian anchovy (*Engraulis australis*), sandy sprat (*Hyperlophus vittatus*), blue sprat (*Spratelloides spp.*) and blue mackerel (*Scomber australasicus*).
6. The presence of large populations of sardine and anchovy in SA waters has been linked to the enhancement of regional productivity by seasonal upwelling of cool nutrient rich water from the Flinders Current.
7. The SA Sardine Fishery (SASF) is Australia's largest fishery by weight. The Total Allowable Catch for 2008 is 30,000 t. This is approximately 11.4% of the estimate of spawning biomass for 2007 of 263,747 t.
8. The SASF has grown rapidly and sustainably despite mass mortality events in 1995 and 1998 each killed over 70% of the adult stock. After each sardine mortality event the distribution and abundance of anchovy expanded to include shelf waters where sardines usually dominate. The abundance of anchovy in shelf waters decreased as the sardine population recovered from the two events.

9. The abundance of blue mackerel in the eastern GAB appears to vary between years. Preliminary surveys suggest that large quantities of blue mackerel occur in the western GAB during summer. The high abundance of blue mackerel (and southern bluefin tuna, SBT) in the western GAB has been linked to the warming influence of the Leeuwin Current.
10. The high productivity and the ecological significance of the Flinders Current System are highlighted by the presence of globally significant populations of predatory fishes, marine mammals and seabirds in the region. Blue whales, short-tailed shearwaters and southern bluefin tuna make conspicuous migrations into the SA waters during each upwelling season. Other species, including the New Zealand fur seal, form large colonies in and near the upwelling centres along the Bonney Coast and in the eastern Great Australian Bight. Many of these predatory species are listed internationally as critically endangered (e.g. SBT), threatened (pelagic sharks), and/or protected (seabirds and marine mammals).
11. The biology, diet and foraging ecology of predatory fishes, seabirds and marine mammals in the Flinders Current System has been studied intensively since 2001. The diets of most predatory species are comprised of small pelagic fishes, cephalopods and crustaceans.
12. A current FRDC-funded study (Project 2005/031) is explicitly examining the importance of small pelagic fishes, especially sardines, in the diets of key predators, with the goal of assessing the need to establish ecological performance indicators for the SASF. This study includes trophodynamic modelling of the Flinders Current System. The final report for this project, which will be finalised in 2008, will provide information to assist future management of the Flinders Current System.
13. Funding to support research on the small pelagic fishes and large marine predators of the Flinders Current System has predominately been provided to support the ecologically sustainable management of commercial fisheries. Some funding has also been provided to support research on Threatened, Endangered and Protected Species and the performance assessment of Marine Protected Areas in commonwealth waters. Relatively little funding has been provide for research to support regional marine planning in the SWMR.

1.0 General Introduction

The South-West Marine Region (SWMR) encompasses the area between Kangaroo Island in SA and Shark Bay in Western Australia (WA). The ‘*South-West Marine Region (SWMR): Key Species Report*’ identified small pelagic fishes as key species for the region and noted that large populations of several species occur off South Australia (SA). The present report builds on the ‘*South-West Marine Region (SWMR): Key Species Report*’ and provides detailed information on the ecological importance of small pelagic fishes in waters off SA.

Three distinct pelagic ecosystems occur off SA (Fig. 1): the gulfs, Spencer Gulf and Gulf St Vincent; the Flinders Current System, which comprises shelf waters of the Bonney Coast and eastern Great Australian Bight (GAB); and the western GAB. The two gulfs, and other inshore waters, are managed by the SA Government and are not directly relevant to the planning processes for the SWMR. Relatively little information is available on the small pelagic fishes of the western GAB. Hence, this report focuses mainly on the small pelagic fishes and large marine predators of the Flinders Current System.

A diverse suite of small pelagic fishes occurs in the pelagic ecosystems off SA. Key species include sardine (pilchard, *Sardinops sagax*), Australian anchovy (*Engraulis australis*), sandy sprat (*Hyperlophus vittatus*), blue sprat (*Spratelloides spp.*), blue (slimey) mackerel (*Scomber australasicus*), redbait (*Emmelichthys nitidus*) and saury (*Scomberesox saurus*). Over the last decade significant biological and ecological information has been collected and published on the biology and ecology of sardine (Ward et al., 2001a, 2001b, 2003, 2006a, 2007; Rogers and Ward, 2007a; Ward and Staunton Smith, 2002), Australian anchovy (Dimmlich et al., 2004; Dimmlich and Ward, 2006), sandy sprat (Rogers and Ward, 2007b), blue sprat (Rogers et al., 2003) and blue mackerel (Ward and Rogers, in press).

Important populations of large pelagic predators also occur off SA, including marine mammals, such as blue whales and New Zealand fur seals; seabirds, such as short-tailed shearwaters, crested terns and little penguins, and predatory fishes, such as southern bluefin tuna (Ward et al., 2005). Blue whales, short-tailed shearwaters and southern bluefin tuna make conspicuous migrations into the region during the upwelling season. Other species, including New Zealand fur seal, form colonies adjacent to areas of enhanced seasonal productivity, including Bonney Coast and eastern Great Australian Bight (Goldsworthy et al., 2003). All of these large pelagic predators are reliant on the presence of large quantities of small pelagic fish, crustaceans and

cephalopods, which are in turn dependent on the enhanced productivity that results from upwelling (Furness and Cooper, 1982). Since 2003, the biology and ecology of marine predators off SA has been studied intensively (Goldsworthy et al., 2003; Caines, 2005; Page et al., 2005; Einoder and Goldsworthy, 2005; Ward et al., 2005; Weibkin, 2005; Ward et al., 2006a; Roberts, 2007; Baylis, et al. in press).

This report assesses the ecological importance of small pelagic fishes in the ecosystems off SA. It mostly focuses mainly on Flinders Current System because this is ecosystem in the SWMR in which the largest populations of small pelagic fishes and large marine predators occur. The aim of this report is to assess the ecological importance of small pelagic fishes in waters off SA. To achieve this aim we:

- describe the physical and biological characteristics of SA's marine ecosystems (Section 2)
- summarise available information on the distribution and abundance of pelagic fishes (Section 3);
- present preliminary dietary and foraging data for key predatory species (Section 4;
- provide preliminary results of a trophodynamic modelling study (Section 5).

2.0 Physical and Biological characteristics of South Australia's Marine Ecosystems

2.1 The Ecosystems

Spencer Gulf and Gulf St Vincent

Spencer Gulf and Gulf St Vincent (Fig. 1) are both inverse estuaries with low to moderate wave energy and mean depths of ~20 m (Interim Marine and Coastal Regionalisation for Australia (IMCRA) Technical Group, 1998). Water temperatures to 30°C and salinities to 45 ppt are recorded in the shallow (<10 m) northern reaches of the gulfs during summer and autumn (Bruce and Short, 1990; IMCRA Technical Group, 1998). No major rivers feed into the gulfs, there is minimal nutrient enrichment and levels of primary and secondary production are relatively low. During summer and autumn, hydrographic frontal systems form at the entrances to the gulfs and in Investigator Strait that delineate gulf and shelf waters (Bruce and Short, 1990). The two gulfs are considered to be 'seasonally sub-tropical systems' in an otherwise temperate region and support several marine taxa with tropical affinities (Rogers et al., 2003).

Shelf waters of eastern GAB and the Bonney Coast

Shelf waters of the eastern GAB and the Bonney Coast have oceanographic and ecological similarities to the eastern boundary current systems off the west coasts of northern and southern Africa and North and South America (Mann and Lazier, 1996). Southern Australia has the world's only northern boundary current. The Flinders Current that flows westward along the shelf slope (Bye, 1972, 1983; Middleton and Cirano, 2002) and is analogous to the poleward undercurrents that flow over the shelf and/or shelf slope in the other ecosystems (Mann and Lazier, 1996). The Flinders Current and the regime of south-easterly winds that facilitate coastal upwelling during summer and autumn is comparable to the temporally variable longshore winds that drive surface flows offshore in the Canary, Benguela, California and Humbolt current systems (Mann and Lazier, 1996; Middleton, 2000; Middleton and Platov, 2003). Downwelling also occurs in the region and can be important for local scale ecological processes (Middleton and Bye, 2007).

Western GAB

The warm Leeuwin Current enters the western GAB (west of Head of Bight, Fig. 1) where sea surface temperatures in shelf waters can reach 23°C (IMCRA Technical Group, 1998). In conjunction with localized wind regimes this drives eastward currents of 20-30 cm.s⁻¹ (Middleton

and Bye, 2007). This warm water of tropical origin intrudes into the relatively stable GAB warm pool (McClatchie et al., 2006) and provides an ecological linkage between the tropical pelagic ecosystems in the north-west of Australia and the cooler temperate systems to the south. This is reflected in the diversity of taxa with tropical affinities that are found in the GAB (Ward et al., 2006b). Oceanographic conditions in the western GAB have been correlated with the presence of Australia's southern bluefin tuna (SBT), *Thunnus maccoyii* fishery in this region. There is also preliminary evidence that significant resources of small pelagic fish occur in this region. Exploratory surveys identified the presence of substantial numbers of blue mackerel, *Trachurus* spp. and sardine eggs in this region in 2006 (Ward and Rogers 2008).

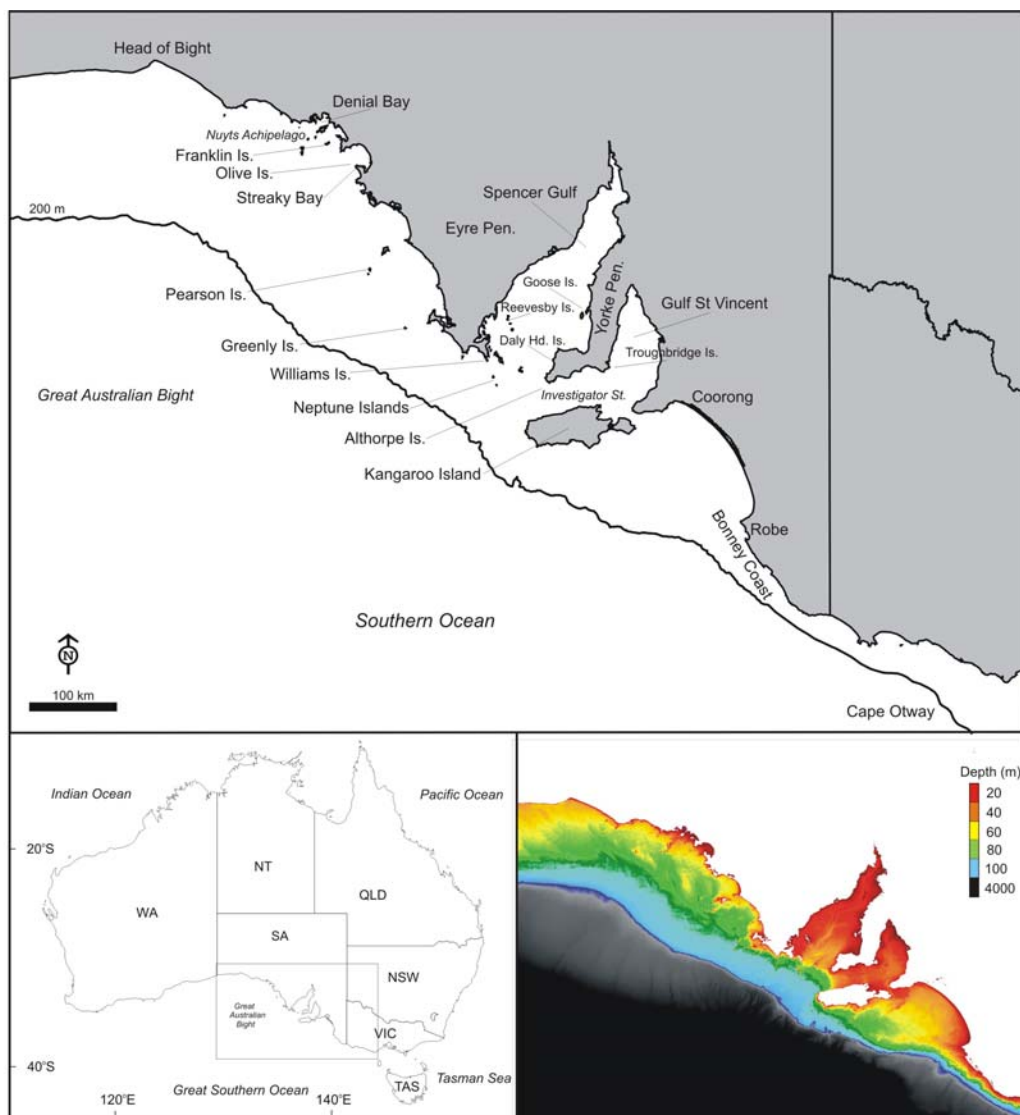


Figure 1. Locations and key regions mentioned in this report. Bathymetry sourced from GeoScience Australia.

2.2 Meteorological conditions and oceanographic features

Oceanographic conditions play an important role in shaping the faunal compositions of marine regions. Small pelagic fishes dominate and are critical ecological components of the structure and function of upwelling systems. During summer and autumn small pelagic fishes aggregate to feed and spawn in regions with water temperatures and plankton concentrations which are suitable for the survival and growth of their eggs and larvae. Summer wind patterns that drive coastal upwelling off the SA coastline, along with frontal systems that form at the mouths of the two gulfs, are the drivers for pelagic productivity in this region (Middleton and Platov, 2003).

Wind patterns and upwelling indices

South-easterly winds that are favourable for upwelling dominate shelf waters of SA during summer and autumn (Middleton, 2000). For example, upwelling favourable winds comprise over 50% of records from Neptune Island for the periods January–April and November–December in both 1999 and 2000 (Fig. 2). The seasonal trends in the upwelling index (UI) were similar in both years, with a positive UI (indicating upwelling) over the summer and negative UI (indicating downwelling) during winter (Fig. 3). The timing of the change in sign of UI differs between years, and occurred in April–May and September–October in 1999 and 2000. Intra-annual variation in UI was higher in 2000 than 1999. The highest UIs were recorded during January and December 1999.

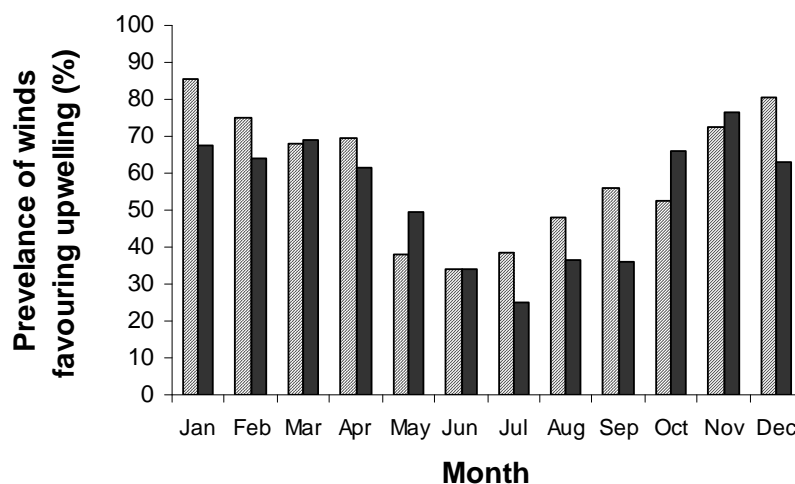


Figure 2. Proportion of 30 minute averaged wind records from Neptune Island during 1999 (shaded bars) and 2000 (solid bars) that favoured upwelling (i.e. were from directions between 45° and 225°). Data provided by the Bureau of Meteorology (Adelaide).

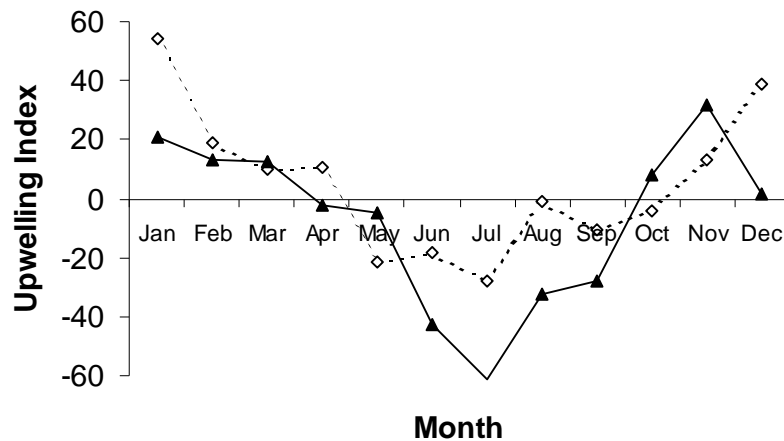


Figure 3. Mean upwelling indices for each month during 1999 (open diamonds) and 2000 (closed triangles) based on 30 minute averaged records of wind strength and direction from Neptune Island. Data provided by the Australian Bureau of Meteorology (Adelaide).

Water temperatures

Bottom water temperatures are generally lower off the Bonney Coast than in the eastern GAB (Middleton and Bye, 2007). For example, in 1999 and 2000 average monthly bottom water temperatures were generally lower at Robe than at Williams Island (Fig. 4). However, variations in mean monthly bottom water temperatures at the two locations were highly correlated ($R^2 = 0.798$). Although high UIs were also recorded during this period, and intra-annual variations in both UI and water temperatures were higher in 2000 than in 1999, mean monthly bottom temperatures were not correlated with monthly UIs at either location (Robe, $R^2 = 0.077$; Williams Island, $R^2 = 0.002$).

SSTs in shelf waters of the eastern GAB are higher offshore than inshore during both winter and summer-autumn (Fig. 5), but narrower ranges of SST are recorded during winter (~ 14.5 – 18.0°C) than summer-autumn (14.0 – 24.9°C). During winter, inshore waters are uniformly cool (~ 15 – 16°C) and SST increases gradually with distance from shore whereas during summer-autumn, patches of cool surface water (~ 15 – 17°C) occur on the Bonney Coast, along the western Eyre Peninsula and near the western tip of Kangaroo Island (Fig. 5 and 7). Offshore waters are warmer during summer-autumn (19 – 23°C) than during winter ($\sim 17^\circ\text{C}$). SSTs during summer-autumn in offshore waters during 2000 were 1 – 2°C warmer than in 1999.

During winter, the water column is isothermal with the lowest water temperatures ($\sim 15^{\circ}\text{C}$) recorded inshore. A strong thermocline is present during summer-autumn at depths of 30–60 m. The difference between surface and bottom temperatures can reach up to 7°C , and increases with water depth (Fig. 7). The thermocline is shallower inshore (~ 20 m) than offshore (~ 40 m), associated with a layer of cool ($< 15^{\circ}\text{C}$) bottom water at the offshore stations of transects 2 and 3 located along the western Eyre Peninsula and transect 4 off the western tip of Kangaroo Island (Fig. 7).

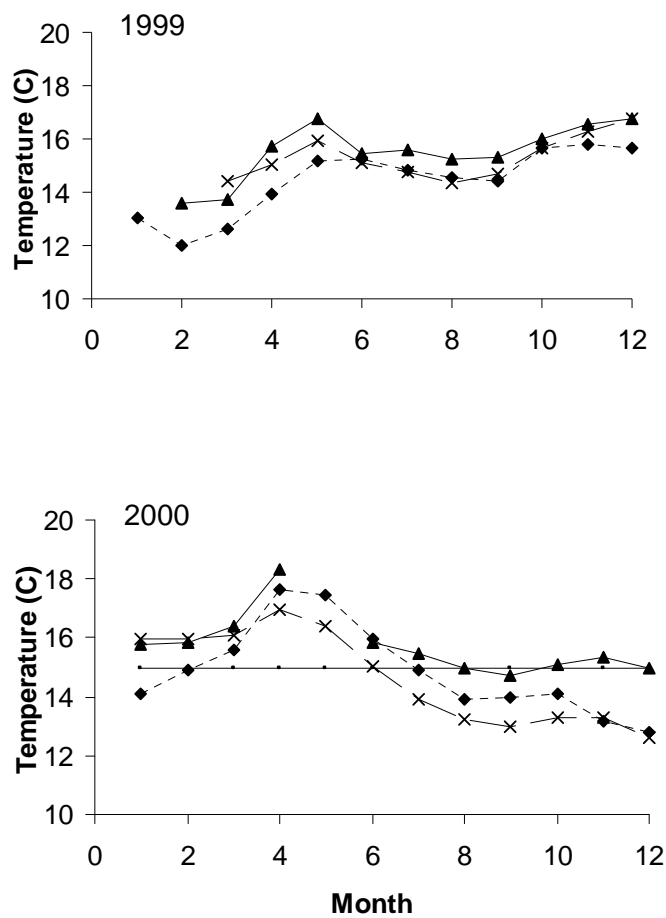


Figure 4. Average monthly bottom temperatures in 1999 and 2000 at Robe (Bonney Coast) (solid diamonds), Williams Island (GAB) (solid triangles) and Flinders Island (GAB) (cross).

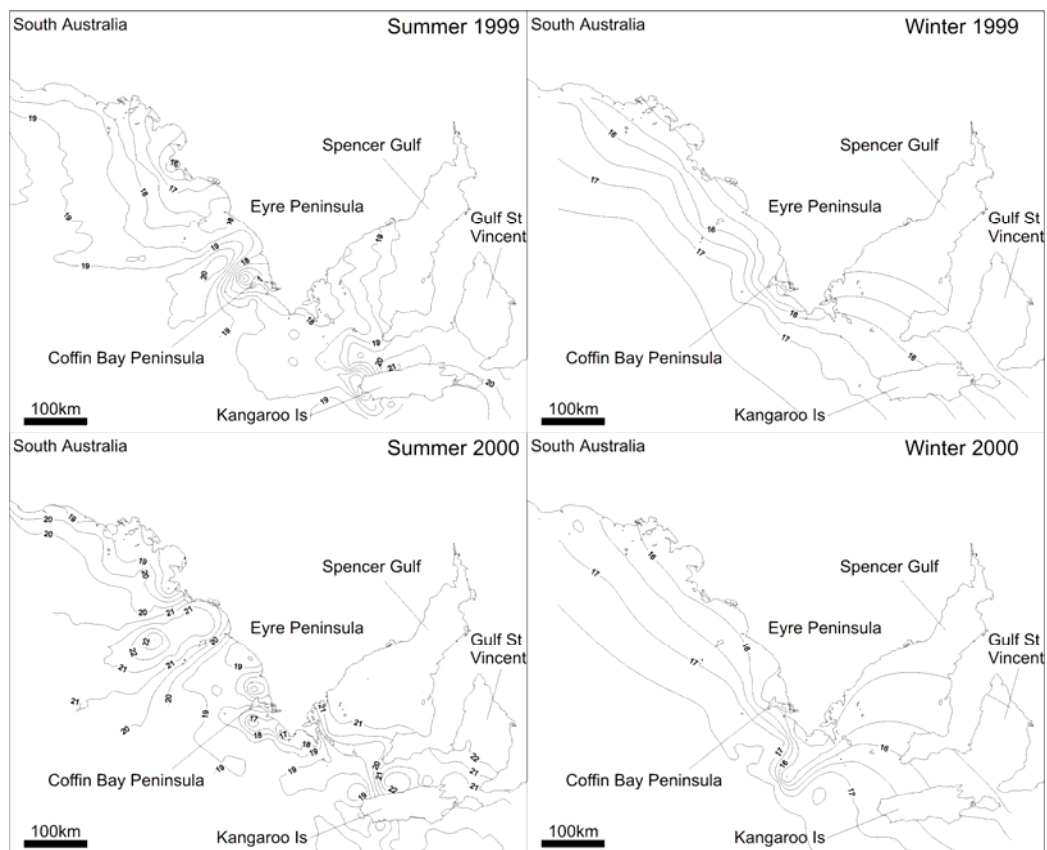


Figure 5. Contour plots of sea surface temperatures obtained from *in situ* measurements taken from the *RV Ngerin* during summer-autumn and winter in 1999 and 2000.

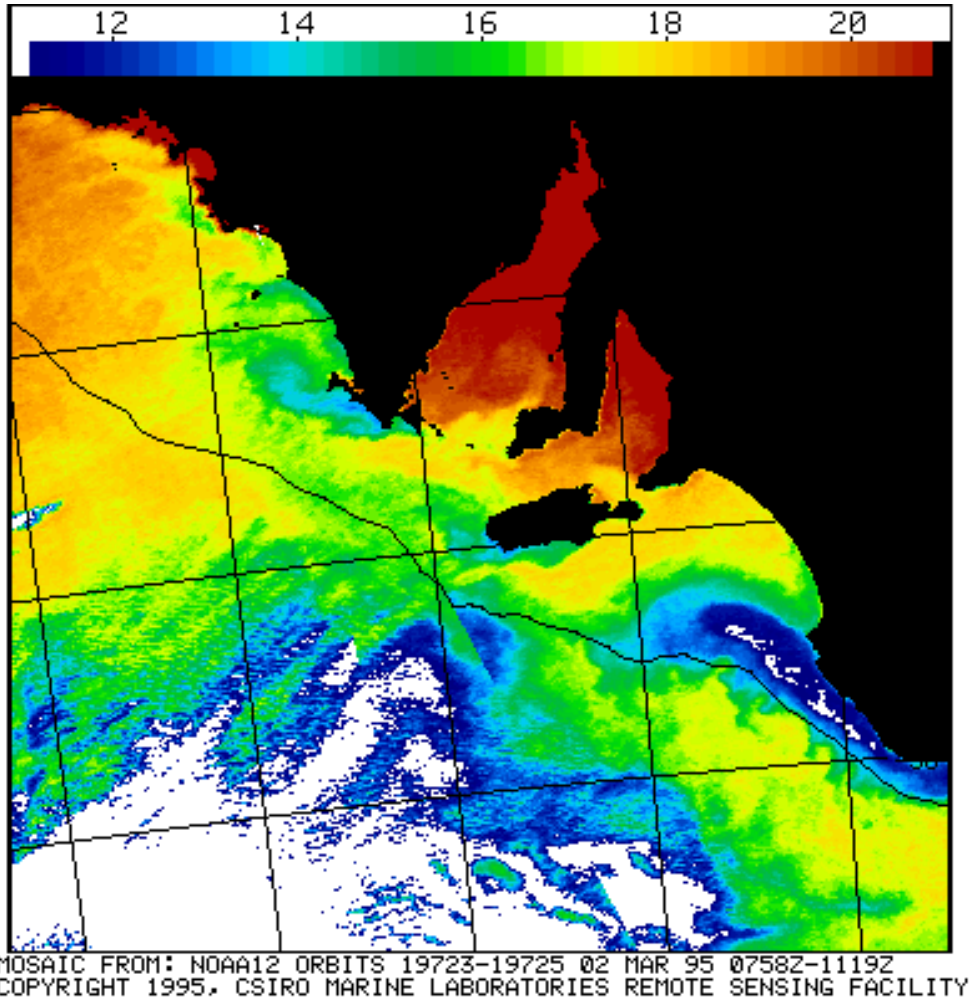


Figure 6. Sea surface temperature satellite image (AVHRR SST) during a summer-autumn upwelling event in waters off South Australia (courtesy CSIRO). Black line is 200 m contour. Blue areas near the coast indicate areas of upwelled water at the surface.

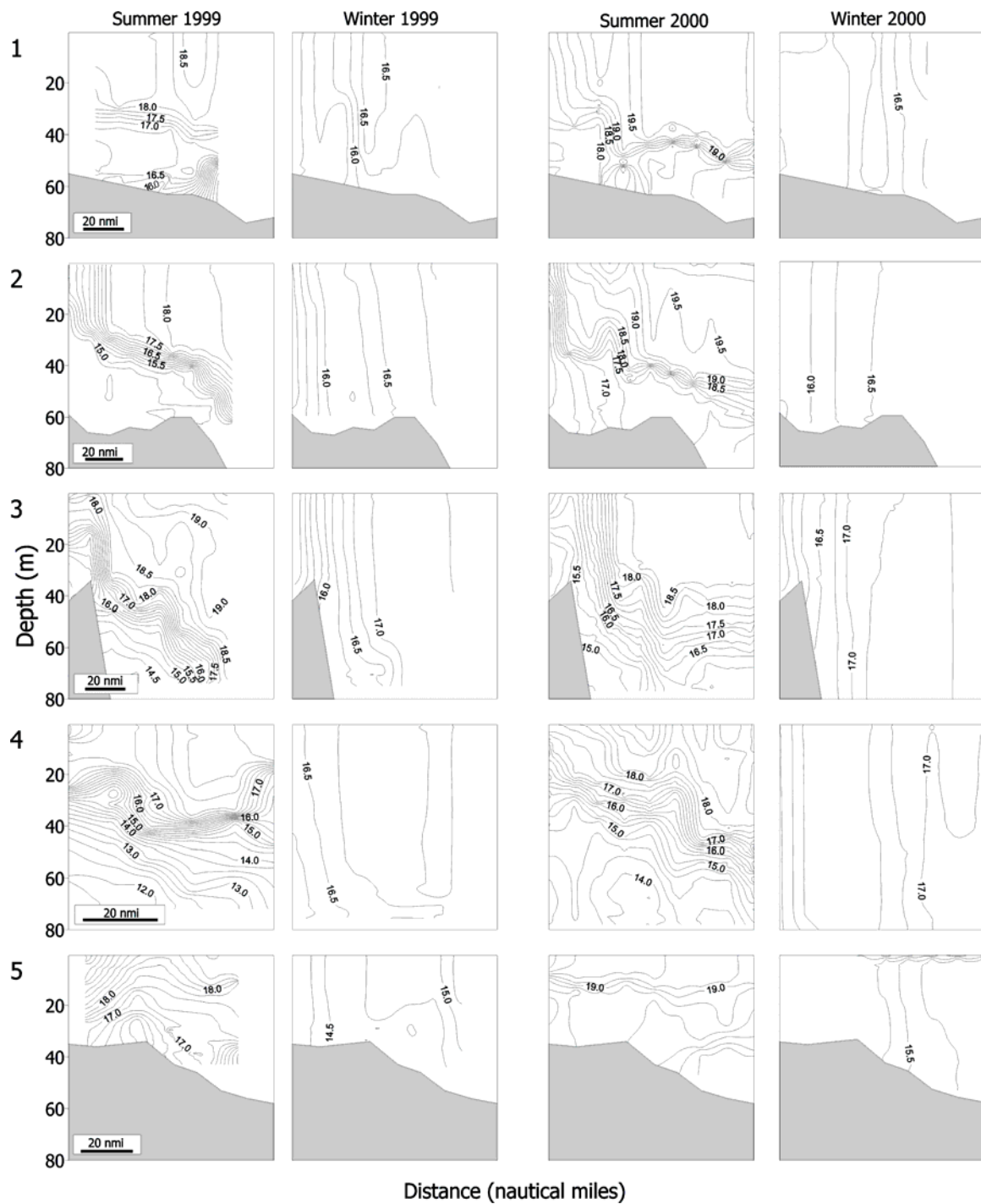


Figure 7. Cross-shelf temperature profiles at selected transects (1-5) in the GAB during summer-autumn and winter of 1999 and 2000.

2.3 Biological oceanography

Small pelagic fish feed on phytoplankton and/or on zooplankton which in turn graze phytoplankton, and hence 'repackage' energy into units that can be consumed by higher trophic levels. Therefore to understand trophic interactions within these ecosystems it is essential to first understand the spatial and seasonal dynamics of the biological oceanography of the region.

SARDI Aquatic Sciences has collected biological oceanography data (SST, salinity, surface Ch-*a* and zooplankton abundance) during annual sardine surveys between 1998 and 2007.

*Surface Chlorophyll-*a* (phytoplankton)*

Chlorophyll-*a* is a pigment found in all phytoplankton, which form a critical component of pelagic food webs. High concentrations of chlorophyll-*a* occur in the cool coastal waters south and west of the Eyre Peninsula and at the entrance of Spencer Gulf during summer-autumn (Fig. 8). In winter, chlorophyll-*a* concentrations are higher at inshore stations than those located offshore.

Relative biomass of zooplankton

During summer-autumn, sites with high levels of zooplankton biomass are located mainly in shelf waters south of the Eyre Peninsula, whereas sites with relatively high zooplankton density were sparsely scattered through the study area during winter (Fig. 10). Levels of zooplankton biomass are higher during summer-autumn than during winter.

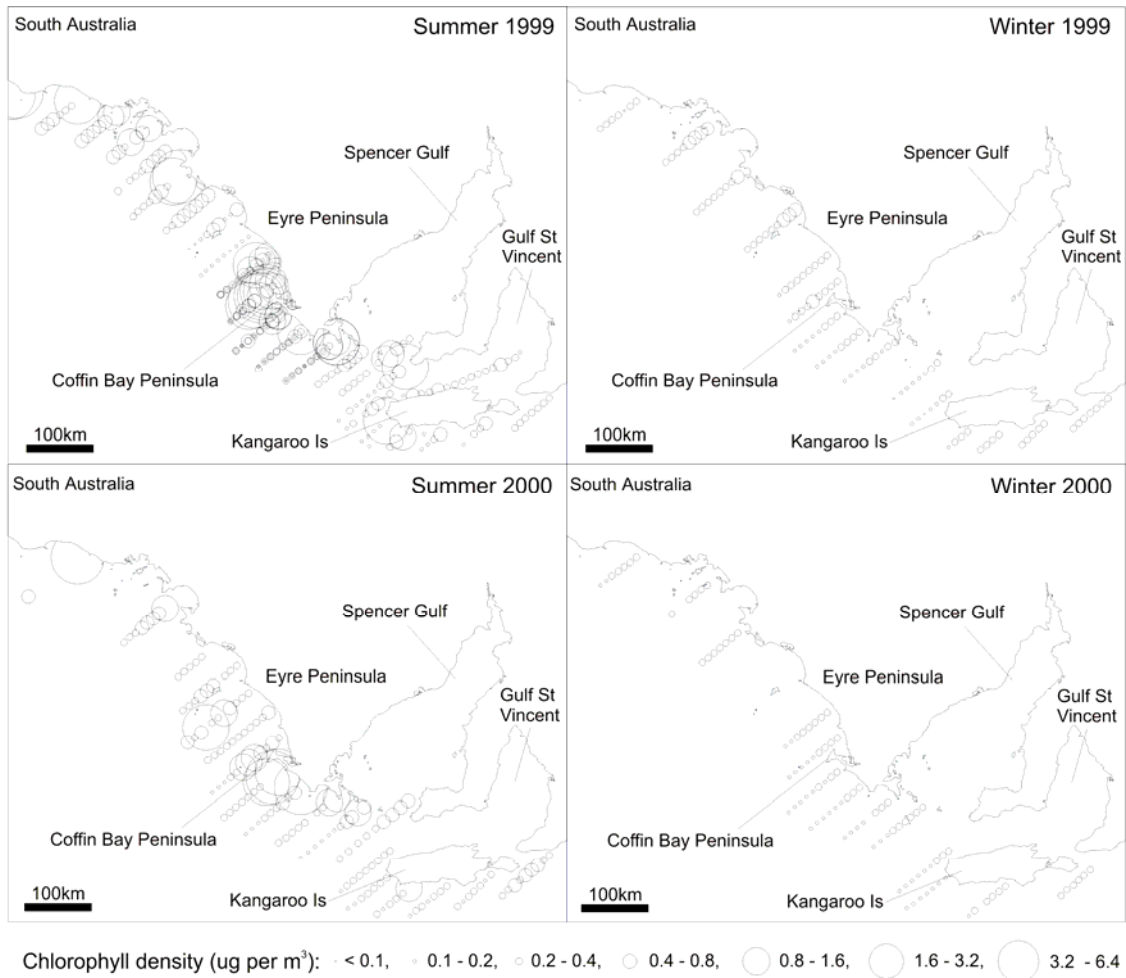


Figure 8. Abundance of chlorophyll-*a* at sites in the GAB during summer-autumn and winter of 1999 and 2000.

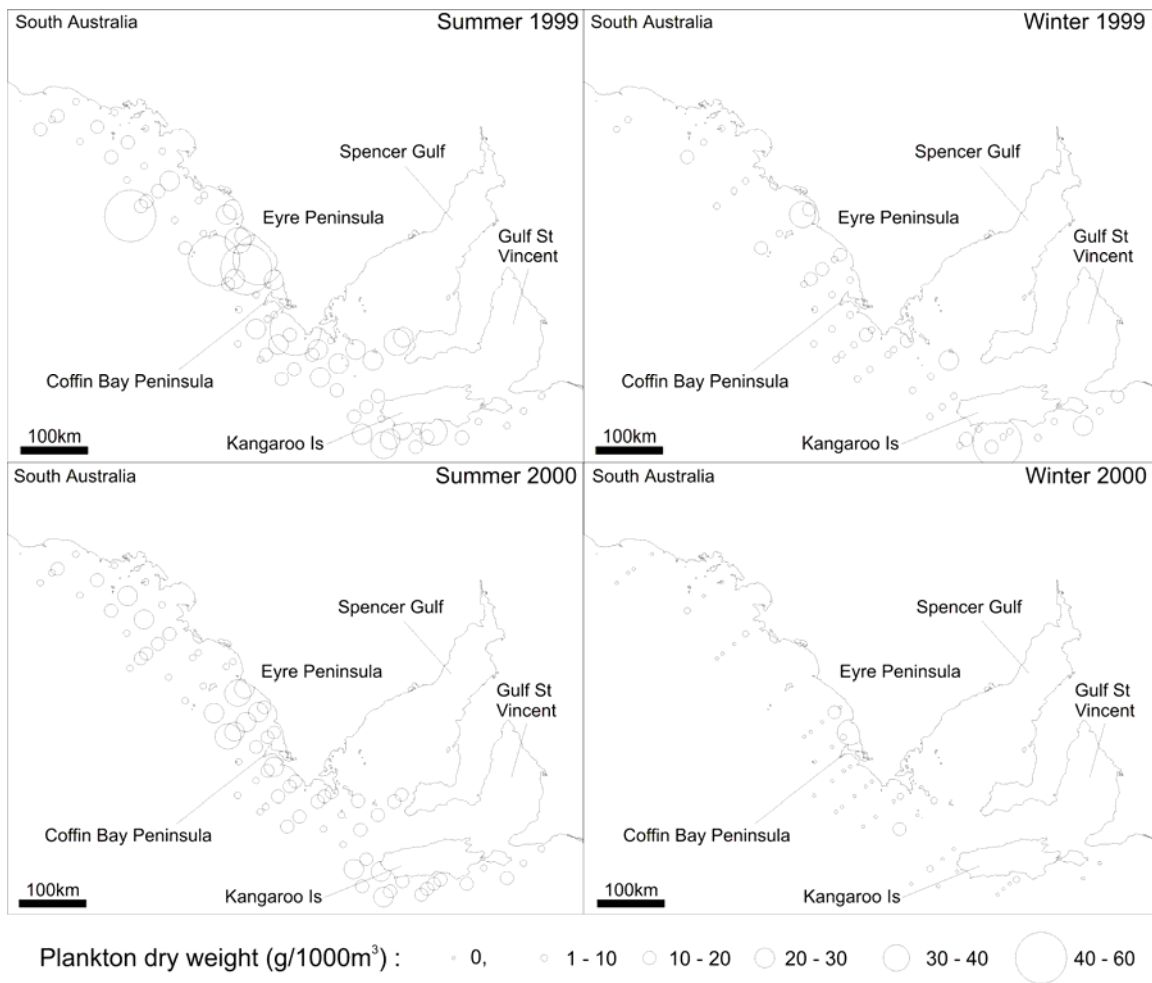


Figure 9. Maps of relative zooplankton biomass in the GAB during summer-autumn and winter of 1999 and 2000.

3.0 Biology, distribution and abundance of small pelagic fishes of South Australia

3.1 Current knowledge

The assemblage of small pelagic fishes off SA include eleven key species belonging to six families, i.e. the Clupeidae, Engraulidae, Scombridae, Carangidae, Emmelichthyidae and Scomberesocidae. Members of family Clupeidae (herring-like fishes) are dominant, with five species occurring in the region. Small pelagic fish species found in SA include sardine (pilchard, *Sardinops sagax*), Australian anchovy (*Engraulis australis*), round herring (maray, *Etrumeus teres*), sandy sprat (*Hyperlophus vittatus*), blue sprat (*Spratelloides spp.*), jack mackerel (yellowtail scad) (*Trachurus declivis* and *T. novaezelandiae*), blue (slimey) mackerel (*Scomber australasicus*), redbait (*Emmelichthys nitidus*) and saury (*Scomberesox saurus*) (Fig. 1).

Research on SA's small pelagic fishes has been undertaken mainly in response to the need for assessment of commercially exploited species in State and Commonwealth waters (see appendix 1. stock assessment reports 1998-2007 and spawning biomass report 1998-2007; McGarvey and Kinloch 2001). Several Ph.D. and Honours projects on small pelagic fishes have been conducted in partnerships between SARDI Aquatic Sciences, the University of Adelaide and Flinders University. Species that have been the focus of work, include sardine *Sardinops sagax* (e.g. Rogers and Ward, 2006; Ward et al., 2001a, 2001b, 2003, 2005, 2006a, 2007; Ward and Staunton Smith, 2002), Australian anchovy *Engraulis australis* (Dimmlich et al., 2004; Dimmilich and Ward, 2007), and blue mackerel *Scomber australasicus* (Ward and Rogers, in press), and to a lesser extent, blue sprat *Spratelloides robustus* (Rogers et al., 2003) and sandy sprat *Hyperlophus vittatus* (Rogers and Ward, 2007).

Since 1986, but especially since 1998, extensive ichthyoplankton and adult surveys have been conducted in shelf and gulf waters of SA (Fig. 11). The timing of surveys, number of stations sampled and orientation of transects where plankton samples were collected has varied between years. Survey results have primarily been used to assess the abundance and distribution of sardine (*S. sagax*), however significant information has also been collected on Australian anchovy (*E. australis*), blue sprat *Spratelloides robustus* and sandy sprat *Hyperlophus vittatus*. In recent years, information has also been collected for round herring (*E. teres*), jack mackerel (yellowtail scad) (*T. declivis* and *T. novaezelandiae*) and blue mackerel (*S. australasicus*). Significant gaps remain in our current knowledge of the fisheries biology and ecology of small pelagic fishes in SA (Table 1). The most substantial of these gaps are relation to population size (for species other than

sardine), recruitment variability, population demographics, fishing/natural mortality (all life history stages), stock structure and ecological roles (Table 1). Few data are available for redbait.

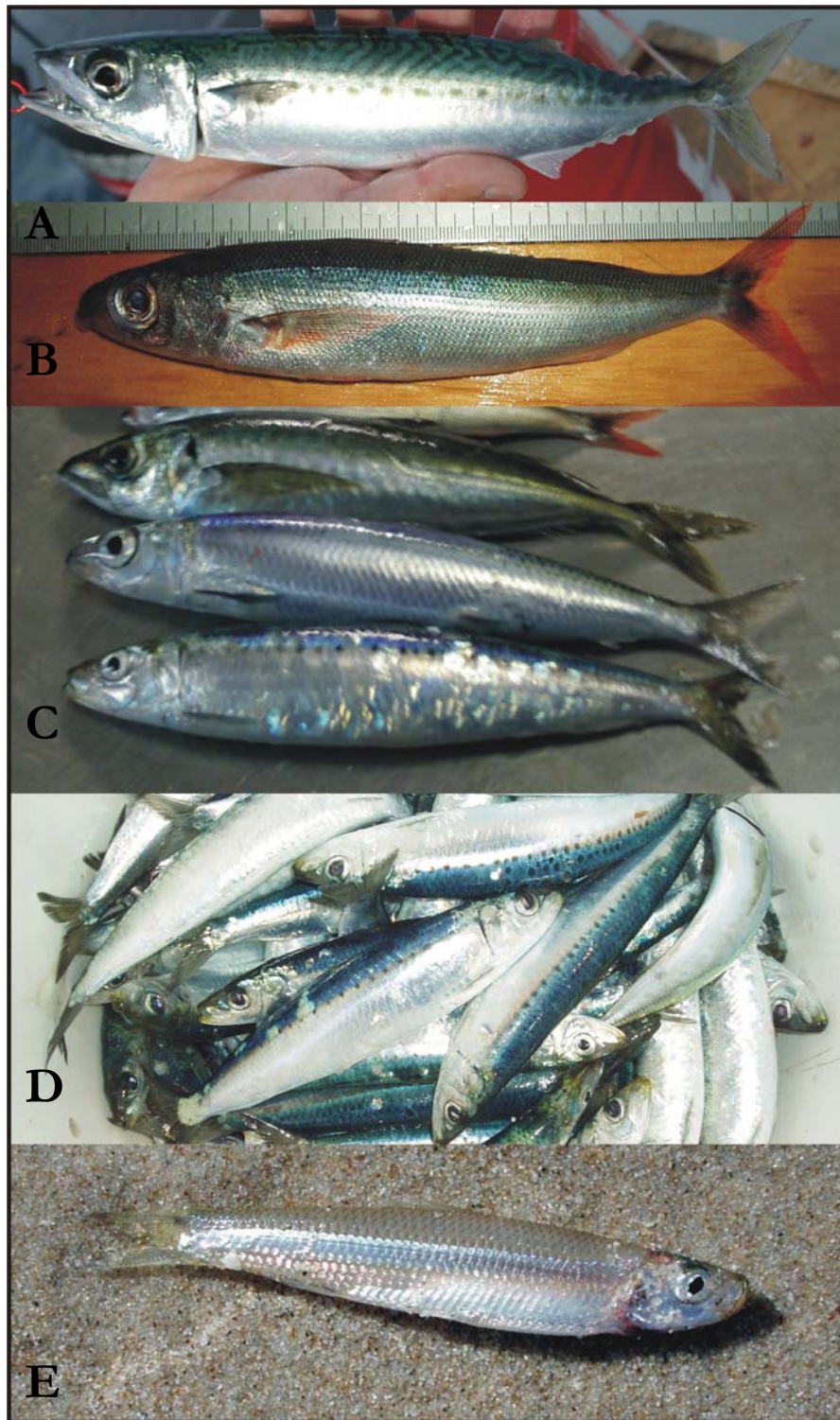


Figure 10. Small pelagic fish species found in SA waters. From top: (A) blue mackerel, (B) redbait, (C)(jack mackerel, round herring, sardine), (D) sardine and (E) sandy sprat (anchovy, blue sprat and saury not shown).

Table 1. Summary of status of the knowledge of small pelagic fishes found in South Australia (based on published and unpublished data). ELH = Early life history, D = Diet, RT = Recruitment, DH = Distribution and habitat, RPS = relationships with primary (phytoplankton) and secondary (zooplankton) production, FD = Fishery catch and effort data, FB = Fishery bycatch information, LF = Length frequency, AS = Age structure, GR = Growth rates, R = Reproductive information, M = Movement, SSt = Stock structure, SB = Spawning biomass, EE = Ecosystem effects of fishing, EI = Ecological importance. Key to colours in available data columns – Most necessary baseline data is available although some gaps still exist = White. Some biological and ecological data available in South Australia and other regions of southern Australia yet significant gaps still exist = Green. Minimal biological data is available for southern Australia or elsewhere = Grey.

Species	Family	Available data	Information gaps
Sardine (pilchard) <i>S. sagax</i>	Clupeidae	ELH, DH, GR, FD, AS, LF, R, FB, SB, EI.	RT, M, SSt, EE, D, RPS
Australian anchovy <i>E. australis</i>	Engraulidae	ELH, DH, LF, GR, AS, EI.	SSt, FD, SB, RT, R, FB, EE, M, D, RPS
Round herring <i>E. teres</i>	Clupeidae	ELH, DH, R, GR, AS, LF, EI.	
Blue sprat <i>S. robustus</i>	Clupeidae	ELH, DH, GR, FD, AS, LF, R, EI	RT, FD, M, SSt, SB, EE, SB, RPS
Sandy sprat <i>H. vittatus</i>	Clupeidae	ELH, DH, GR, FD, FB, AS, LF, R	RT, M, SSt, EE, EI, RPS
Blue mackerel <i>S. australasicus</i>	Scombridae	FD, LF, AS, GR	ELH, RT, FB, R, M, SSt, SB, EE, EI, RPS
Jack mackerel <i>Trachurus</i> spp.	Carangidae	ELH, DH, LF, AS, GR, FD, D	RT, FB, R, M, SSt, SB, EE, EI, RPS
Redbait <i>E. nitidus</i>	Emmelichthyidae	LF, AS, FD, DH, GR, R, D	
Saury <i>S. saurus</i>	Scomberesocidae		

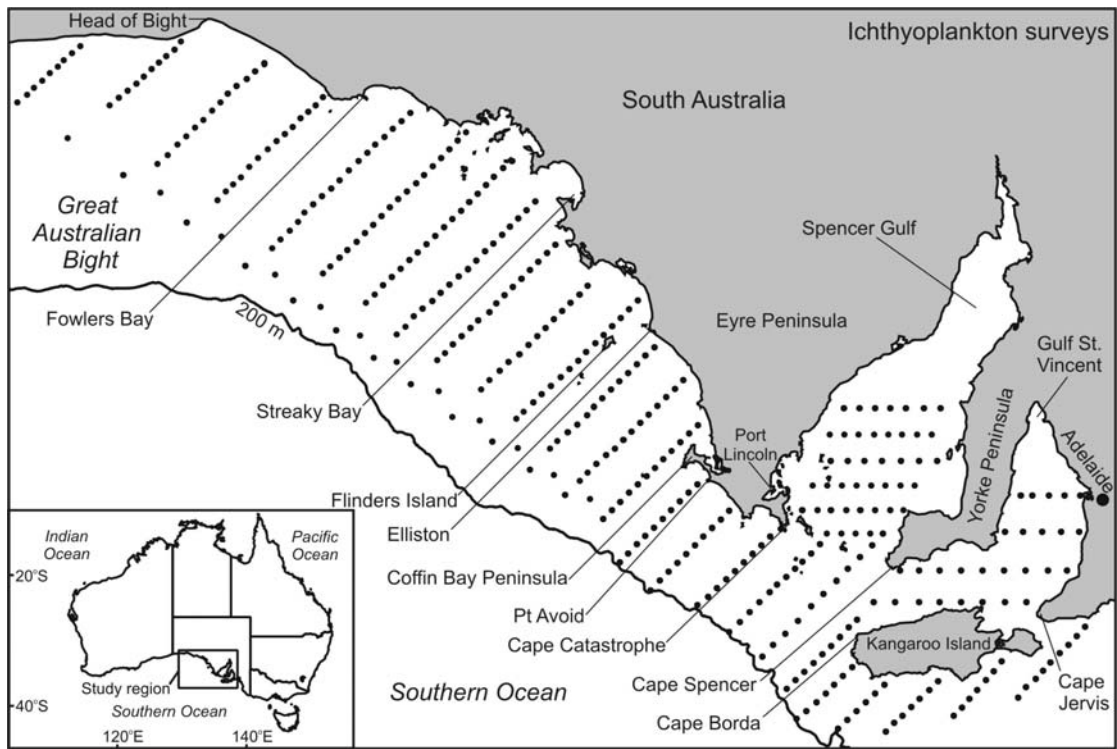


Figure 11. Map shows the location of stations and transects in the SARDI Aquatic Sciences ichthyoplankton surveys conducted between 1998 and 2007.

3.2 Sardine *S. sagax*

Australian sardine, *S. sagax*, is found throughout shelf waters of southern Australia and is the most well studied of Australia's small pelagic fishes (Rogers and Ward, 2006). SA is the centre of the Australian distribution of *S. sagax*. Sardine is taken by the purse seine fishery in southern Spencer Gulf, Investigator Strait and in the eastern GAB (Fig. 12).

The spawning season varies between locations, occurring during summer and autumn off SA (e.g. Ward et al., 2001a, 2003; Ward and Staunton-Smith, 2002). *S. sagax* spawn in the southern regions of both gulfs and throughout shelf waters, but do not spawn extensively in inshore bays and inlets (Dimmlich et al., 2004; Dimmlich and Ward, 2006). Growth coefficients for adults suggest that growth rates in SA may be higher than those in oligotrophic waters in other parts of Australia and at the lower end of those recorded in the productive waters off southern California and South Africa (Rogers and Ward, 2007). Approximately 50% of males and females mature at ~145 and 150 mm fork length (FL), respectively. During the spawning season, females spawn batches of approximately 10,000 to 26,000 eggs every five to ten days.

Eggs and larvae can be collected during all months but peaks in abundance coincide with the upwelling season in summer-autumn (January-April). Eggs are distributed throughout shelf waters and in the lower parts of the two gulfs and are abundant in the eastern GAB, Investigator Strait and southern Spencer Gulf (Fig. 13).

The Daily Egg Production Method (DEPM) has been used to estimate the spawning biomass of *S. sagax* in SA since 1995. The best estimate of spawning biomass in 1995 was 165,000 t, but this fell by over 70% to 37,000 t in 1996, following an unprecedented single species mass mortality event. Estimates of spawning biomass increased to reach 146,000 in 1998, but fell by over 70% to be ~36,000 t in early 1999, following a second mass mortality event. The estimate of spawning biomass for 2007 was 263,747 t. In the early years of the SASF, the Total Allowable Catch (TAC) for the following calendar year was set as a proportion of the spawning biomass (i.e. 10.0% to 17.5%, depending on the size of the spawning biomass). More recently, a conservative baseline TAC was set at 30,000 t which will be maintained as the effective TAC while the estimates of spawning biomass remains between 150,000 and 300,000, which corresponds to exploitation rates of 20% and 10%, respectively.

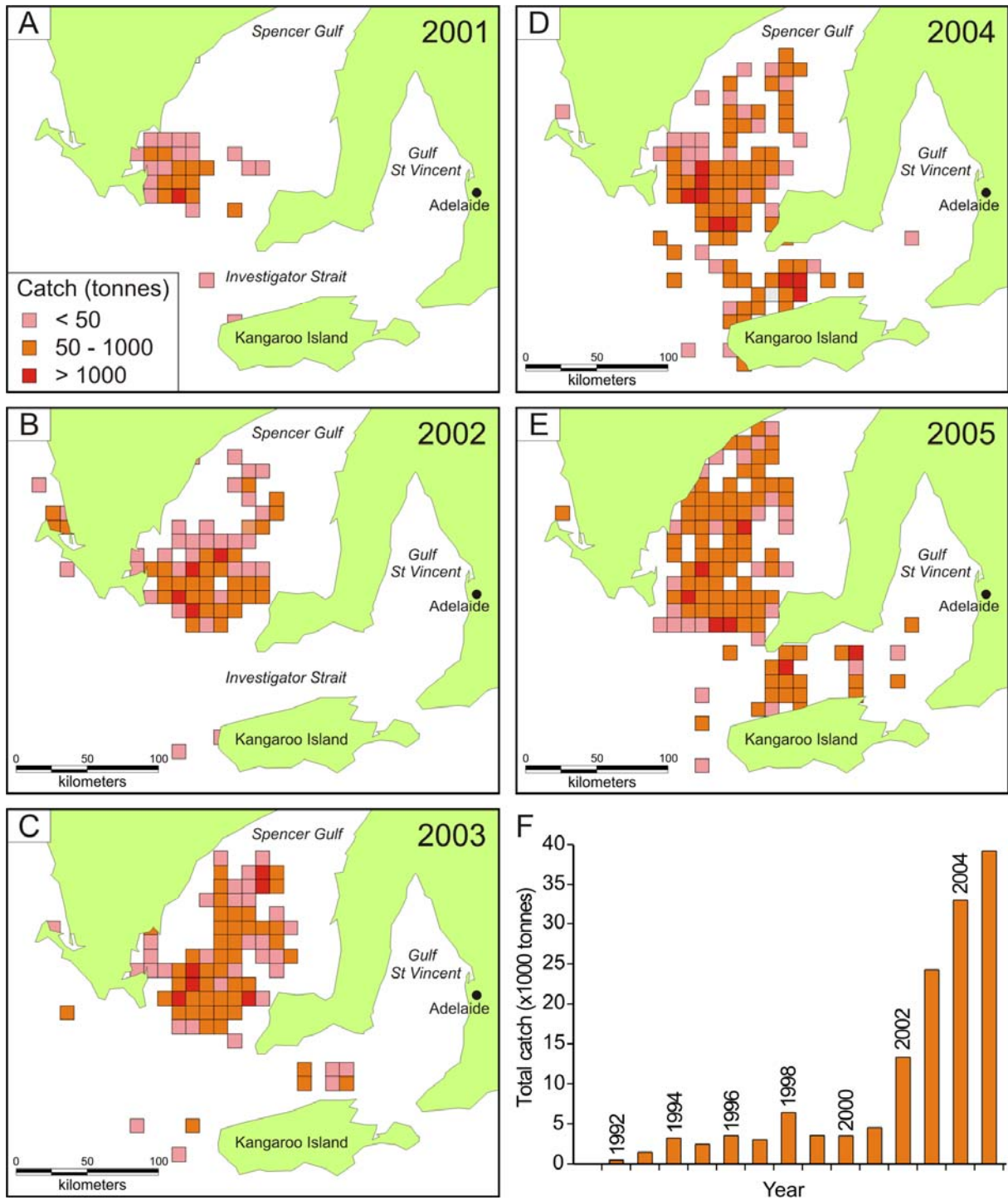


Figure 12. Spatial patterns of sardine catches in SA waters between 2001 and 2005 (A-E). Total annual catch in the SA sardine fishery between 1991 and 2005 is also presented (F).

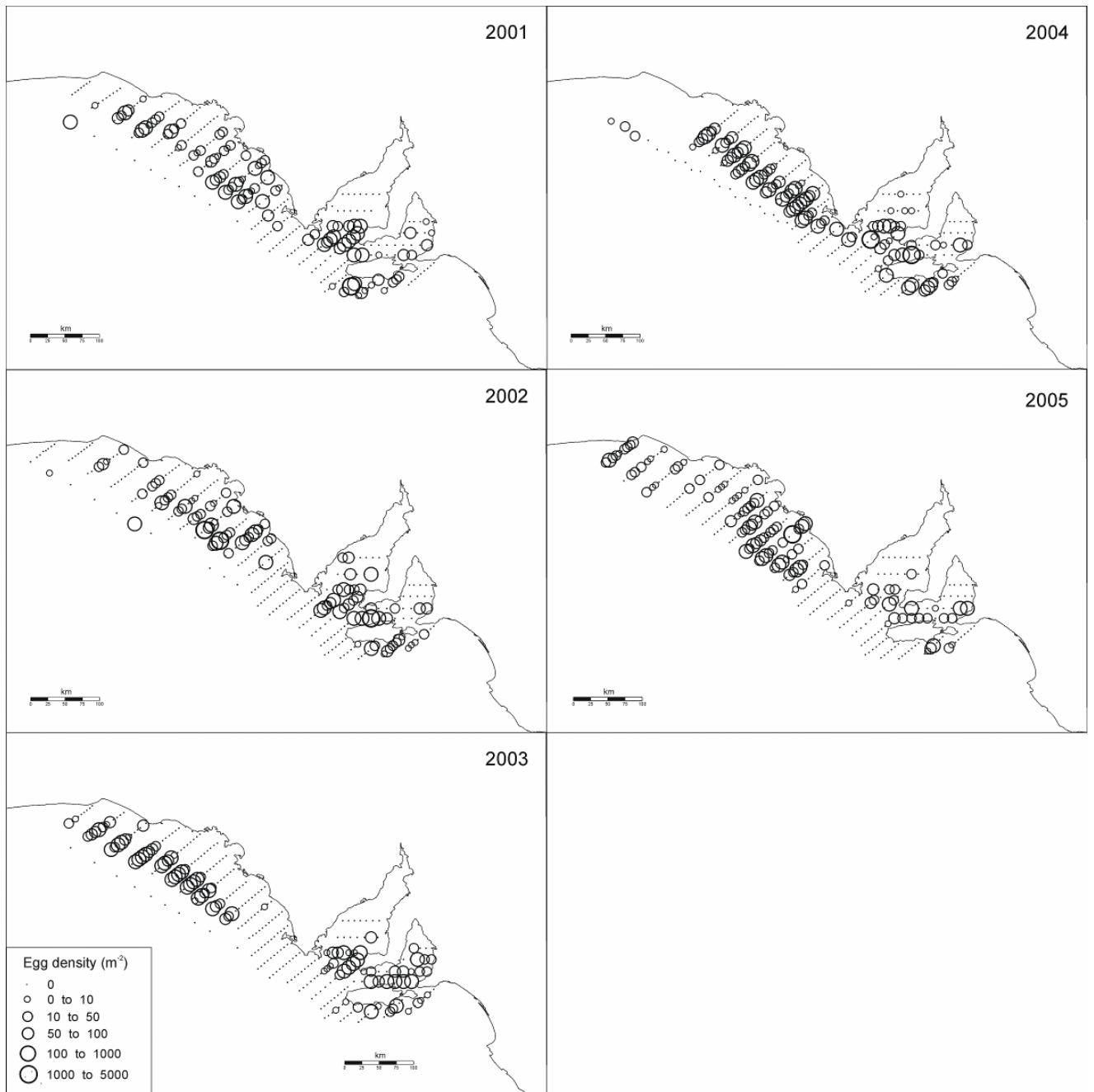


Figure 13. Density of *S. sagax* eggs (number. m^{-2}) at stations sampled off southern Australia between 2001 and 2005.

3.3 Australian anchovy *E. australis*

Australian anchovy, *E. australis*, is found throughout coastal waters of temperate and sub-tropical Australia (Kailola et al., 1993). Small fisheries have taken this species for many years in New South Wales (NSW), Victoria (VIC) and Western Australia (WA) (e.g. Kailola et al., 1993); no large fisheries specifically for *E. australis* have been established. The main spawning season occurs between spring and autumn in southern Queensland (QLD) (Ward et al., 2003), and off Victoria and SA (Hoedt and Dimmlich, 1995; Ward et al., 2001a; Dimmlich et al., 2004; Neira, 2005). Off eastern Australia spawning appears to be confined mainly to shallow embayments, whereas off southern Australia significant spawning activity also occurs in shelf waters (Ward et al., 2003; Dimmlich et al., 2004). Anchovy spawn in gulf and shelf waters of SA and can utilise low and high temperature-salinity habitats, such as in the northern parts of the two gulfs (high SST-salinity) and in the upwelling regions in the eastern GAB (low SST-salinity).

Direct ageing by otolith increment analysis, corroborated by length-based growth models and visual analysis of modal length progressions, suggests that *E. australis* in SA grow faster during their first year than other similar species, such as *E. mordax* and *E. encrasicolus* (Dimmlich and Ward, 2006). Only fish up to 1 year of age occur in northern Spencer Gulf and the southern gulf is inhabited by fish to 3 year olds. Older anchovy are found mainly in offshore shelf waters. This offshore movement with age that occurs in SA may enable anchovy to utilise the wide range of environments that provide suitable spawning and nursery areas for this species (Dimmlich and Ward, 2006). The peak spawning season of *E. australis* in SA coincides with the upwelling season when productivity is enhanced.

Anchovy eggs are abundant throughout gulf and shelf waters, but the highest densities occurred in the northern parts of Spencer Gulf and Gulf St Vincent where SSTs are high (24°C–26°C). In contrast, larvae >10 mm TL are mainly in shelf waters near upwelling zones where SSTs were relatively low (<20°C) and levels of chlorophyll-*a* (Chl-*a*) relatively high (Fig. 14). Levels of survival may be higher in the upwelling zones than the northern gulfs (Dimmlich et al., 2004). The abundance of anchovy eggs and larvae in shelf waters increased when sardine abundance was reduced by large-scale mortality events, and decreased as sardine numbers subsequently recovered (Ward et al., 2001b). Anchovy may only be able to utilise upwelling zones effectively when the sardine population is low. At other times, northern gulf waters may provide a refuge for the anchovy that cannot be used by sardine.

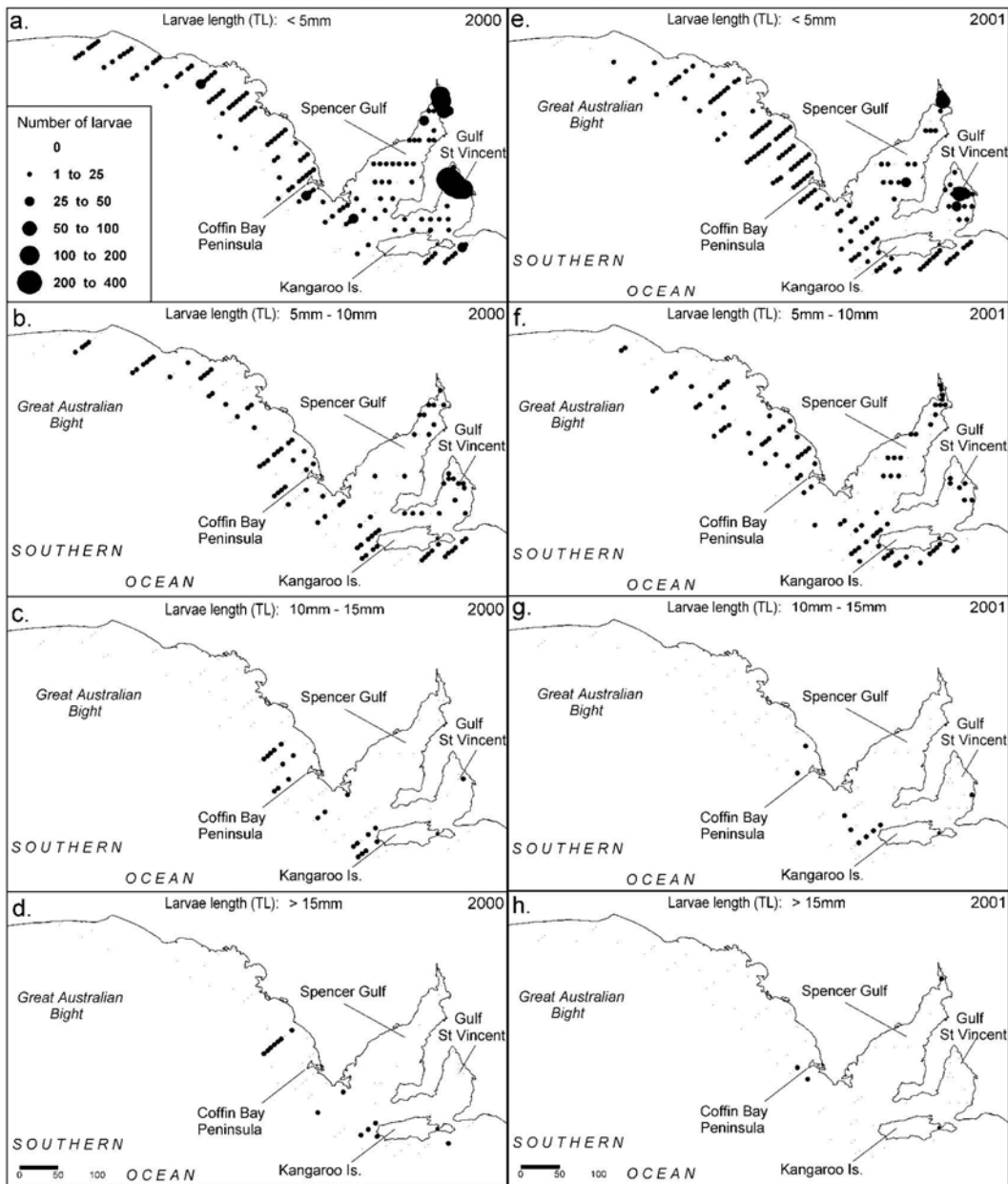


Figure 14. Numbers of *E. australis* larvae of each size class (<5 mm, 5 mm – 10 mm, 10 mm – 15 mm, >15 mm) at each site during February-March surveys in 2000 and 2001.

3.4 Blue sprat *S. robustus*

The life history of *S. robustus* is dissimilar to other small to medium sized temperate clupeoids, but similar to those of many small sub-tropical and tropical clupeoids, including other *Spratelloides* species (Rogers et al., 2003). Gulf St Vincent and Spencer Gulf may be considered to be “seasonally subtropical systems” in an otherwise temperate region, which support a suite of species, including *S. robustus*, that have life history strategies similar to those of sub-tropical and tropical taxa. *S. robustus* reached 50% maturity at ~60 mm FL after ~135 days. Females spawn multiple batches of demersal eggs every 1–2 days. Batch fecundities are low (mean = 755.75, S.D = 341.48) and increased linearly with length and weight.

Unlike the other small pelagic fishes considered in this report, *Spratelloides* have benthic eggs which are difficult to locate and sample. *S. robustus* spawn from October to February and larvae are found at very low densities in Spencer Gulf, Gulf St Vincent and Investigator Strait (Fig. 15). However, this species is also known to occur in inshore environments in the eastern GAB, including Streaky Bay and Denial Bay (Fig. 1). The oldest fish examined was 82 mm FL and 241 days old, which suggests *S. robustus* may live for <1 year. Growth rates were high during larval stages ($0.34 \text{ mm}\cdot\text{day}^{-1}$) and remained high throughout juvenile ($0.33 \text{ mm}\cdot\text{day}^{-1}$) and adult stages ($0.19 \text{ mm}\cdot\text{day}^{-1}$).

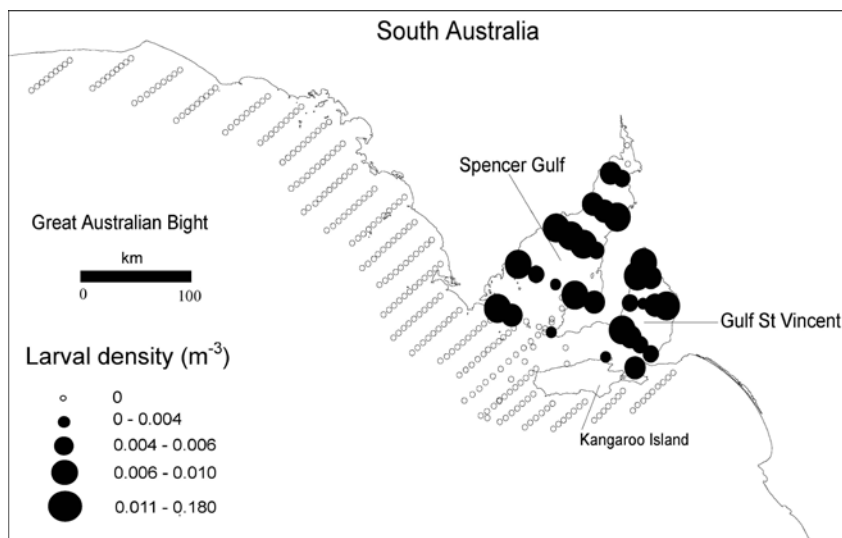


Figure 15. Distribution and density of *S. robustus* larvae collected between November 1986 and March 2000. Open circles represent stations at which no larvae were found.

3.5 Sandy sprat *H. vittatus*

Sandy sprat or whitebait, *H. vittatus* is a small (100 mm FL) species found in inshore waters of southern Australia. The average growth rate for larvae (20.1–27.6 mm, total length, TL) in the Coorong lagoon was 0.12 mm.day⁻¹ and the oldest fish collected was ~4 years old (Rogers and Ward, 2007b). Males and females attain 50% sexual maturity at 59 and 58 mm, FL, respectively and all individuals are sexually mature at ≥75 mm TL, at ~1.5 years of age. The spawning season extends from October to February (spring and summer) and peaks during November. Mean egg densities are highest between September and November. Females produced batches of pelagic eggs at mean frequencies of 5 days and batch fecundities range between 743 and 5,600 hydrated oocytes.

In SA, *H. vittatus* eggs are found in gulf waters (Fig. 16) and low densities of larvae have been found off south-eastern Kangaroo Island, however the broader spatial distribution of this species is poorly understood. Off WA this species is predominantly found close to shore (Gaughan et al., 1996). The life history of *H. vittatus* is similar to those of larger, iteroparous clupeoids that occur in southern temperate Australian waters, e.g. sardine *S. sagax* and Australian anchovy *E. australis*, and dissimilar to those of small tropical clupeoids and the sympatric blue sprat *S. robustus*, which is semelparous (Rogers and Ward, 2007b).

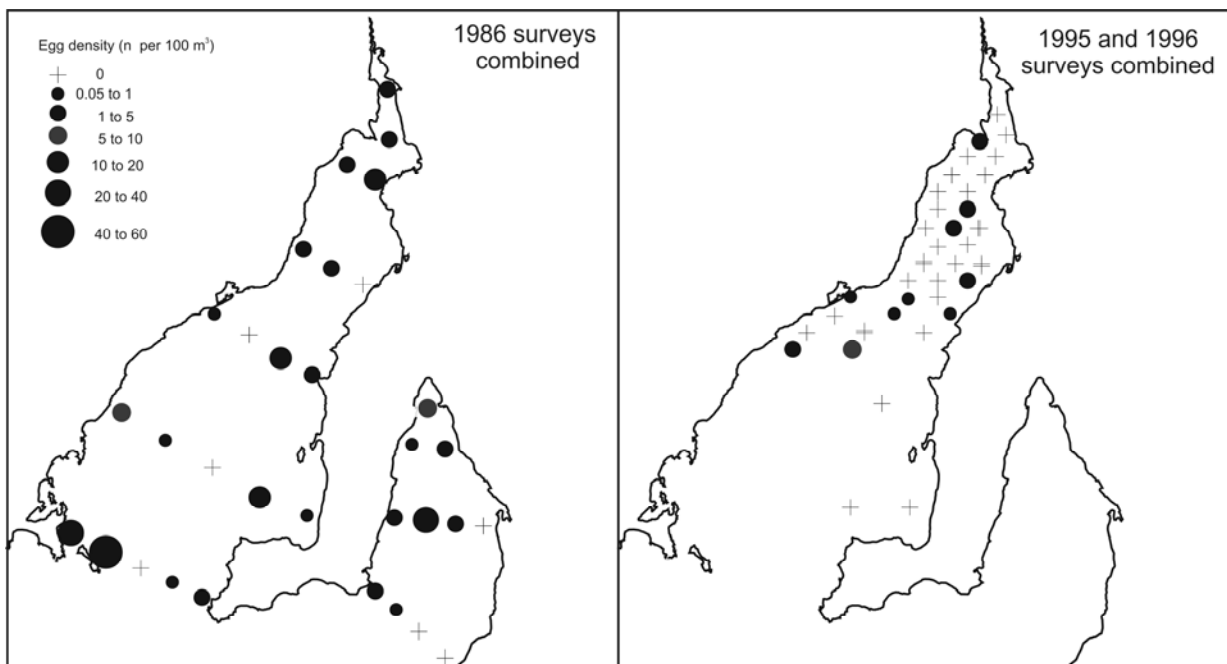


Figure 16. Density of *H. vittatus* eggs collected during ichthyoplankton surveys in 1986, 1995 and 1996.

3.6 Maray *E. teres*

Maray or round herring, *E. teres*, occurs throughout temperate and subtropical Australian waters from approximately Fraser Island (QLD) to Shark Bay (WA). However, *E. teres* does not appear to be highly abundant in any location and few data have been published on its biology in Australian waters. The otoliths are not suitable for ageing using normal approaches. Where biological and ecological data are available, the location and timing of spawning appear to coincide with those of *S. sagax* (Ward et al., 2003). Eggs occur at low densities throughout shelf waters of SA and distributions are highly variable between years (Fig. 17).

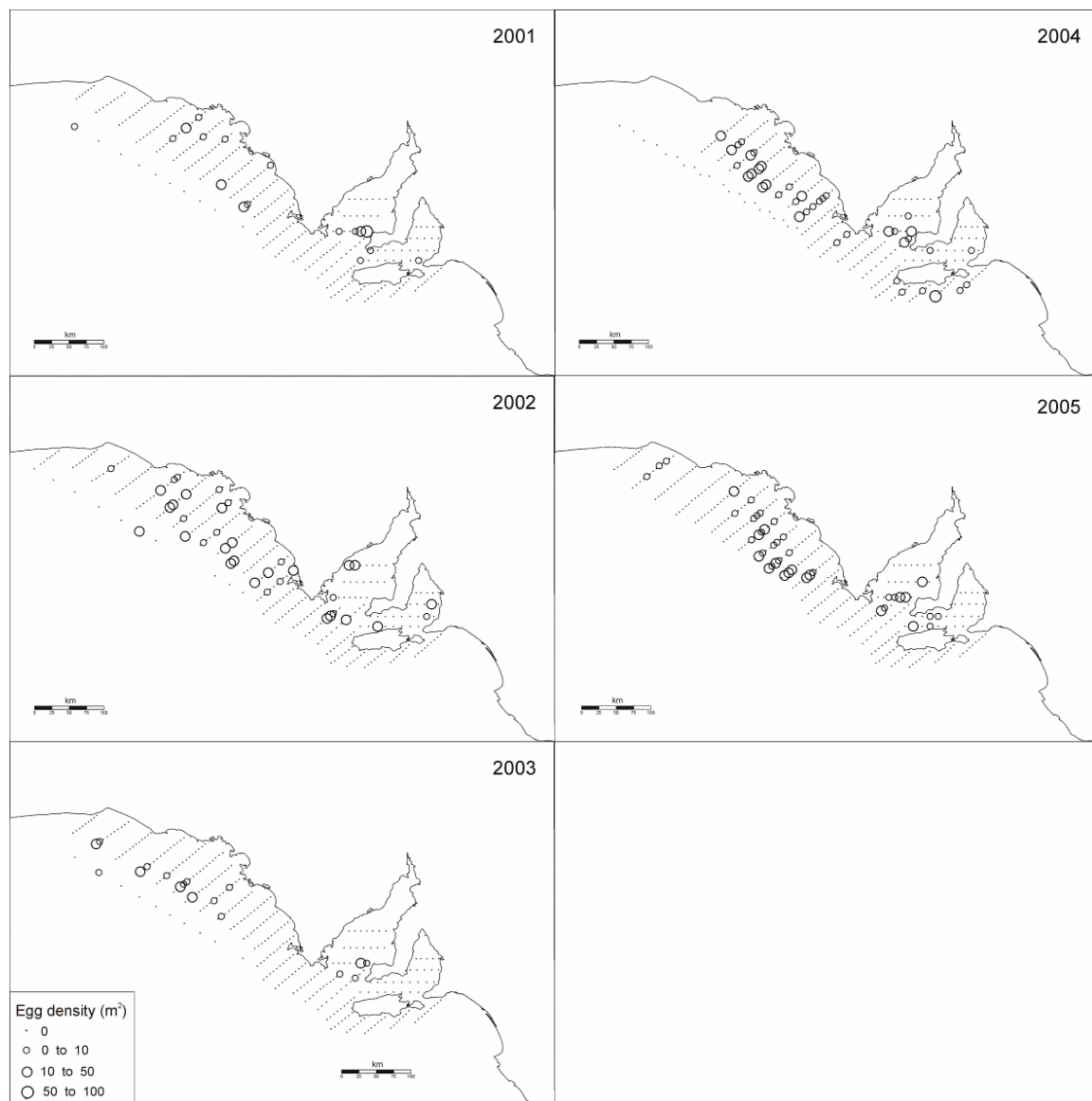


Figure 17. Density of *E. teres* eggs (number.m⁻²) at stations sampled off SA between 2001 and 2005.

3.7 Blue mackerel *S. australasicus*

Blue mackerel *S. australasicus* occurs throughout the Pacific Ocean, including South-east Asia, Australasia, and New Zealand and in the northern Indian Ocean and Red Sea. In Australia it is found mainly in southern temperate and subtropical waters between southern QLD to WA (Ward et al., 2001). Juveniles and small adults usually occur in inshore waters and larger adults form schools in depths of 40–200 m across the continental shelf (Kailola et al., 1993). Until recently, there have been few studies of the biology and ecology of this species in Australian waters (Ward and Rogers, in press).

Like many other pelagic fishes, it is challenging to age *S. australasicus* using standard approaches, as the majority of otoliths are difficult to read, and these difficulties increase as fish age increases (Ward and Rogers, in press). Growth rates and trajectories of males and females from waters off SA are similar. Both sexes grow rapidly during the first 2 years of life, and reach ~250 mm after ~2 years.

Approximately 50% of males and females are sexually mature at 237 and 287 mm FL, respectively. Mean spawning frequencies range from 2 to 11 days in southern Australia. Mean batch fecundity is ~70,000 oocytes per batch and 134 oocytes per g of weight. Fecundity increases exponentially with fish length and weight.

Most of the eggs collected off southern Australia have been obtained from stations located over the mid-shelf (Fig 18). High egg and larval densities are recorded at stations located in depths of 40–120 m with SSTs of 18–22°C. The location of spawning off southern Australia appears to vary substantially between years. Results of an exploratory survey suggest that the western GAB is an important spawning area, however this region has not yet been sampled intensively and inter-annual variation there is poorly resolved.

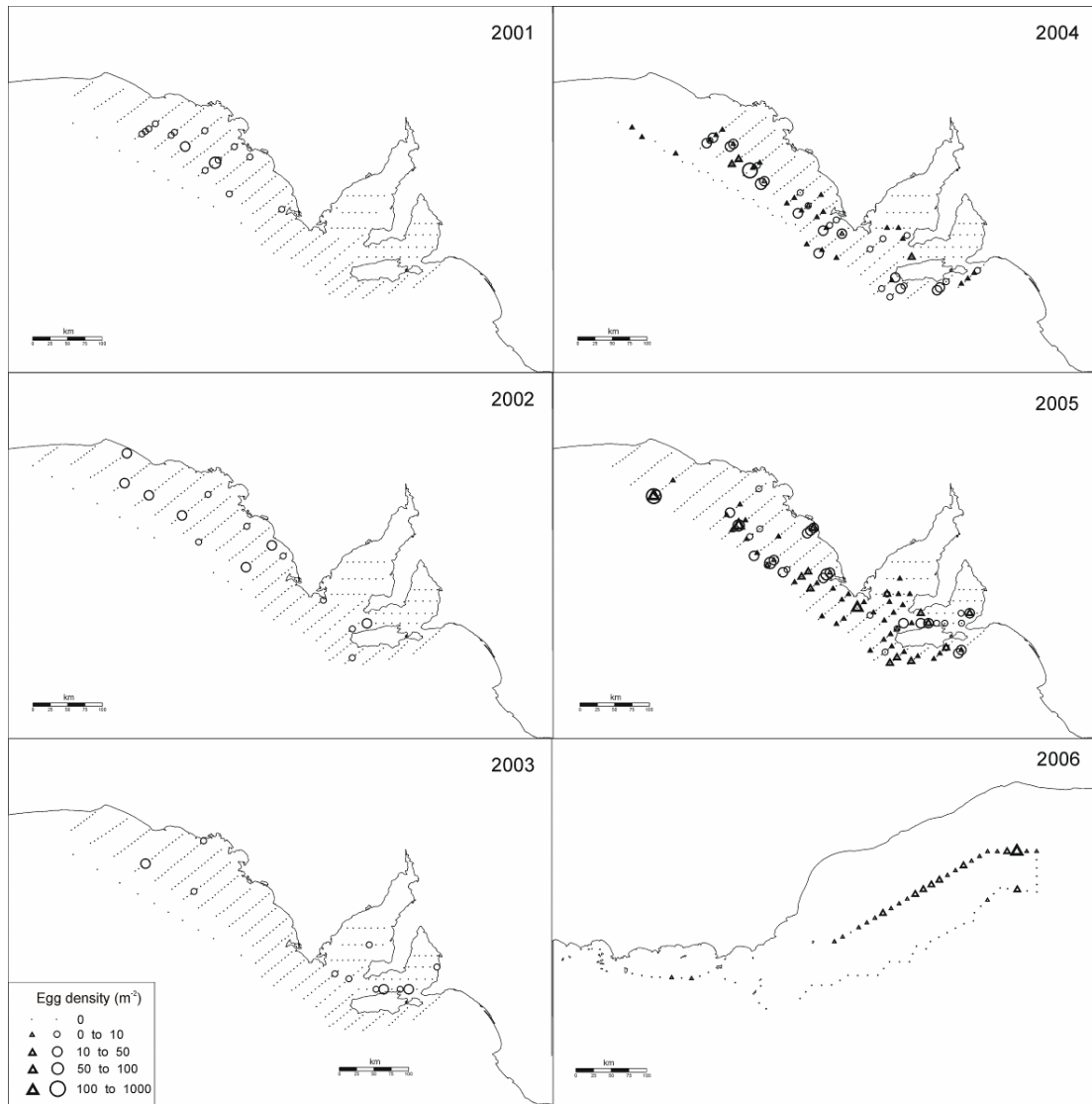


Figure. 18. Distribution and abundance of *S. australasicus* eggs in samples taken from southern Australia between 2001 and 2005 and the western GAB in 2006. Circles and triangles represent samples collected with CalVET and Bongo net, respectively.

3.8 Jack mackerel *T. declivis* and yellowtail scad *T. novaezelandiae*

Jack mackerel *T. declivis* and yellowtail scad, *T. novaezelandiae* both occur throughout temperate and sub-tropical Australian waters. The eggs and larvae of these two species are difficult to distinguish on the basis of morphological characteristics alone and were not differentiated during a recent study (Ward and Rogers, in press). However, *T. declivis* appears to be more abundant off Victoria and eastern Australia and in the GAB, whereas *T. novaezelandiae* is thought to be most abundant off NSW (Kailola et al. 1993). Adult reproductive data suggest that *T. declivis* spawns during summer in the GAB (Stevens et al. 1984). Substantial quantities of *Trachurus* eggs were found during a recent exploratory survey in the western GAB in 2006 (Fig. 19), whereas densities in the eastern GAB were relatively low between 2003 and 2005.

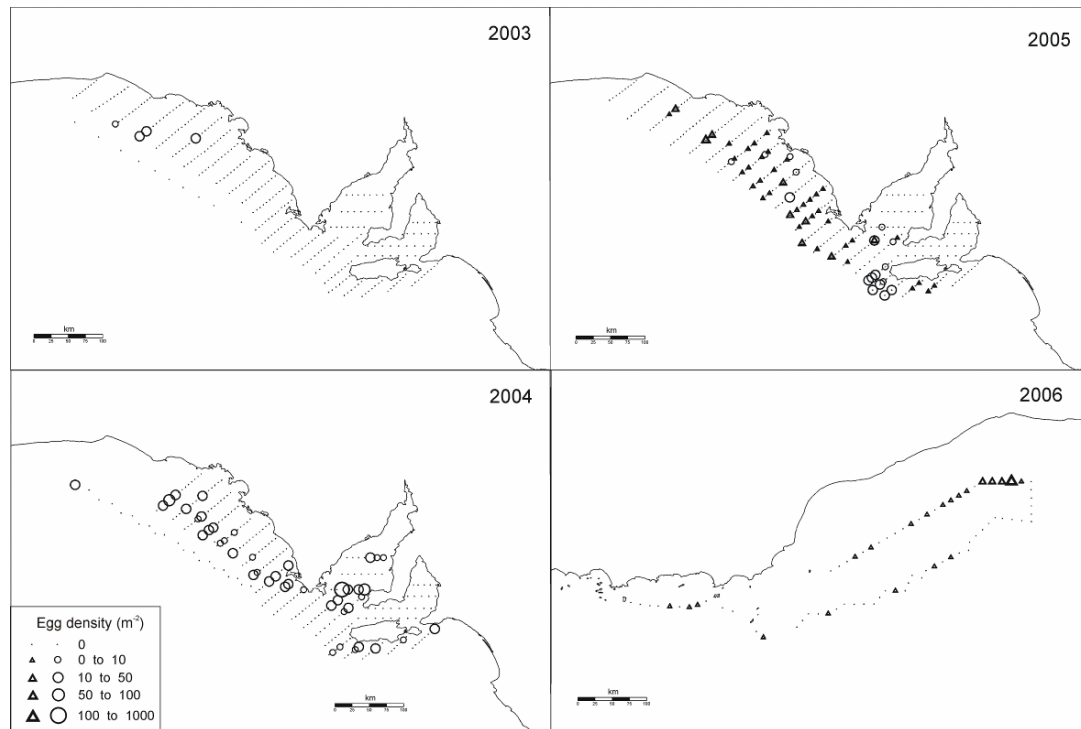


Figure 19. Density of *Trachurus* spp. eggs (number.m⁻²) at stations sampled off southern Australia between 2003 and 2006. Circles and triangles represent samples collected with the CalVET and Bongo nets, respectively.

4.0. Diets of Small Pelagic Fishes

4.1 Background

This section provides a summary of a recently completed Honours project that quantified the trophic role of small pelagic fishes in this region, examined the diets of sardine (*S. sagax*), anchovy (*E. australis*), blue mackerel (*S.australasicus*), jack mackerel (*T. declivis*), maray (*E. teres*) and redbait (*E. nitidus*) at locations in Spencer Gulf and the eastern GAB (Fig. 10). Stomach contents were collected from 370 individuals from which 14 prey taxa groups were identified (Daly, 2007).

4.2 Morphological identification of stomach contents

Crustaceans, principally Australian krill (*Nyctiphanes australis*), were the most common prey item (24-70%), but other crustaceans and fish larvae were also regularly found in stomachs. This study indicated that three trophic guilds characterised the small pelagic fish community of the eastern GAB. The first guild included anchovy, blue mackerel and jack mackerel, which predominantly consumed crustaceans and larval fish. Sardine and redbait comprised the second guild, and preyed mostly on crustaceans and plant material. Maray was the sole member of the third guild and preyed principally on krill. Results from this study will be integrated in the trophodynamic model being developed for the eastern GAB and the SASF.

Of 579 stomachs of small pelagic fishes examined, 370 contained prey, which were summarised into 14 prey taxa groups (Table 2). Australian krill (*N. australis*) was the most important prey group for percent biomass (BM), frequency of occurrence (FOO) and numerical abundance (NA). More than 65 % of maray stomachs examined comprised krill. Anchovy, blue mackerel and jack mackerel utilised more fish larvae than krill and sardine mostly preyed on krill and other crustaceans. The major components of the diets of small pelagic fish groups and the significant differences between these predators are outlined below.

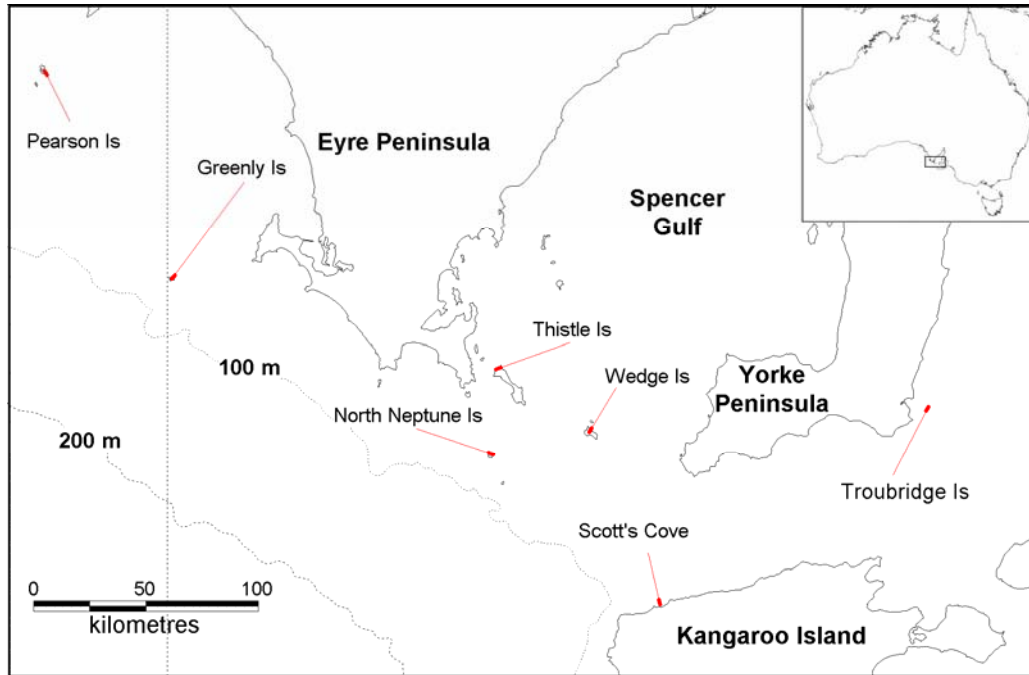


Figure 20. Map of study region showing locations where samples were collected for dietary analysis.

4.3 Sardine

A total of 272 sardines were examined and 228 stomachs contained prey remains (Table 2). In total, 12 prey taxa were present with krill (29.6% BM) and unidentified crustacean (22.2 % BM) contributing the highest biomass. Krill occurred in greater numbers (65.3% NA) than crustacean (27.0% NA) and crab zoea, decapods, copepods and polychaetes were identified, but contributed < 0.5% of total prey biomass. Fish eggs (8.8% FOO) occurred more than fish larvae (0.3% FOO), but overall, fish contributed <10% of the total prey biomass. Plant material contributed the third highest biomass (15.7% BM) but had the lowest numerical abundance (0.2% NA) and frequency of occurrence (0.3% FOO). Salps (*Thetys* spp.) (8.4% BM) and ostracods (*Loxococoncha* spp.) (9.4% BM) had substantial biomass contributions but low numerical abundance (2.9% and 1.1%, respectively) (Table 3).

4.4 Anchovy

Of the 23 anchovy stomachs examined, 17 stomachs contained prey (Table 2). Of the 5 prey taxa identified, krill (32.9% BM) and fish larvae (33.3% BM) were the most abundant (Table 2). Krill had a greater numerical abundance and frequency of occurrence compared to fish larvae (krill- 46% NA, 6.7% FOO, fish larvae- 29.2% NA

& 4.2% FOO). Unidentified crustaceans (22.4% BM) and parasites (*Digenium spp.*) (11.3% BM) also contributed to the diet (Table 2).

4.5 Blue Mackerel

Of the 18 blue mackerel examined, 17 stomachs contained prey remains. Fish larvae (33.3% BM) and krill (30.1% BM) were present in similar proportions (Table 2). Fish larvae (≤ 15 mm) contributed 100% of stomach contents for 3 samples of blue mackerel. Fish larvae could not be identified to species but otoliths recovered were identified as a clupeoid species. Krill were found in more stomachs (47.8% FOO) and in greater numbers (62% NA) than fish larvae (13.0% FOO) and (19% NA). Unidentified crustaceans (20% BM), plant material (8.5% BM) and pteropod shells (6.4%) were also found.

4.6 Jack Mackerel

Of the 60 jack mackerel examined, 41 stomachs contained prey remains (Table 2). Of these, 41 (68%) contained prey remains from 9 taxa. Krill (24.8% BM) and fish larvae (25.5% BM) contributed the highest percent prey biomass to diets. Jack mackerel had similar quantities of unidentified crustaceans (14.6%), salps (14%) and polychaetes (15.1%), yet salps only occurred in a few samples (1.8% FOO) and (1.3% NA) (Table 3).

4.7 Maray

Of the 70 maray examined only 12 stomachs contained prey items. Five prey taxa were identified and krill comprised 69.4% of the total biomass and 92.7% by number (Table 2). Unidentified crustaceans (10.0 % BM), fish larvae (12.3 % BM), crab zoea (5.8 % BM) and fish eggs (2.4 % BM) were also present in stomachs.

4.8 Redbait

Of the 136 redbait examined, 55 stomachs contained prey remains, which comprised 11 taxa (Table 2). Krill was the most important prey (35.5 % BM, 30.4 % FOO and 55.9 % NA). Unidentified crustaceans (20.7 % BM) and pteropod shells (13.9 % BM) were also common prey taxa and other prey comprised of decapods, copepods, fish eggs, salps, digenia, plant material, echinoderms and polychaetes (Table 2).

Table 2. Percentage prey biomass (BM), frequency of occurrence (FOO) and numerical abundance (NA) for 14 prey groups consumed by small pelagic fish species. The numbers in parentheses indicate 1) total number of individuals, 2) number of individuals with stomach contents, 3) total mass of identified prey (g), 4) total gut mass (g) and 5) total mass of unidentified remains). “A dash (-)” indicates that the prey group was comprised < 0.1 %. Prey groups are summarised into 3 major groups: crustacean, fish and other prey, which are highlighted in bold.

PREY TYPE	Sardine			Anchovy			Blue mackerel			Jack mackerel			Maray			Redbait		
	BM	FOO	NA	BM	FOO	NA	BM	FOO	NA	BM	FOO	NA	BM	FOO	NA	BM	FOO	NA
	(272/228/235.1/242.6/7.5)			(23/17/13.7/14.3/0.6)			(18/17/54.9/55.1/0.2)			(60/41/67.3/67.5/0.2)			(70/12/2.5/2.6/0.1)			(136/55/12.3/13.3/1)		
CRUSTACEAN	52.3	72.6	92.3	55.3	66.7	86	50.1	65.2	77	42.1	78.6	84.3	85.3	86.4	98.1	60.2	55.4	76.6
Krill	29.6	45.0	65.3	32.9	29.2	46	30.1	47.8	62	24.8	55.4	72.7	69.4	54.5	92.7	35.5	30.4	55.9
Unidentified Crustacean	22.2	24.7	27.0	22.4	37.5	40	20	17.4	15	14.6	14.3	11.0	10.1	9.1	2.2	20.7	18.8	20.0
Crab Zoea	0.1	0.9	-	-	-	-	-	-	-	2.2	5.4	0.6	5.8	22.7	3.2	-	-	-
Decapod	0.1	0.9	-	-	-	-	-	-	-	0.3	1.8	-	-	-	-	0.5	2.7	0.1
Copepod	0.3	1.2	-	-	-	-	-	-	-	0.2	1.8	-	-	-	-	3.5	3.6	0.6
FISH	5.1	9.2	1.6	33.4	20.8	6.8	33.3	13.1	19	25.5	1.8	2.4	14.7	13.6	1.9	1.5	5.4	0.4
Fish Larvae	1.4	0.4	-	33.3	4.2	6.7	33.3	13.1	19	25.5	1.8	2.4	12.3	4.5	1.4	-	-	-
Fish Eggs	3.7	8.8	1.6	0.1	16.7	0.1	-	-	-	-	-	-	2.4	9.1	0.5	1.5	5.4	0.4
OTHER	42.6	18.2	6.1	11.3	12.5	7.2	16.6	21.7	4	32.4	19.6	13.3	0	0.0	0.0	38.3	39.2	23.0
Salp	8.4	7.1	2.9	-	-	-	1.7	8.7	0.6	14	1.8	1.3	-	-	-	3.8	5.4	1.1
Digenium	4.9	5.6	1.4	11.3	12.5	7.2	-	-	-	-	-	-	-	-	-	0.3	0.9	-
Plant Material	15.7	0.3	0.2	-	-	-	8.5	4.3	1.2	-	-	-	-	-	-	9.3	3.6	1.7
Pteropod shell	4.2	2.4	0.5	-	-	-	6.4	8.7	2.2	3.3	3.6	0.6	-	-	-	13.9	26.6	19.3
Echinodermata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.7	0.9	0.1
Ostracoda	9.4	2.4	1.1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Polychaeta	-	0.6	-	-	-	-	-	-	-	15.1	14.3	11.4	-	-	-	8.3	1.8	0.8

4.9 Guild structure among small pelagic fishes

Based on 60 % similarity in the diets among small pelagic species, three distinct dietary guilds were identified (Fig. 11). Guild One was broadly characterised as crustacean and larval fish predator, Guild Two as crustacean and other species (plant and ostracods), and Guild Three as crustacean (krill) predators (Table 2 and Figure 21). The characteristics of each guild are detailed below:

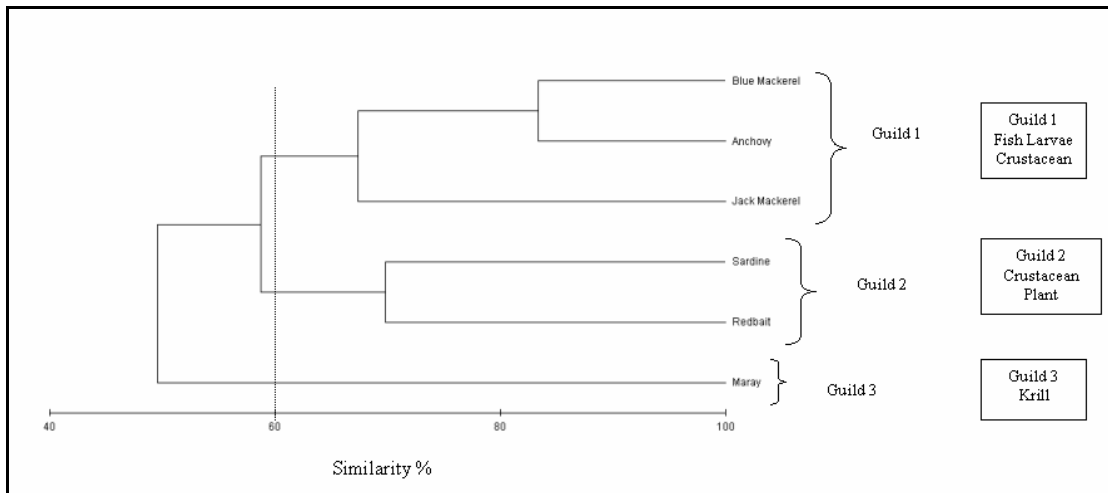


Figure 21. Bray-Curtis similarity dendrogram of the diets of six small pelagic fish species based on proportional percentage biomass contribution of 14 prey taxa grouped into 3 similarity guilds at 65%. The prey species that were responsible for large differences between guilds are indicated.

5.0 Distribution, diets and foraging patterns of key predators

5.1 Background

Information on the diets and foraging patterns of key pelagic predators has been collected in South Australian shelf and gulf waters by the Pelagic Ecology and Pelagic Fishes SubPrograms at SARDI Aquatic Sciences since 1999. PhD and Honours student projects have contributed significantly to the information provided in this section which is incorporated in the food web from the trophodynamic model that is currently being developed (Section 6).

In the past decade, the Commonwealth legislation and policies have provided the impetus for the development of an ecosystem-based approach to fisheries assessment and management. This has led to the development of a large scale project to assess the need for an ecosystem allocation for the SA Sardine Fishery (SASF). This has involved investigations of the diets of key pelagic predators, including juvenile southern bluefin tuna (SBT) (*Thunnus maccoyii*), Western Australian salmon (*Arripis truttacea*), little penguins (*Eudyptula minor*), shearwaters (*Puffinis spp.*), Australasian gannets (*Morus serrator*), terns (*Sterna spp.*), Australian sea lions (*Neophoca cinerea*), New Zealand fur seals (*Arctocephalus forsteri*), Australian fur seals (*Arctocephalus pusillus doriferus*) and some shark species, including bronze whalers (*Carcharhinus brachyurus*), thresher shark (*Alopias vulpinus*) and hammerheads (*Sphyrna zygaena*) and the development of a preliminary trophodynamic model for the eastern GAB. This work has also been supported by several Ph.D. and Honours projects at the University of Adelaide. The completion of FRDC project (2005/031) in 2008 will enhance current knowledge of the ecological importance of small pelagic fishes and foraging strategies of key predators in this region. Outcomes of this project will also assist future marine planning of the SWMR.

5.2 Southern Bluefin Tuna *Thunnus maccoyii*

Southern bluefin tuna (SBT), *T. maccoyii* occur in waters of the southern hemisphere between 30°S and 50°S, to nearly 60°S. It can reach up to 2.5 m in length and 400 kg in weight. It is currently classified as Critically Endangered (IUCN Redlist). Juvenile SBT aggregate in the GAB during each summer and autumn (Gunn and Young 1996; Young et al. 1996, 1997) and achieve >80% of their annual growth during this 3-4 month period (Hearn 1986; Young et al. 1999). Kloser et al. (1998) hypothesised that these juvenile may use the warm waters of the central GAB as a thermal refuge from which to forage.

The locations where SBT have been collected for dietary analysis and patterns of SBT fishery catches are shown in figure 22. Juvenile SBT sampled during feeding studies (n = 41) ranged from 59 to 104 cm FL with a mean of 83 cm FL (± 2 SE). Sardine and anchovy occurred in 36.6% and 19.5% of

stomachs examined, respectively; 51.2% of the stomachs contained at least one of these species (Table 3). Sardine comprised 51.8% by weight of the identifiable gut contents, and 30.8% by weight of all the gut contents (Table 3). Blue mackerel, arrow squid, jack mackerel, trevalla, skipjack trevally, and leatherjackets occurred in <10% of stomachs examined (Table 3). Although blue mackerel was found in the stomachs of only four individuals, this species is larger than many of the other prey items and comprised 30.2% by weight of the identifiable gut contents.

Table 3. Food items in the stomachs of southern bluefin tuna collected in waters of the GAB in 1999 and 2000. n = number of stomachs containing each prey species; %Wt = total weight of prey species (Wt)/total weight of identified prey species.

Taxa	n	% n	Wt (g)	% Wt.
Sardine <i>S. sagax</i>	15	36.6	633.0	50.0
Anchovy <i>E. australis</i>	8	19.5	106.7	8.4
Saury <i>S. saurus</i>	2	4.9	45.1	3.6
Blue mackerel <i>S. australasicus</i>	4	9.8	369.3	29.2
Arrow squid spp.	3	7.3	34.3	2.7
Jack mackerel <i>Trachurus</i> spp.	1	2.4	11.9	0.9
Spotted trevalla <i>S. punctata</i>	1	2.4	64	5.1
Skipjack trevally <i>P. wrighti</i>	1	2.4	1.4	0.1
Leatherjacket <i>Meuschenia</i> spp.	1	2.4	1.0	0.1
Unidentified	33	80.0	836.7	
Total	41		2103.42	100.0

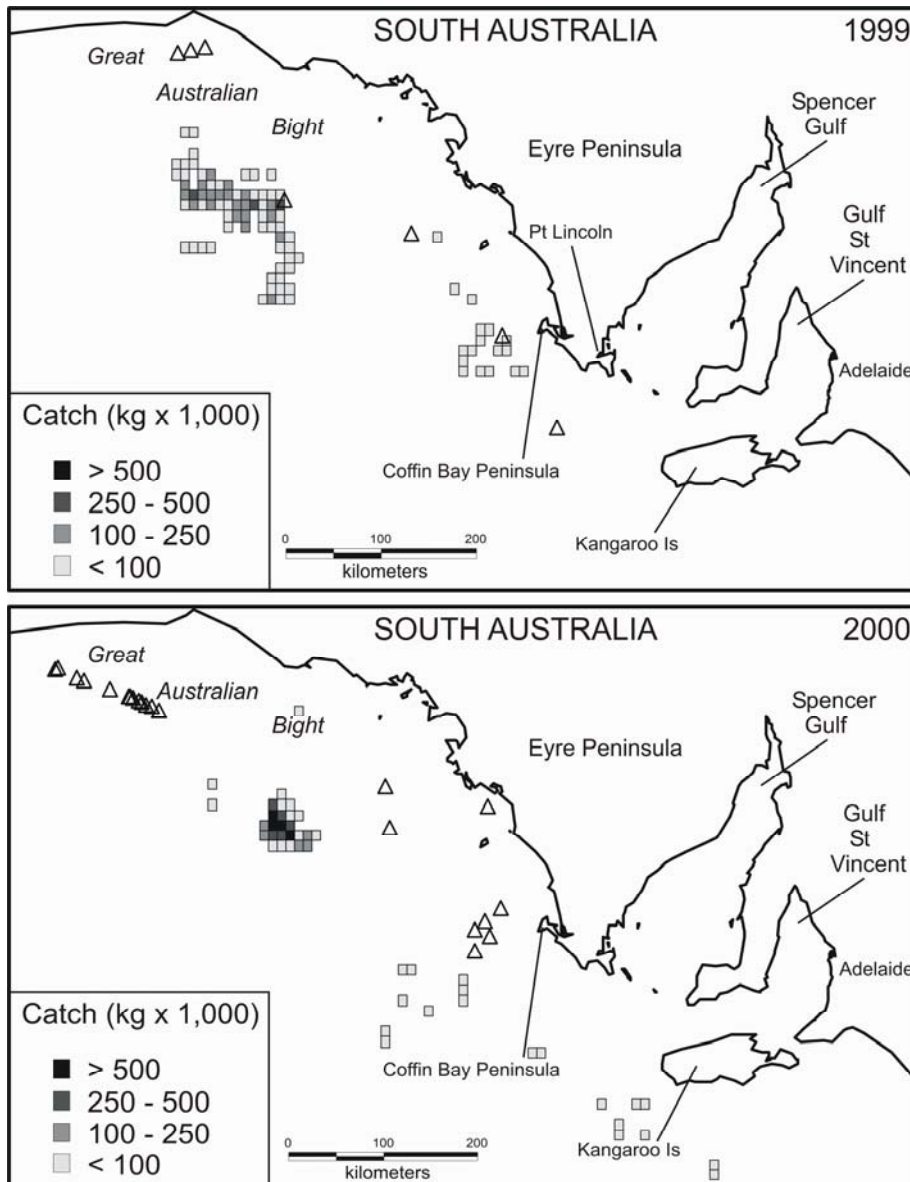


Figure 22. Distribution of commercial catches in 6 x 6 nautical mile grid squares and locations where juvenile SBT were collected for dietary studies (open triangles).

5.2 Other large pelagic fishes

Of 818 stomachs examined during a recent Honours study of the diets of pelagic fishes, 386 contained prey remains, which represented 32 separate taxa (Caines, 2005). Samples were collected from commercial catches and by fishery independent sampling at locations in Spencer Gulf, Investigator Strait and the GAB. Fishes were the most important prey group, with the exception of for barracouta (*Thyrsites atun*) and swallowtail (*Centroberyx lineatus*), which feed in the surface layer at night (Table 5). Barracouta consumed slightly more cephalopods than fishes. Cephalopods were the next most important prey group with biomass mainly comprised of arrow squid (*Nototodarus gouldi*).

A total of 195 tuna (southern bluefin *T. maccoyii*, albacore *T. alalunga*, Australian bonito *Sarda australis* and skipjack *Katsuwonus pelamis*) were sampled using deep diving lures in the eastern GAB between 1999 and 2005. Of these, 179 contained prey remains, comprising 1,190 individual prey items from 17 taxa. Fishes comprised 82.2% of the diet and cephalopods made up ~17.5% (Table 4). Sardine was the most important prey species (37.1%), occurring in 29.5% of stomachs examined (Table 4).

A total of 439 stomachs from Western Australian salmon (*Arripis truttacea*) were examined. Only 74 (18%) contained prey remains. Fish was the most important prey group, and contributed 99.4% to prey biomass. Cephalopods contributed 0.6% of prey biomass. The most important fish prey by biomass were redbait (28.5%) and anchovy (17.1%).

A total of 42 stomachs from yellowtail kingfish *Seriola lalandi* were examined. Of these, 33 (78.6%) contained a combined total of 880 individual prey items, which represented 11 different taxa. Fish (50.8%) and cephalopod (45.8%) were important prey with krill making up the remaining 3.4%.

Of the 33 barracouta captured, 24 (72.7%) contained the remains of 53 individual prey, which represented seven taxa. Fish were more important prey items than cephalopods and arrow squid contributed the entire cephalopod component. (Table 4). Krill were present in small numbers.

One sample of 23 snook *Sphyraena novaehollandiae* was collected from Althorpe Island. Prey items were found in 19 fish and 8 different prey taxa were represented. In total, 29 prey items were recovered. The most important prey group was fish, which comprised 92.6% of the total prey biomass. Cephalopods comprised 7.2% of total biomass.

Table 4. Percentage prey biomass for 24 prey groups of 7 pelagic predators. The prey groups are summarised to 3 major prey groups: fishes, cephalopods, and other prey

PREY TYPE	TUNA		KINGFISH		SALMON		BARRACOUTA		SNOOK		BONITO		SWALLOWTAIL	
	Biomass (%)	Biomass (g)	Biomass (%)	Biomass (g)	Biomass (%)	Biomass (g)	Biomass (%)	Biomass (g)	Biomass (%)	Biomass (g)	Biomass (%)	Biomass (g)	Biomass (%)	Biomass (g)
Fish	82.2	9010.2	50.8	2256.1	99.4	710.4	43.5	187.7	92.6	142.3	100	196.1	-	-
Pilchard	37.1	4043.1	2.3	102.4	9.4	71.9	2.7	11.9	18.8	28.8	100	196.1	-	-
Anchovy	18.2	1992.6	-	-	17.1	145.3	3.8	16.3	13.9	21.3	-	-	-	-
<i>Trachurus</i> sp.	17.2	1882.6	8.5	377.8	-	-	1.1	4.9	-	-	-	-	-	-
Redbait	9.0	986.9	12.3	546.2	28.5	199.1	29.2	125.8	-	-	-	-	-	-
Swallowtail	0.3	35.9	1.1	50.0	-	-	-	-	-	-	-	-	-	-
Saury	0.2	21.5	-	-	-	-	-	-	-	-	-	-	-	-
Blue sprat	0.1	7.9	-	-	-	-	-	-	-	-	-	-	-	-
Tommy rough	0.1	6.2	0.9	38.4	5.8	25.1	-	-	-	-	-	-	-	-
Blue mackerel	-	3.9	3.6	158.4	-	-	6.7	28.9	-	-	-	-	-	-
Silver fish	-	-	-	-	5.6	48	-	-	-	-	-	-	-	-
Silver trevally	-	-	20.5	911.7	-	-	-	-	-	-	-	-	-	-
Species C	-	-	1.6	71.2	-	-	-	-	-	-	-	-	-	-
Slender bullseye	-	-	-	-	7.8	67.9	-	-	51.8	79.7	-	-	-	-
Common bullseye	-	-	-	-	3.6	31.3	-	-	-	-	-	-	-	-
Garfish	-	-	-	-	11.3	65.7	-	-	-	-	-	-	-	-
Silverbelly	-	-	-	-	2.8	12	-	-	-	-	-	-	-	-
Labridae	-	-	-	-	7.6	44.1	-	-	-	-	-	-	-	-
Maray	-	-	-	-	-	-	-	-	8.1	12.5	-	-	-	-
Cephalopods	17.5	1917.0	45.8	2031.5	0.6	2.6	56.5	244	7.2	11.1	-	-	-	-
Arrow squid	17.4	1906.5	44.7	1982.4	0.6	2.6	56.5	244	7.2	11.1	-	-	-	-
<i>Sepia</i> sp.	0.1	10.5	1.1	49.1	-	-	-	-	-	-	-	-	-	-
Other	0.3	29.7	3.4	150.2	-	-	-	-	0.2	0.2	-	-	100	20
Mantis shrimp	0.3	29.7	-	-	-	-	-	-	-	-	-	-	-	-
Crab zoe	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Australian krill	-	-	3.4	150.2	-	-	-	-	0.1	0.1	-	-	85	17
Copepods	-	-	-	-	-	-	-	-	0.1	0.1	-	-	15	3
TOTAL	100	10956.9	100	447.8	100	713	100	431.7	100	153.6	100	196.1	100	20

5.3 Arrow squid *Nototodarus gouldi*

From the stomach contents of 164 arrow squid sampled from the eastern GAB, 23 prey taxa were identified in the diet (Roberts, 2007). At a broad scale, fish were dominant by biomass at 40.8% (33.3% FOO, frequency of occurrence). The most important prey of arrow squid in this region was krill (24.7%, 22.3%), unidentified fish (22%, 17.3%), unidentified cephalopod (11.8%, 7.9%), jack mackerel (6.3%, 4.3%), nereid polychaetes (5.1%, 15.4%), arrow squid (4.9%, 5.7%), sardine (4.2%, 3.2%), unidentified crustacean (4.2%, 3.6%) and amphipod (4.1%, 7.5%).

Nineteen prey taxa were identified from the stomachs of arrow squid from the western GAB, of which fish (46.7%, 44.0%), cephalopods (34.4%, 35.1%) and crustaceans (18.3%, 18.7%) were dominant. The most common prey were unidentified fish (28.1%, 22.0%), cephalopods (22.0%, 20.8%), crustaceans (10.1%, 12.1%), krill (8.2%, 6.6%), arrow squid (6.5%, 8.8%), anchovy (4.8%, 3.3%), maray (4.8%, 6.6%) and ommastrephids (4.5%, 3.3%).

5.4 New Zealand fur seal *Arctocephalus forsteri*

New Zealand fur seals (NZFS), *A. forsteri* consume the greatest biomass of pelagic resources of all marine mammal and seabird species that breed on the islands and along the coast in the GAB (Goldsworthy et al. 2003). *A. forsteri* are abundant in SA waters with >17,600 pups produced over the 2005/06 breeding season (Goldsworthy et al. unpublished data, Shaughnessy 2006), representing ~84% of Australia's total NZFS population. The majority of NZFS breeding populations off SA are found on Liguanea, Neptune Islands and Kangaroo Island. Collectively, these islands account for 86% of Australia's pup production. NZFS are present year round and feed predominantly on pelagic fish and squids (Page et al. 2005). NZFS feed on other key predators of small pelagic fishes including arrow squids and little penguins. If current estimates of population growth are sustained, the NZFS population in SA may double within the next 10–15 years. Upwelling appears to affect the foraging patterns of this species and seals from Kangaroo Island forage mainly on the shelf during the summer-autumn upwelling season (Fig. 13) and up to 500 km offshore during winter (Fig. 14) when upwelling is not occurring (A. Bayliss, unpublished data)(Page, et al. 2006).

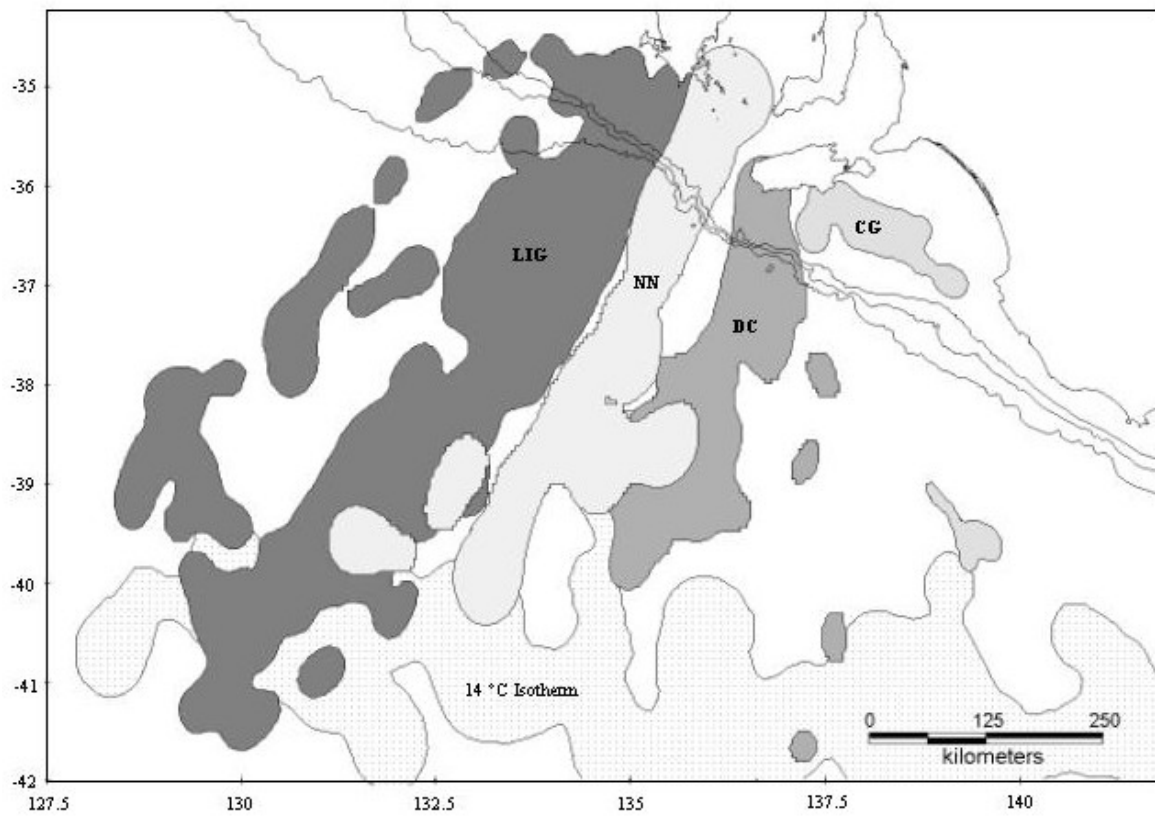


Figure 23. The autumn meta-home range of female NZFS from four breeding colonies in SA, Cape Gantheaume (CG), Cape du Couedic (DC), North Neptune Island (NN), and Liguanea Island (LIG), and the average location of the 14 °C isotherm calculated for April.

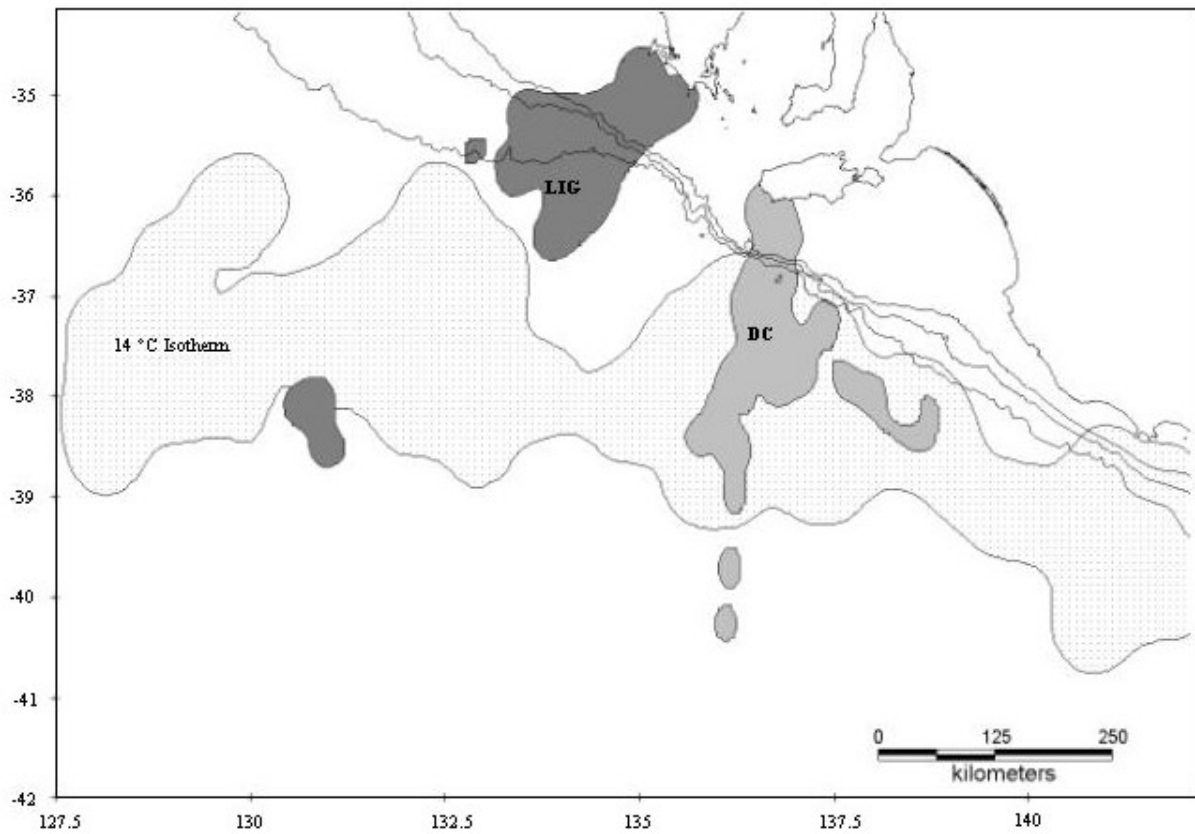


Figure 24. The winter meta-home range of female NZFS from Cape du Couedic (DC) and Liguanea Island (LIG), and the average location of the 14 °C isotherm in June/July.

5.5 Crested terns *Sterna bergii*

Crested terns, *Sterna bergii* have an extensive global range and form breeding colonies in tropical and subtropical coastal areas and on islands between South Africa and the western Pacific region. In South Africa, the number of breeding pairs of crested tern within colonies was related to the combined biomass of anchovy and sardine (Crawford et al., 2003). In Victoria, up to 88% of the diet of crested tern chicks is comprised of anchovy (*E. australis*), jack mackerel (*T. declivus*) and barracouta (*Thyrites atun*) (Chiaradia et al., 2002).

More than 30 colonies comprising between 13,000 and 25,000 breeding pairs occur in SA (Copley, 1996) and at least 19 breeding colonies are located within Spencer Gulf and Gulf St Vincent. Recent population estimates in SA suggest there were between 2,500 and 3,500 breeding pairs at Troubridge Island in 2004/05 and 2005/06 and up to 5,000 pairs in 2006/07 (L. McLeay, unpublished data). At Goose Island in Spencer Gulf there were between 1,500 and 2,500 breeding pairs in 2005/06, however for the first time in 20 years no breeding occurred at Goose Island in 2006/07. Between 500 and 1,500 breeding pairs were counted at Daly Head Island in the 2004/05 season.

A total of 20 prey species groups were identified from 442 observations of prey delivery to chicks at Troubridge Island in 2005/06. *S. sagax*, *E. australis* and *S. robustus* comprised 34% of all observations. Leatherjackets (Monacanthidae) and barracouta represented 17.9% and 13.1%, respectively. A total of 31 species groups comprising 601 individuals were identified from regurgitations of adults. A total of 31 species groups comprising 573 individuals were identified from regurgitations of chicks.

Data for the top ten taxa present in diet samples of chicks and adults are presented in Table 5. *S. sagax*, *E. australis* and *S. robustus* comprised ~50% of individual prey items present in chick and adult diet samples combined. Degen's leatherjackets *Thamnaconus degeni* comprise nearly 30% of all individuals found in adult diet samples. *E. australis* was more prevalent in the diet of chicks than those of adults (30% v 10%). *S. sagax* comprised ~10% of individual prey in diet samples collected from both chicks and adults (L. McLeay, unpublished data).

Table 5. Percent occurrence of different prey types fed to crested tern chicks at Troubridge Island in 2005/06.

Prey spp	ADULTS		CHICKS	
	N observations	% occurrence	N observations	% occurrence
Degen's leatherjacket (<i>Thamnaconus degeni</i>)	170	28.3	22	3.8
Unidentified Clupeoids	168	28.0	86	15.0
<i>Engraulis australis</i>	62	10.3	174	30.4
<i>Sardinops sagax</i>	54	9.0	62	10.8
Insects	26	4.3	0	0.0
<i>Hyporhamphus melanochir</i>	23	3.8	17	3.0
Family Monacanthidae	21	3.5	18	3.1
<i>Parapriacanthus elongatus</i>	14	2.3	0	0.0
Unidentified fish	14	2.3	32	5.6
<i>Thyrsites atun</i>	14	2.3	46	8.0
<i>Spratelloides robustus</i>	0	0	27	4.7
<i>Arripis georgianus</i>	0	0	35	6.1
	N	566	519	

5.6 Little penguins *Eudyptula minor*

Little penguins *E. minor* feed on sardines anchovies and sprats in Victoria and Tasmania (Montague and Cullen, 1988; Dann et al., 2000; Chiaradia et al., 2003). Little penguins mostly consumed anchovies and sardines until the mid 1980s (Montague and Cullen, 1988; Cullen et al., 1992) when bait fishing increased in the region. Sardine mass mortalities in 1995 and 1998 (Ward et al., 2001b) coincided with further reduction of these prey species in the diets of these populations (Dann et al., 2000), which affected breeding success. The little penguin population in SA represents a mid to high-level predator of small pelagic fish in the eastern GAB and southern gulf waters.

Penguins from six colonies across the eastern GAB and gulfs (Troubridge, Reevesby, Olive, Franklin, Greenly and Pearson Islands) prey on anchovy, sardine, blue sprat, saury, bullseye, blue mackerel, redbait, silver belly, sand trevally and arrow squid. Species including leatherjackets, garfish, pipefish were also taken in sea-grass habitats. Diets varied between region and season but anchovies (80–100 mm) were the dominant prey consumed at all colonies (Fig. 15) especially during the winter breeding season. Some colonies, such as Franklin Island in the Nuyts Archipelago almost exclusively consumed anchovies (>95% of the diet by weight). Juvenile sardines ranging in size from 50–80 mm were also common at all colonies especially throughout winter. Conversely, squid only equated to <1% of penguin diet biomass.

Little penguins from different colonies display significant variation in foraging distances and trip durations during the breeding season (Fig. 16) (Wiebkin, 2005). For example, birds from Pearson Island foraged across a wide area of up to 100 km from the colony and mostly towards shallower water, in an easterly direction, whereas birds from Reevesby Island, most foraged 35–40 km from the colony. By comparison, there was a very localised foraging area of only 5–10 km around the Troubridge Island colony. Birds from the Pearson and Troubridge Island colonies were tracked during 2004 and 2005 and showed minimal inter-annual variation in foraging distance. This supports the suggestion that these areas hold reliable food sources during the breeding seasons. Pearson Island foraging trips ranged from 1-12 days at sea with 17.2% of trips longer than 2 days. Troubridge Island birds generally only spent 1 day at sea with only 2% of trips longer than 2 days duration.

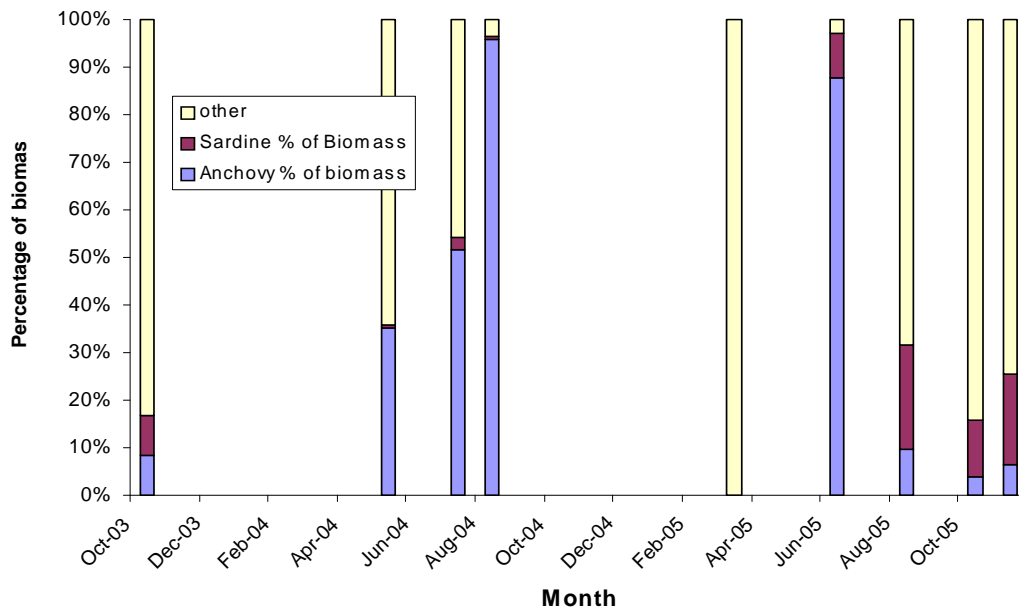


Figure 25. Percentage of anchovy and sardine in the diet of little penguins at Troubridge Island.

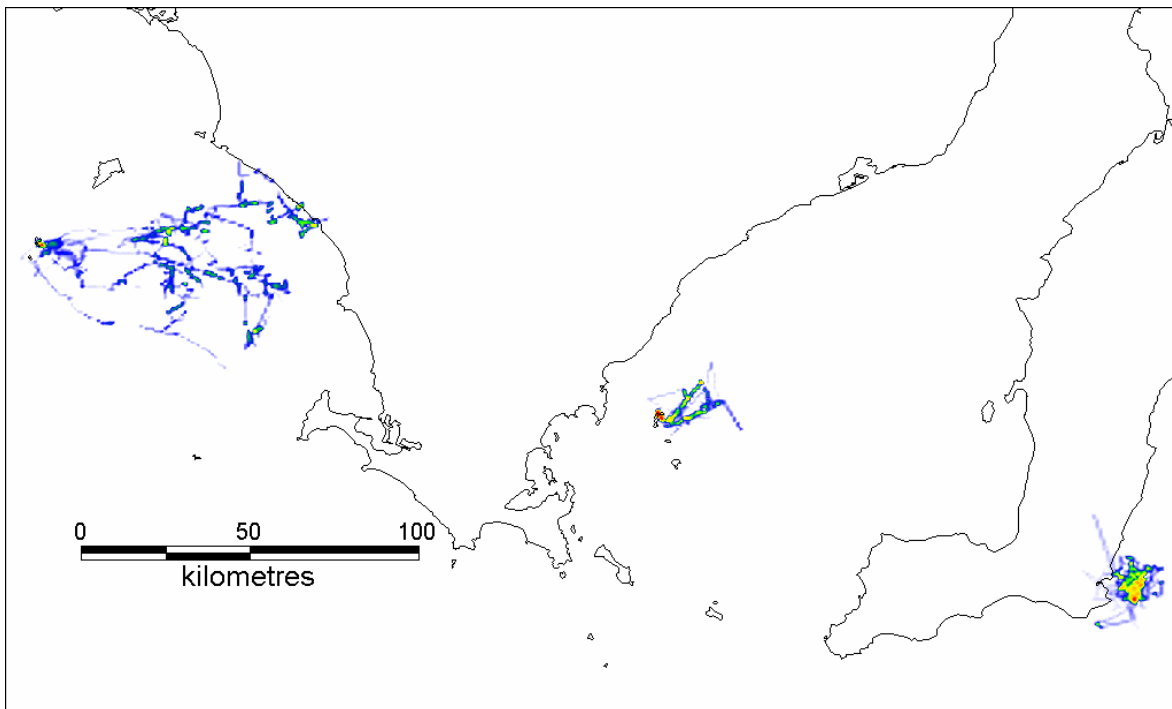


Figure 26. Proportional time spent foraging in areas of 1 x 1 km grids by breeding little penguins from Pearson (n=11), Reevesby (n=5) and Troubridge Island (n=24) colonies in winter 2004. Proportional time spent in each grid is indicated by colour where blue indicates <1%, yellow <2%, green <3% and red <4%.

5.7 Short-tailed shearwater *Puffinus tenuirostris*

The short-tailed shearwater (STSW) *Puffinus tenuirostris* represent ~60% of the seabird community present in SA during summer. There are 33 offshore island colonies that support an estimated 800,750–900,750 breeding pairs (Copley, 1996). During the 90 day chick rearing period, each adult shearwater conducts both single day short duration and long duration foraging trips. Satellite tracking shows that adults forage over neritic waters during the short foraging trips and along frontal zones in the Southern Ocean during long trips (Fig. 17)(Einoder and Goldsworthy 2005). A preliminary assessment of broad prey types in meals delivered after short duration trips throughout the chick-rearing period indicates that 65% were fish, 30% were krill, and 5% were squid. These preliminary results reflect the broad prey groups documented by dietary studies in other parts of the broad distribution of this species (Montague et al., 1986; Skira, 1986; Weimerskirch and Cherel, 1998).

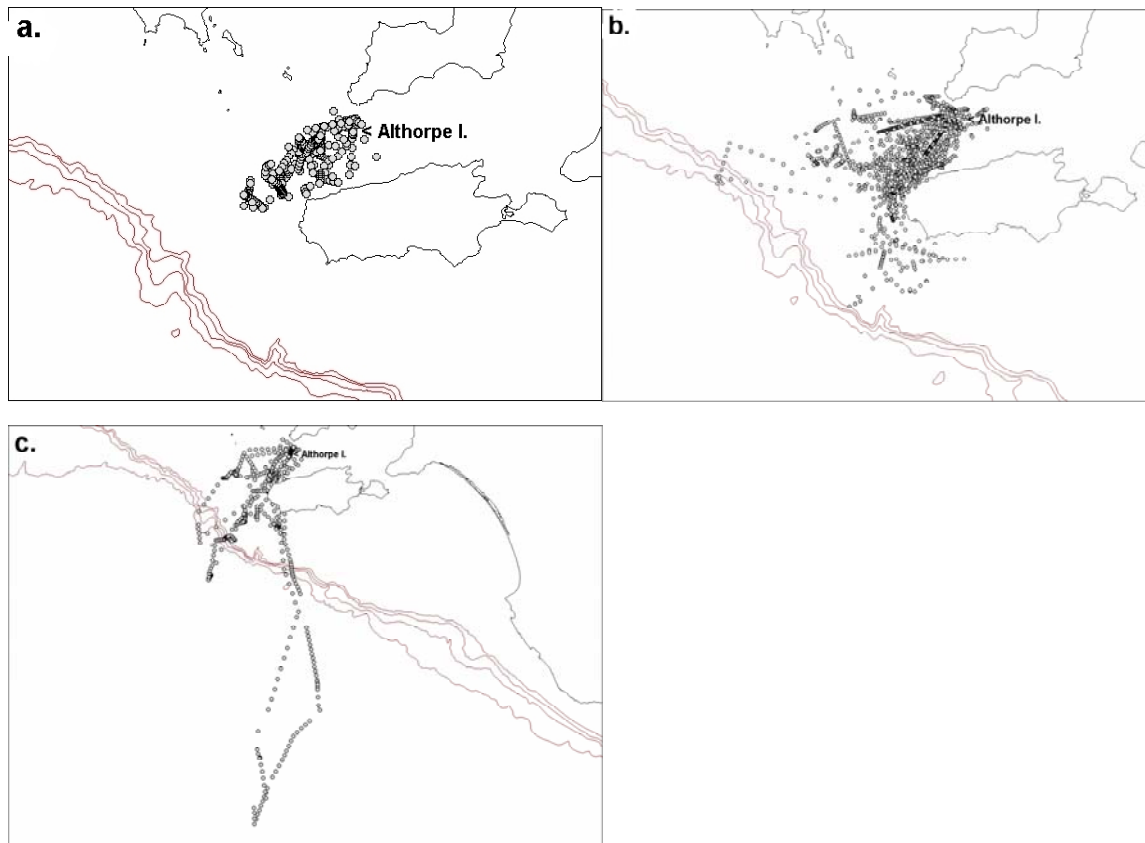


Figure 27. The at-sea movements of satellite tracked short-tailed shearwaters undertaking foraging trips from Althorpe Island. in: a.) February 2005 (n = 6); b.) February 2006 (n = 27); c.) and February 2007 (n = 6). Points represent the output of the time-track program giving a location every 15 minutes.

5.8 Pelagic sharks

There is a general lack of information on the roles of sharks in pelagic ecosystems due to the difficulties associated with studying these large and scarce apex predators. This is especially true in SA waters where only limited, unpublished dietary information collected by SARDI Aquatic Sciences during observer programs is available for some species including bronze whaler *Carcharhinus brachyurus*, thresher shark *Alopias vulpinus* and smooth hammerhead *Sphyrna zygaena*.

Bronze whaler Carcharhinus brachyurus

Thirty seven bronze whaler *C. brachyurus* stomachs from GAB waters were examined for dietary analysis with 30 stomachs (81.1%) containing prey items (Table 3). A total of 271 prey items were found. Sardine were the most consumed prey (91.0%). Bronze whaler sharks were also found to prey upon cephalopods (mostly Ommastrephidae, 4.7%) and crustaceans with a crab claw found in one stomach. Large amount of sardines were found in 46.7% of the stomachs dissected with up to 41 sardines found in one stomach.

Thresher shark Alopias vulpinus

Twenty four thresher shark *A. vulpinus* stomachs from GAB waters were examined for dietary analysis with 16 stomachs (66.7%) containing prey items. A total of 239 prey items were found and *E. australis* being the most consumed prey (87.6%). The lack of cephalopod and the high proportion of anchovies in the diet of *A. vulpinus* are consistent with previous studies (Preti et al. 2001; Preti et al. 2004).

Smooth hammerhead Sphyrna zygaena

Ten smooth hammerhead *S. zygaena* stomachs from GAB waters were examined for dietary analysis with 9 stomachs (90.0%) containing prey items (Table 3). A total of 47 prey items were found with cephalopods being the most consumed category (68.8%). Smooth hammerhead mostly preyed upon Loliginidae (40.4%) and Ommastrephidae (27.2%), with osteichthyes (mostly unidentified fish) participating in 31.0% of the diet. Sardine were also found in the stomachs dissected but did not strongly contribute to the diet of smooth hammerheads. The high proportion of cephalopod remains found in the stomach of *S. zygaena* was consistent with previous studies (Stevens, 1989; Cortés, 1999).

6.0 Conceptual Food-web

6.1 Background

Information on the diets of predators in Section 5 was used to develop the preliminary conceptual food-web model in this section. This information will be used to develop a trophodynamic model for the GAB pelagic ecosystem, which is a key output of a current FRDC Project (2005/031) to be completed in 2008.

Based on dietary data available in summer-autumn 2007, a conceptual food web detailing the trophic relations among species groups was developed using ECOPATH software (Christensen and Pauly, 1993, Polovina, 1984). At the time of preparation of this report, this model excluded a number of important taxa (e.g. sharks and some species of small pelagic fish), and many other groups were poorly resolved (e.g. cephalopods) (Fig. 18). Given that most of the input data has focused around large pelagic predators, including seals, seabirds and large pelagic fish, the trophic relationship between these species and their prey are the most resolved. Two main groups of small pelagic fish were designated for this food-web, one including sardines and anchovies, and another group including redbait and jack mackerel. This will be revised following the results of a recently completed small pelagic fish dietary study. Presently other small pelagic species are not included but will be considered in future model runs.

NZFS formed the highest trophic level (4.51), followed by the kingfish/samsonfish group (4.48), sea lions (4.37), dolphins (4.32), shags (4.32) and little penguins (4.12). Most of the fish groups occurred at trophic levels between 3 and 4, with the exception of sardines/anchovies (2.60) (Fig. 18). Small pelagic fish clearly underpin the diets of large pelagic fish, fur seals, dolphins, little penguins and terns. A number of key findings from this provisional model have been used to direct further work to ultimately improve the model. Three critical points are briefly summarized below:

6.2 Diets of small pelagic fish

Provisional analyses confirmed the importance of small pelagic fish in the eastern GAB ecosystem. These species underpin populations of large pelagic fish, squid and seabirds, seals and some cetaceans. The current model poorly resolves the trophic relationships of individual small pelagic species. To this end, an Honours project was developed in 2006 and was

completed in November 2007. The project resolved the diets of the main small pelagic fish species in the eastern GAB (see above), and this information will be integrated in future model being developed throughout 2008.

The role and importance of arrow squid

One of the most responsive species to changes in the abundance of small pelagic fish (in terms of positive changes in biomass) is arrow squid. As with most cephalopod species, arrow squid biomass can respond rapidly to changes in the biomass of available prey, because of their rapid generation time and semelparous life-history. Trophic analyses suggest that arrow squid are key predators of small pelagic fishes; as such any species that predate on or competes with arrow squid may exert significant controls on the amount of small pelagic fish consumed by arrow squids and as a consequence, the biomass of small pelagic fish that may be available to other predators. Results from an Honours project completed in 2007 (presented herein) will form model inputs and facilitate a better understanding of the diets of arrow squid in the eastern GAB.

The role of pelagic sharks

Trophodynamic analyses clearly demonstrated the paucity of information on the ecological role and importance of pelagic shark species in the GAB. These species are apex predators and occupy similar trophic levels to those occupied by seals and seabirds. Some dietary information from stomach samples collected as bycatch is available and more will be collected during 2008 as part of a PhD project on pelagic sharks.

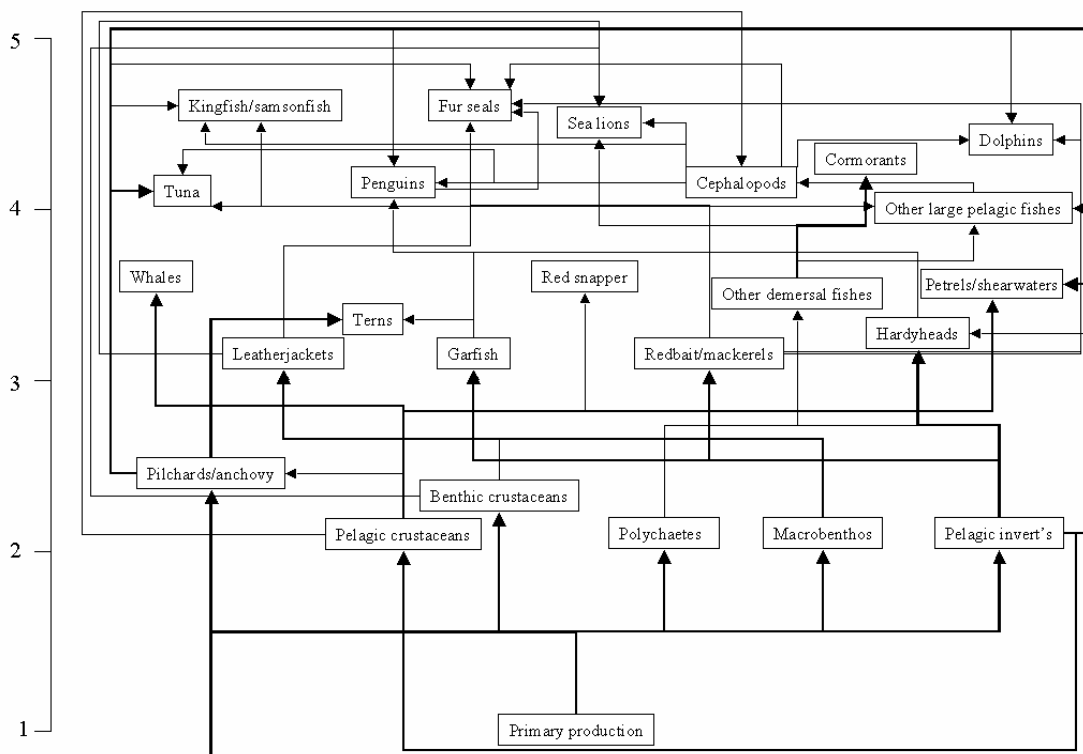


Figure. 28. Simplified food-web summarising the main trophic interactions among species groups in the eastern GAB. Species' trophic levels are indicated on the left. To improve clarity, dietary contributions $\geq 50\%$ are indicated by bold lines, contributions $< 50\%$ are indicated by fine lines and contributions $< 10\%$ have been omitted.

7.0 General Discussion

7.1 Summary

Marine waters off SA support three distinct ecosystems (Fig. 1), the two gulfs, shelf waters of the Bonney coast and the eastern and western GAB. Gulf St Vincent and Spencer Gulf are managed by the SA Government, and a comprehensive and representative system of marine protected areas is currently being established for these environments, under separate arrangements to the marine planning process which is underway for the SWMR. Relatively little information is available on the small pelagic fishes of the western GAB. Hence, this report focuses mainly on the small pelagic fishes and large marine predators of the shelf waters of the Bonney coast and the eastern, which is becoming known as the Flinders Current System.

Sardines, maray, blue mackerel and *Trachurus* spp. are abundant in the mouths of both gulfs and in waters overlying the continental shelf. Anchovy are also abundant over the inner continental shelf during years when sardine abundance is reduced. Studies to investigate the factors that are associated with inter-annual variations in the composition of the pelagic fish assemblage off Flinders Current System are currently underway.

The dominant oceanographic feature of the Flinders Current system is the upwelling events that occur during summer and autumn off the Bonney Coast and in the eastern GAB. The high abundance of sardines and anchovy recorded in the eastern GAB has been linked to the enhancement of primary productivity through upwelling. The occurrence of large numbers of blue mackerel and SBT in the western GAB has also been correlated with the warming influence of the Leeuwin Current.

The ecological importance of the Flinders Current ecosystem is highlighted by the presence of regionally important populations of marine mammals, seabirds and pelagic sharks that aggregate in, or migrate to, this region during summer and autumn. Information presented in this report suggests that small pelagic fishes (and cephalopods) are critical components of the diets of many large marine and land-breeding predatory species, most of which are internationally listed as threatened (pelagic sharks), critically endangered (SBT) and/or protected (seabirds and marine mammals).

7.2 Status of Current Knowledge

By Australian standards the biology and ecology of the assemblage of small pelagic fishes in waters off SA is relatively well known, with approximately 12 papers in peer reviewed journals and 22 technical reports being published since 1998. Significant information is available for sardine, anchovy and blue mackerel and some data has been collated on blue and sandy sprats. However, significant gaps remain in current knowledge of several species, such as maray, which have low commercial potential. This bias in our current knowledge base for small pelagic fishes reflects the dominance of funding for fisheries related research and relative paucity of funding for research to address other management issues in the Flinders Current System.

The biology, diet and foraging ecology of predatory fishes, seabirds and marine mammals in the Flinders Current System is also well studied by Australian standards. Since 2001, a significant number of papers, reports and theses have been published on key marine predators. A large proportion of the funding for these studies has been provided by the SA Government, fishing industry and Fisheries Research Development Corporation to ensure that SA fisheries in the region are managed according to the principles of Ecologically Sustainable development. A current study (FRDC Project 2005/031) is explicitly examining the relative importance of small pelagic fishes, especially sardines, in the diets of key predators in the region, with the goal of assessing the need to establish ecological performance indicators for the SASF. Integral to this assessment is detailed modelling of the trophodynamic structure and ecological function of the Flinders Current System. The outcomes of this project, which will be finalised in 2008, will provide a sound basis for future management of the Flinders Current Ecosystem, including the populations of marine predators which forage on small pelagic fishes.

References

- Baylis, A. M. M., Page, B., Goldsworthy, S. (in press b). Seasonal changes in upwelling activity effect the foraging locations of a wide-ranging central place forager, the New Zealand fur seal. *Canadian Journal of Zoology*.
- Bruce, B. D. and Short, D. A. (1990). Observations on the distribution of larval fish in relation to a frontal system at the mouth of Spencer Gulf, South Australia. *Bureau of Rural Resources Proceedings* **15**: 124-137.
- Bye, J. A. T. (1972). Oceanographic circulation south of South Australia. Antarctic Oceanography II. The Australian-New Zealand Sector. Antarctic Research Series. *American Geophisics Union*. **19**: 95-100.
- Bye, J. A. T. (1983). The General-Circulation in a Dissipative Ocean-Basin with Longshore Wind Stresses. *Journal of Physical Oceanography* **13**(9): 1553-1563.
- Chiaradia, A., Dann, P. Jessop, R. and Collins, P. (2002). The diet of crested tern (*Sterna bergii*) chicks on Phillip Island, Victoria, Australia. *Emu* **102**: 367-371.
- Chiaradia, A., Costalunga, A. and Knowles, K. (2003) The diet of Little Penguins (*Endyptula minor*) at Phillip Island, Victoria, in the absence of a major prey-Pilchard (*Sardinops sagax*). *Emu*, **103**: 43-48.
- Christensen, V., and Pauly, D. (1993). Flow characteristics of aquatic ecosystems. (In "Trophic models of aquatic ecosystems"; Eds. Christensen, V., and Pauly, D.) ICLARM Conference Proceedings No. 26, p. 338-352.
- Caines, R., (2005). Trophic Guild-Structures in Pelagic Fish Communities in the Eastern Great Australian Bight Ecosystem. Honours thesis, University of South Australia.
- Copley, P.B. (1996). The status of seabirds in South Australia. Pp 139-181 In: The status of Australia's seabirds: Proceedings of the National seabird Workshop, Canberra, 1-2 November 1993. Biodiversity Group, Environment Australia: Canberra vii + 237 pp.

- Cortés, E. (1999). Standardised diet compositions and trophic levels of sharks. *ICES Journal of Marine Science* **56**: 707-717.
- Cullen, J. M., Montague, T. L. and Hull, C. (1992). Food of Little Penguin *Eudyptula minor* in Victoria: Comparison of three localities between 1985 and 1988. *Emu*, **91**: 318-341.
- Crawford, R. J. M., Cooper, J., Dyer, B. M., *et al.*, (2003). Populations of surface nesting seabirds at Marion Island, 1994/95-2002/03. *African Journal of Marine Science*, **25**: 427-440.
- Daly, K. 2007. The diet and guild structure of the small pelagic fish community in the eastern Great Australian Bight, South Australia. Honours Thesis, University of Adelaide.
- Dann, P., Norman, F. I., Cullen, J. M., Neira, F. J. and Chiaradia, A. (2000). Mortality and breeding failure of little penguins, *Eudyptula minor*, in Victoria, 1995-96, following a widespread mortality of pilchard, *Sardinops sagax*. *Marine and Freshwater Resources*. **51**: 355-362.
- Dimmlich, W. F., Breed, W. G., Geddes, M. and Ward, T. M. (2004). Relative importance of gulf and shelf waters for spawning and recruitment of Australian anchovy, *Engraulis australis*, in South Australia. *Fisheries Oceanography* **13**(5): 310-323.
- Dimmlich, W. F. and Ward, T. M. (2006) Ontogenetic shifts in the distribution and reproductive patterns Australian anchovy (*Engraulis australis*) determined by otolith microstructure analysis. *Marine and Freshwater Research* **57**(5): 373-381.
- Einoder, L. D. and Goldsworthy, S. D. (2005) Foraging flights of short-tailed shearwaters (*Puffinus tenuirostris*) from Althorpe Island: assessing their use of neritic waters. *Transactions of the royal society of South Australia*. **129**: 209-216
- Furness, R. W. and Cooper, J. (1982). Interactions between breeding seabird and pelagic fish populations in the Southern Benguela region. *Marine Ecology Progress Series*, **8**: 243-250.

- Gaughan D. J, Fletcher W. J, Tregonning R. J. and Goh, J. (1996): Spatial and seasonal distribution of eggs and larvae of sandy sprat, *Hyperlophus vittatus* (Clupeidae), off South western Australia. *Marine and Freshwater Research* **47**: 971–9.
- Goldsworthy, S. D., Bulman, C., He, X., Larcombe, J. and Littnan, C. (2003). Trophic interactions between marine mammals and Australian fisheries: an ecosystem approach. In: Gales, N., Hindell, M. and Kirkwood, R. (eds) *Marine mammals and humans: towards a sustainable balance*. CSIRO Publishing: Melbourne, pp 62-99
- Gunn, J. and Young, J. (1996). Environmental determinants of the movement and migration of juvenile southern bluefin tuna. In: *Fish Movement and Migration. Workshop Proceedings*. D. A.
- Hearn, W. S. (1986). Mathematical models for evaluating marine fisheries. University of New South Wales, Sydney, 195pp.
- Hoedt, F. E. and Dimmlich, W. F. (1995). Egg and Larval Abundance and Spawning Localities of the Anchovy (*Engraulis australis*) and Pilchard (*Sardinops neopilchardus*) near Phillip Island, Victoria. *Marine and Freshwater Research* **46**(4): 735-743.
- Interim Marine and Coastal Regionalisation for Australian Technical Group (1998). Interim Marine and Coastal Regionalisation for Australian: an ecosystem-based classification for marine and coastal environments. Version 3.3. Environment Australia, Commonwealth Department of the environment. Canberra 104p.
- Kailola, P. J., Williams, M. J., Stewart, P. C., Reichelt, A. M. and Grieve, C. (1993). Australian Fisheries Resources. Canberra, Bureau of Resource Sciences, Department of Primary Industries and Energy and the Fisheries Research and Development Corporation.
- Kloser, R., Ryan, T., Sakov, P., Young, J., Stanley, C. and Davis, T. (1998). Assessment of acoustics as a research tool to determine the distribution, biomass and behaviour of southern bluefin tuna school and their prey in the Great Australian Bight. In: *Report of the Tenth Workshop*, 2 Vols. 14-17 September. Hobart, Tasmania: CSIRO.

- Mann, K. H. and Lazier, J. R. N. (1996). *Dynamics of Marine Ecosystems*. Oxford: Blackwell Scientific, 394 pp.
- McClatchie, S., Middleton, J. F. and Ward, T. M. (2006). Water mass analysis and alongshore variation in upwelling strength in the eastern Great Australian Bight. *Journal of Geophysical Research* **111**: 1-13.
- McGarvey, R. and Kinloch, M. A. (2001). An analysis of the sensitivity of stock biomass estimates derived from the daily egg production method (DEPM) to uncertainty in egg mortality rates. *Fisheries Research* **49**(3): 303-307.
- Middleton, J. F. (2000). Wind-forced upwelling: the role of the surface mixed layer. *Journal of Physical Oceanography*. **30**:745-763.
- Middleton, J. F. and Cirano, M. (2002). A northern boundary current along Australia's southern shelves: The Flinders Current. *Journal of Geophysical Research C: Oceans* **107**(9): 3129–3143.
- Middleton, J. F. and Platov, G. (2003). The mean summertime circulation along Australia's southern shelves: a numerical study. *Journal of Physical Oceanography* **33**: 2270-2287.
- Middleton, J. F. and Bye, J. A. T. (2007). A review of the shelf-slope circulation along Australia's southern shelves. Cape Leuwin to Portland. *Progress in Oceanography* **75**: 1-41.
- Montague, T. L., Cullen, J. M., and Fitzherbert, K., (1986). The diet of the short-tailed shearwater *Puffinus tenuirostris* during its breeding season. *Emu*, **86**: 207-213.
- Montague, T. L. and Cullen, J. M. (1988). The diet of the Little Penguin (*Eudyptula minor*) at Phillip Island, Victoria. *Emu*, **88**: 138-148.
- Neira, F. J. (2005). Summer and winter larval fish assemblages around offshore oil and gas platforms in south-eastern Australia. *Estuarine Coastal and Shelf Science* **63**: 589-604.
- Page, B., McKenzie, J. and Goldsworthy, S. D. (2005). Dietary resource partitioning among sympatric New Zealand and Australian fur seals. *Marine Ecology Progress Series* **293**: 283-302.

- Page, B., McKenzie, J., Sumner, M. D., Coyne, M. and Goldsworthy, S. D. (2006). Spatial separation of foraging habitats among New Zealand fur seals. *Marine Ecology Progress Series* **323**: 263-279
- Polovina, J. J. (1984). Model of a coral reef ecosystem I. The ECOPATH model and its application to French Frigate Shoals. *Coral Reefs* **3**:1-11.
- Preti, A., Smith, S. E., Ramon, D. A. (2001). Feeding habits of the common thresher shark (*Alopias vulpinus*) sampled from California-based drift gill net fishery. *California Cooperative Oceanic Fisheries Investigations Report* **42**: 145-152.
- Preti, A., Smith, S. E. and Ramon, D. A. (2004). Diet differences in the thresher shark (*Alopias vulpinus*) during transition from a warm-water regime to a cool-water regime off Californian-Oregon, 1998-2000. *California Cooperative Oceanic Fisheries Investigations Report* **45**: 118-125.
- Roberts, M., (2007). A comparison of morphological and molecular methods to identify the prey of arrow squid in South Australia. Honours Thesis, University of Adelaide.
- Rogers, P. J., Geddes, M. and Ward, T. M. (2003). Blue sprat *Spratelloides robustus* (Clupeidae: Dussumieriinae): A temperate clupeoid with a tropical life history strategy? *Marine Biology* **142**: 809-82.
- Rogers, P. J., and Ward, T. M. (2006). Sardine (*Sardinops sagax*). Fishery Assessment Report. Report to Primary Industries and Resources South Australia. South Australian Research and Development Institute (Aquatic Sciences). SARDI Report No. RD03/0198-3. SARDI Report Series No. 139. 98 pp.
- Rogers, P. J. and Ward, T. M. (2007a). Application of a “case building approach” to investigate the age structure and growth dynamics of Australian sardine *Sardinops sagax* off South Australia *Marine and Freshwater Research* **58**(1): 1-14

- Rogers, P. J. and Ward, T. M. (2007b). Life history strategy of sandy sprat *Hyperlophus vittatus* (Clupeidae): a comparison with temperate and tropical clupeoids of the Indo-Pacific. *Journal of Applied Ichthyology*, **23**(5): 583-591.
- Shaughnessy, P. (2006). Population assessment of fur seals and sea lions at some colonies in South Australia, 2005-06. Report to Department for Environment and Heritage, South Australia. 33 pp., April 2006.
- Skira, I. J. (1986). Food of the short-tailed shearwater, *Puffinus tenuirostris*, in Tasmania. *Australian Wildlife Research*, **13**: 481-488.
- Stevens, J. D., Hausfeld, H. F. and Davenport, S. R. (1984). Observations on the biology, distribution and abundance of *Trachurus declivis*, *Sardinops neopilchardus* and *Scomber australasicus* in the Great Australian Bight. Hobart, CSIRO Marine Laboratories. 164. 29pp.
- Stevens, J. D. and Lyle, J. M. (1989). Biology of three hammerhead sharks (*Eusphyra blochii*, *Sphyrna mokarran* and *S. lewini*) from Northern Australia. *Australian Journal of Marine and Freshwater Research*, **40**: 129-146.
- Weimerskirch, H. and Cherel, Y. (1998). Feeding ecology of short-tailed shearwaters: breeding in Tasmania and foraging in the Antarctic? *Marine Ecology-Progress Series*, **167**: 261-274.
- Ward, P. J., Timmiss, T. and Wise, B. (2001). A review of biology and fisheries for mackerel. Bureau of Rural Sciences, Canberra. 120.
- Ward, T. M., Hoedt, F., McLeay, L., Dimmlich, W. F., Jackson, G., Rogers, P. J. and Jones, K. (2001a). Have recent mass mortalities of the sardine *Sardinops sagax* facilitated an expansion in the distribution and abundance of the anchovy *Engraulis australis* in South Australia? *Marine Ecology Progress Series*, **220**: 241-251.
- Ward, T. M., Hoedt, F., McLeay, L., Dimmlich, W. F., Kinloch, M., Jackson, G., McGarvey, R., Rogers, P. J. and Jones, K. (2001b). Effects of the 1995 and 1998 mass mortality events on the spawning biomass of sardine, *Sardinops sagax*, in South Australian waters. *ICES Journal of Marine Science*, **58**: 865-875.

- Ward, T. M. and Staunton-Smith, J. (2002). Comparison of the spawning patterns and fisheries biology of the sardine, *Sardinops sagax*, in temperate South Australia and sub-tropical southern Queensland. *Fisheries Research*, **56**: 37-49.
- Ward, T. M., Staunton Smith, J., Hoyle, S. and Halliday, I. (2003). Spawning patterns of four species of predominantly temperate pelagic fishes in the sub-tropical waters of southern Queensland. *Estuarine, Coastal and Shelf Science*, **56**: 1125-1140.
- Ward, T. M., Goldsworthy, S. D. and Page, B. (2005). Trophodynamics of the GAB: assessing the need for an ecological allocation in the SA pilchard fishery. Fisheries Research and Development Corporation Final Report. Publication No. RD03/0166-2. 90pp.
- Ward, T. M., Rogers, P. J., Stephenson, P., Schmarr, D. K., Strong, N. and McLeay, L. J. (2005). Implementation of an Age Structured Stock Assessment Model for Sardine (*Sardinops sagax*) in South Australia. Final report to Fisheries Research and Development Corporation. 130.
- Ward, T. M., McLeay, L. J., Dimmlich, W. F., Rogers, P. J., McClatchie, S., Mathews, R., Kampf, J. and Van Ruth, P. D. (2006a). Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine, anchovy and southern bluefin tuna in the eastern Great Australian Bight. *Fisheries Oceanography*, **15**(3): 191-207
- Ward, T. M., Sorokin, S. J., Currie, D. R., Rogers, P. J. and McLeay, L. J. (2006b). Epifaunal assemblages of the eastern Great Australian Bight: Effectiveness of a benthic protection zone in representing regional biodiversity. *Continental Shelf Research*, **26**: 25-40.
- Ward, T. M. and Rogers, P. J. (in press) Evaluating the application of egg-based method for Stock Assessment of Blue Mackerel, *Scomber australisicus*, in southern Australia. Final Report to the Fisheries Research and Development Corporation. 502p
- Wiebkin, A., Page, B., Goldsworthy, S., Paton, D., and Ward, T., (2005). Satellite tracking Little Penguins in South Australia. Oamaru Penguin Symposium, New Zealand

- Wiebkin, A., Page, B. Goldsworthy, S., Paton D. and Ward, T, (2005). A taste for small pelagic fishes: Diets of Little Penguins in South Australia's Sardine Fishery. ASFB Conference, Darwin
- Young, J. W., Bradford, R. W., Lamb, T. D. and Lyne, V. D. (1996). Biomass of zooplankton and micronecton in the southern bluefin tuna fishing grounds of eastern Tasmania. *Marine Ecology-Progress Series*, **138**: 1-14.
- Young, J. W., Lamb, T. D. Russell, W. and Bradford, R. W. (1997). Feeding ecology and annual variation in diet of the southern bluefin tuna (*Thunnus maccoyii*) in relation to the coastal and oceanic waters off eastern Tasmania. *Environmental Biology of Fishes*, **50**: 275-291.
- Young, J. W., Nishida, T. and Stanley, C. (1999). A preliminary survey of the summer hydrography and plankton biomass of the eastern Great Australian Bight. Southern Bluefin Tuna Recruitment Monitoring and Tagging Program. In: *Report of the Eleventh Workshop*. CSIRO, Hobart, 15pp.

Appendix 1. Sardine Fishery Assessment and Spawning Biomass Reports

- Rogers, P. J., Stephenson, P., McLeay, L. J., Dimmlich, W. F. and Ward, T. M. (2004). Sardine (*Sardinops sagax*). South Australian Research and Development Institute Aquatic Sciences. 75.
- Rogers, P. J. and Ward, T. M. (2005). Sardine (*Sardinops sagax*). South Australian Research and Development Institute Aquatic Sciences Series No. 139. 98.
- Ward, T. M., Kinloch, M., G.K., J. and Neira, F. J. (1998). A Collaborative Investigation of the Usage and Stock Assessment of Baitfish in Southern and Eastern Australian Waters, with Special Reference to Pilchards (*Sardinops sagax*). South Australian Research and Development Institute (Aquatic Sciences). Final Report to Fisheries Research and Development Corporation. 324pp.
- Ward, T. M. and McLeay, L. J. (1998). Use of the Daily Egg Production Method to Estimate the Spawning Biomass of Pilchards (*Sardinops sagax*) in Shelf Waters of Central and Western South Australia in 1998. Report to the South Australian Sardine Working Group. South Australian Research and Development Institute Report. 41.
- Ward, T. M. and McLeay, L. J. (1999). Pilchards (*Sardinops sagax*). South Australian Fishery Assessment Series 99/1. 50.
- Ward, T. M. and McLeay, L. J. (1999). Spawning biomass of Pilchards (*Sardinops sagax*) in shelf waters of central and western South Australia in 1999 Report to the South Australian Pilchard Working Group. 41.
- Ward, T. M., McLeay, L. J., Dimmlich, W. F. and Rogers, P. J. (2000). Pilchard (*Sardinops sagax*). South Australian Research and Development Institute (Aquatic Sciences). 53.
- Ward, T. M., McLeay, L. J., Dimmlich, W. F. and Rogers, P. J. (2000). Spawning Biomass of Pilchard (*Sardinops sagax*) in Shelf waters of central and western South Australia in 2000. Report to Primary Industries and Resources South Australia. South Australian Research and Development Institute (Aquatic Sciences). 32.

- Ward, T. M., McLeay, L. J., Rogers, P. J. and Dimmlich, W. F. (2001). Spawning Biomass of Pilchard (*Sardinops sagax*) in South Australia in 2001. Report to Primary Industries and Resources South Australia Fisheries. South Australian Research and Development Institute (Aquatic Sciences). 31.
- Ward, T. M., McLeay, L. J., Rogers, P. J., Schmarr, D., Dimmlich, W. F. and Deakin, S. (2001). Sardine (*Sardinops sagax*). South Australian Research and Development Institute (Aquatic Sciences). 2001/16. 83.
- Ward, T. M., McLeay, L. J., Rogers, P. J., Dimmlich, W. F., Schmarr, D. and Deakin, S. (2002). Spawning Biomass of Sardine (*Sardinops sagax*) in South Australia in 2002. Report to Primary Industries and Resources South Australia Fisheries. South Australian Research and Development Institute (Aquatic Sciences). 33.
- Ward, T. M., McLeay, L. J., Rogers, P. J., Dimmlich, W. F., Schmarr, D. and Deakin, S. (2002). Sardine (*Sardinops sagax*). South Australian Research and Development Institute (Aquatic Sciences). 33.
- Ward, T. M., McLeay, L. J., Rogers, P. J. and Dimmlich, W. F. (2003). Spawning biomass of Sardine (*Sardinops sagax*) in South Australia in 2003. Report to Primary Industries and Resources South Australia. South Australian Research and Development Institute (Aquatic Sciences) 33.
- Ward, T. M., Rogers, P. J., McLeay, L. J., Schmarr, D. and Dimmlich, W. F. (2003). Sardine (*Sardinops sagax*). South Australian Research and Development Institute Aquatic Sciences. 72.
- Ward, T. M., McLeay, L. J. and McClatchie, S. (2004). Spawning Biomass of Sardine (*Sardinops sagax*) in South Australia in 2004. Report to Primary Industries and Resources South Australia. South Australian Research and Development Institute (Aquatic Sciences). 38.
- Ward, T. M., McLeay, L. J. and Rogers, P. J. (2005). Spawning Biomass of Sardine (*Sardinops sagax*) in South Australian waters in 2005. Report to Primary Industries and Resources

South Australia Fisheries. South Australian Research and Development Institute (Aquatic Sciences). 48.

Ward, T. M., Rogers, P. J. and McLeay, L. J. (2006). Spawning biomass of Australian sardine (*Sardinops sagax*) in gulf and shelf waters of South Australia in 2006. Report to Primary Industries and Resources South Australia Fisheries. South Australian Research and Development Institute Aquatic Sciences. 42.

Ward, T. M., Ivey, A. R. and McLeay (2007). Spawning biomass of sardine (*Sardinops sagax*) in South Australia in February - March 2007. SARDI Aquatic Sciences Publication No. F2007/000566-2. 36.

Ward, T. M., Ferguson, G. and Rogers, P. J. (2007). Australian Sardine (*Sardinops sagax*) Fishery. SARDI Aquatic Sciences Publication No. F2007/000765-2. 74.