

# Determination of spawning areas and larval advection pathways for King George whiting in southeastern Australia using otolith microstructure and hydrodynamic modelling.

## II. South Australia

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**ABSTRACT:** Two hypotheses regarding the origin of post-larval *Sillaginodes punctata* that recruit to nursery areas in South Australia were assessed. These were that post-larvae originate either hundreds of kilometres to the west and are delivered by weather-determined ocean currents or they originate from numerous spawning grounds located only <150 km from numerous nursery areas. The hypotheses were tested in 2 ways. We compared recruitment rates and early life-history characteristics amongst post-larvae sampled at 4 sites located up to 500 km apart. Recruitment rates, size structures of recruits and age, size and growth rates of recently-settled fish did not reflect systematic variation amongst sites, suggesting that recruitment was determined at a local, rather than regional scale. We also used numerical hydrodynamic modelling to identify larval advection pathways and possible spawning locations, using larval duration and capture site as input to the model. This modelling suggested that recruits originated at spawning locations that were only a short distance from each nursery area. Results from both studies suggested that the South Australian population is divisible into numerous, discrete, self-recruiting populations, which contrasts with the situation in Victoria where the population constitutes a single large stock. This difference is a likely consequence of regional differences in current regimes, and the influence on larval advection.

**KEY WORDS:** Stock structure · Larval advection · Hydrodynamic numerical modelling · Otolith microstructure · South Australia · *Sillaginodes punctata*

### INTRODUCTION

Marine species are usually divided throughout their geographic distribution into a number of populations or unit stocks, which represent discrete self-recruiting populations. The population dynamics of such stocks are likely to be independent, and because of the restricted exchange of individuals may have divergent

genotypes (Carvalho & Hauser 1994, King 1995, Bailey 1997). Such stocks represent the logical target of studies of population characteristics, and the appropriate scale at which fisheries should be managed. The geographic boundaries of such unit stocks depend on the mobility of the different life-history stages, and the existence of barriers to movement.

For marine finfishes with a bi-partite life-cycle, the potential for transport of eggs and larvae by ocean currents is considerable (Norcross & Shaw 1984, Victor 1987, van der Veer 1998). Since determining the path-

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ways and distance of larval transport through direct means is neither logistically tractable nor affordable, hydrodynamic modelling has become an important tool for understanding larval transport processes (Bartsch & Coombs 1997, van der Veer 1998, Jenkins et al. 1999). Such modelling applied at a large spatial scale has described larval advection pathways, determined the relationship between spawning and nursery areas (Dight et al. 1988, 1990, McShane et al. 1988), and accounted for patterns of variation in recruitment rates (van der Veer et al. 1998). At smaller spatial scales, numerical hydrodynamic models have identified likely settlement sites, and thereby accounted for small-scale patchiness in patterns of recruitment (Black & Moran 1991, Jenkins et al. 1997).

In the companion paper (Jenkins et al. 2000, in this issue), hydrodynamic modelling was used in reverse simulation to predict the likely areas from which King George whiting *Sillaginodes punctata* collected from 3 nursery areas along the eastern part of the southern coastline of Australia had originated. The model predicted that such recruits may have all originated from a single region located several hundred kilometres to the west, and the extent of their transport reflected the influence of strong eastward-directed currents in the vicinity of the continental shelf during the austral winter and spring (Jenkins et al. 2000). The results suggested that the different populations constitute a single large stock (Jenkins et al. 1997, 2000). These findings are in accordance with its long larval duration (Jenkins & May 1994, Fowler & Short 1996), and lack of phylogeographic structure throughout the range of King George whiting (L. Haigh & S. Donnellan unpubl.).

If the advection of larvae to South Australian nursery areas occurs over the same spatial scale as that in Victoria, recruitment may depend on spawning events that occur as far west as Western Australia. Such a scenario is not unlikely since the Australian salmon *Arripis trutta* and Australian herring *A. georgiana* that recruit to South Australian nursery areas in winter and spring originate from Western Australian spawning grounds, and are thought to be transported along the southern coastline by the Leeuwin Current (Petruševics & Bye 1995, Jones & Dimmlich unpubl.). Against this, however, several spawning grounds for King George whiting have recently been discovered in South Australia that are located only 100 to 200 km from some important nursery areas (Fowler et al. 1999, 2000). The study described here was concerned with distinguishing between these alternative hypotheses for the origin of larvae that recruit to South Australian nursery areas.

We compared the temporal patterns of recruitment to 4 South Australian sites that were located up to

500 km apart, and also considered the early life-history characteristics of the post-larvae collected from these sites. The basis of this was that if post-larvae from different nursery areas originated from a spawning region located to the west then some systematic variation amongst sites in recruitment rates and early life-history characteristics would be expected. Such a difference, for example, was found in the pre-settlement duration of post-larvae from 3 Victorian bays, which demonstrated a systematic increase the further east that the nursery areas were located (Jenkins et al. 2000). Here we compared: the relative rates of recruitment and size structures of post-larvae caught on several sampling occasions; the mean age, size and growth rate of the most recent recruits at each site; and the hatch dates of post-larvae from the different sites.

Furthermore, the numerical hydrodynamic models used in the Victorian study (Jenkins et al. 2000) were applied for the South Australian region using local estimates of larval duration, capture dates and location of nursery areas. The study was done for the recruitment season of 1994, using the biological information gained from ageing post-larvae from each of the 4 sites. Model simulations predicted the potential locations of spawning that provided the recruits to the 4 sites.

### The system

The 4 sites considered in this study were chosen on the basis of a history of receiving good recruitment (Jones et al. 1990), were readily accessible and easy to sample. They were up to 500 km apart and included 2 shallow, estuarine systems, each located in 1 of the 2 South Australian gulfs, i.e., Barker Inlet in Gulf St. Vincent, and Franklin Harbor in Spencer Gulf (Fig. 1). The 2 others were embayments on the west coast of Eyre Peninsula, i.e., Coffin Bay and Streaky Bay which each experience a more oceanic influence than the former two. Each site was a semi-enclosed, protected system supporting shallow beds of the seagrasses *Zostera* and *Heterozostera* spp. into which post-larval King George whiting settle (Jenkins et al. 1997).

Current patterns in the vicinity of the southern Australian coastline are largely influenced by weather systems. In summer, slow-moving high pressure systems are located south of the continent, track from west to east, and result in the South Australian region experiencing winds directed from the southeast. In winter, however, the high pressure systems lie over the continent causing a predominance of winds from the west (Lewis 1981, Schahinger 1987). This seasonal switch in weather patterns generally occurs in April-May and persists for 5 to 7 mo (Petruševics & Bye 1995), which

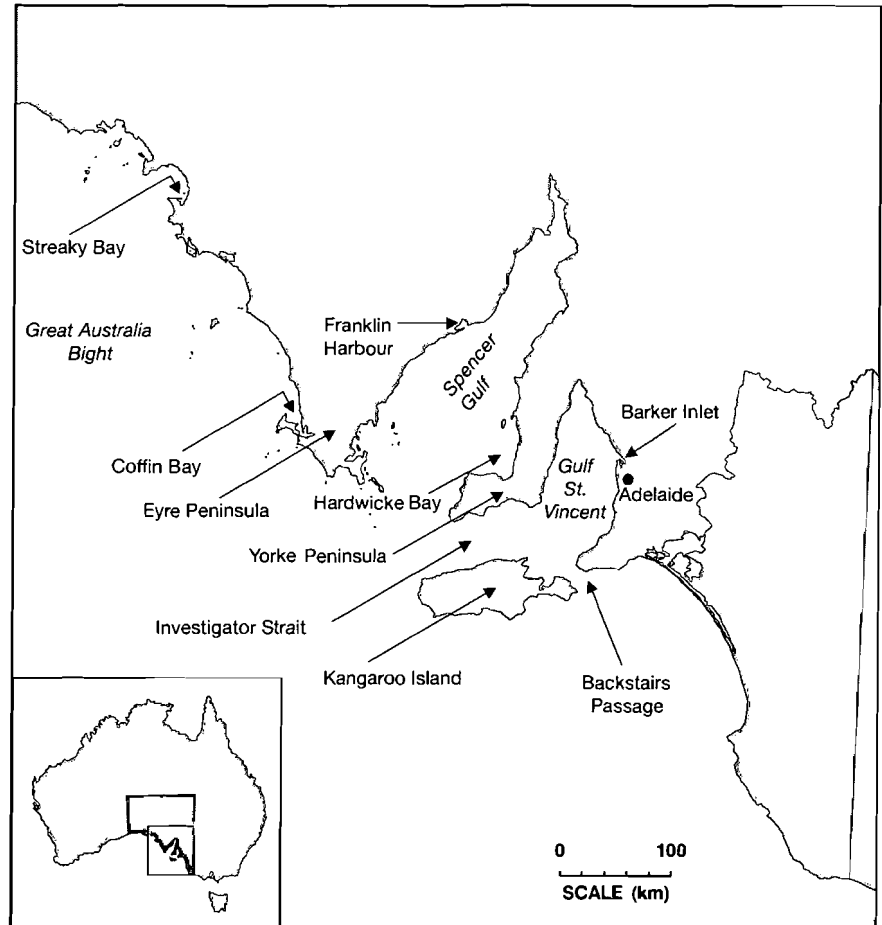


Fig. 1. Map of part of South Australia including the 4 post-larval sample sites and other geographic features. Inset shows area relative to Australian coastline

corresponds to the spawning and larval advection period for King George whiting in South Australia (Fowler & Short 1996, Fowler et al. 1999). The near-shore circulation on the continental shelf is dominated by wind-forcing, coastal trapped waves and other continental shelf waves, whilst the influence of oceanic currents is minimal (Petrusevics pers. comm.). Alternatively, ocean currents are strongest off-shore beyond the edge of the continental shelf.

Empirical measurements have confirmed that the southeast current flow along the continental shelf of South Australia is strongest during winter (Hahn 1986), when its influence extends into Bass Strait and to the west coast of Tasmania. However, such along-shelf movement is dominant near the shelf-break and continental slope, and decreases on the continental shelf (Petrusevics & Bye 1995). Consequently, the vicinity of Streaky and Coffin Bays on the west coast of Eyre Peninsula, experiences weak easterly-directed currents from the eastward-directed winds.

The dominant currents and circulation in the region of Gulf St. Vincent, Spencer Gulf and Investigator Strait are wind-generated and directed slightly to the

left of wind direction (Petrusevics 1991). General patterns in both gulfs are similar, with a cyclonic gyre exchanging gulf water with oceanic water from outside the gulf (Bullock 1975, Bye 1976). In Spencer Gulf, water enters on the western side, leaves on the eastern side and movement is basically clockwise (Bullock 1975). In Gulf St. Vincent circulation consists of an inflow along the west coast, an outflow through the central region, and an anti-cyclonic circulation adjacent to Fleurieu Peninsula (Bye 1976). The inflow to the gulf is continuous with an eastward flow on the north coast of Investigator Strait. The outflow in winter generally turns eastward through Backstairs Passage.

There are also secondary oceanographic features that may restrict larval movement in the vicinity of Spencer Gulf and Gulf St. Vincent. Frontal zones form at the entrances to both gulfs through summer and reach their strongest in autumn (Bruce & Short 1992, Petrusevics 1993), the peak spawning period for King George whiting (Fowler et al. 1999). Since larvae accumulate in such frontal zones (Bruce & Short 1992), advection either into or out of the gulfs may be inhibited.

In the region of southeastern South Australia and southwestern Victoria the width of the continental shelf decreases substantially, and the winter winds are predominantly from the northwest to southwest cycle (Lewis 1981, Schahinger 1987). Consequently, there is a strong easterly directed oceanographic set. The eastward-flowing water through this region is characteristically of high salinity, sub-tropical surface waters, which are presumed to originate from outflows from the South Australian gulfs and the Great Australian Bight, where water becomes highly saline during the summer months (Lewis 1981, Schahinger 1987).

## MATERIALS AND METHODS

**Field sampling.** Barker Inlet was sampled 10 times (approximately fortnightly between June and November) through the recruitment season, whilst the other 3 sites were each sampled only 3 times (July, September and October). Sampling was performed by 2 people dragging a small seine net over a transect distance of 40 m after which it was bundled up and carried to the beach where the catch was sorted. Post-larvae were removed, counted and preserved in 70% ethanol. The net had a semicircular perimeter of 7 m, a mouth of 5 m, a drop of 2 m, a mesh size of 1 mm and was held upright in the water column by float and lead lines. At each site an area of 600 m<sup>2</sup> was sampled on each occasion based on a regime of 3 transects of 40 m length and 5 m width.

**Processing samples.** Size structures of catches were developed after individual fish were measured for standard length (SL: tip of the snout to posterior edge of hypural plates) to the nearest 0.1 mm using Vernier calipers. When the combined total from the 3 transects exceeded 200 individuals, only a random sub-sample of this number was measured. Size structures were qualitatively used as indicators of the temporal pattern of recruitment. We divided each catch into 'small' (i.e., <20.5 mm SL) and 'large' (≥20.5 mm SL) individuals, and used the former as an index of recent recruitment (Hamer & Jenkins 1996).

Thirty of the smallest post-larvae from each site and occasion were selected for ageing, assuming they were the most recent recruits. Ages were estimated by analysis of the microstructure of their sagittae (Fowler & Short 1996). Fish were measured and their sagittae removed under a binocular microscope. One sagitta was fixed with Super Glue to a microscope slide with the proximal surface facing upwards, and then ground and polished to the primordium using 2 grades of lapping film (9 and 3 µm). With the otolith displayed on a video screen by an image analysis system the otolith increments were counted from the anterior tip to the

primordium. Two successive counts were made for 1 sagitta from each fish. When these differed by <5% their mean was used as an estimate of the number of increments, but when they exceeded this difference further counts were made until a satisfactory count was achieved or the otolith was rejected. Because the first increment forms at first-feeding approximately 5 d after hatching (Bruce & Short unpubl.) post-larval age was calculated by adding 5 to the otolith count. Sagittae of King George whiting from South Australia do not display the transition in microstructure that relates to time of entry of post-larvae to a bay or inlet that is characteristic of Victorian fish (Jenkins & May 1994). Consequently, here we used our estimates of post-larval age to approximate the pre-settlement duration. Average growth rates were calculated by dividing fish size by age. Estimates of age were also used to calculate the date of hatch of each fish, from which we constructed frequency distributions for hatch dates.

Our estimates of recruitment, and the age, size, and growth rates of the small post-larvae were compared amongst sites and occasions (July, September and October) using 2-factor analyses of variance, (both factors fixed), using the software package SPSS Version 8.0. Prior to analysis the data were tested for homogeneity of variances using Levene's test (Snedecor & Cochran 1980). Where variances were heterogeneous, data were transformed using square root or natural logarithm transformations. Where an ANOVA indicated significant differences, Student-Newman-Keuls tests were used to identify differences amongst means at the appropriate data level.

**Numerical modelling.** The numerical hydrodynamic models used in the companion paper by Jenkins et al. (2000) were also used here to determine the likely sites at which post-larvae were spawned based on their larval duration, the nursery area at which they were captured and the prevailing weather conditions through the larval period. This process involved the integration of 2 different types of models: a 3-dimensional Eulerian scheme hydrodynamic model (Model 3DD, Black 1995) and a Lagrangian advection/diffusion model that described larval dispersal (Model POL3DD, Black 1996). The hydrodynamic modelling techniques for setting boundary conditions and the model calibration are described in the companion paper. The hydrodynamic model incorporates the important larval transporting mechanisms of local wind-driven circulation and coastal trapped waves (Middleton & Black 1994), along the South Australian coast, as discussed above.

Larvae were modelled as moving randomly throughout the depth range, but passively with respect to the direction of water movement. Studies to date have shown that temporal and spatial distribution of late-

stage post-larval King George whiting are simulated accurately when assumed to behave as passive particles (Jenkins & Black 1994, Jenkins et al. 1997). This may be because the swimming ability of even the late-stage larvae is extremely limited (Welsford 1996, Jenkins et al. 1998).

Two types of simulations were done using the hydrodynamic models for 1994, and the biological information collected in that year. Firstly, the dispersal model was used in reverse simulation mode to predict the possible spawning locations from which post-larvae collected from 4 sample sites may have originated. In this case, particles were released at the end-point of their larval phase at the time of their capture. The model was then used to move backwards through time by reversing the directions of the currents to estimate the path of advection and initial spawning location of the larvae. Post-larval age was used as our estimate of larval duration, and the day of capture represented the day of arrival in the nursery area. A post-larva was represented in the model as 10 neutrally buoyant particles seeded at the mouth of the particular bay or harbour on the day of its arrival. It was then tracked in reverse to its place of origin, for the period of the larval duration. Output from the model was a map displaying the likely spawning region, represented by the densities of particles assigned to each  $10 \times 10$  km model cell within this region. The probabilities were obtained by recording particle positions in each cell within the model grid at every time step. The total number of occurrences in each model cell provides a map of the relative intensity of particle visits to each cell.

For each of Franklin Harbor, Coffin Bay and Streaky Bay 1 model run was executed using biological data from samples collected in July, September and October. For Barker Inlet 3 model runs were possible due to the more frequent sampling. These runs were for post-larvae that arrived 'early' in the season (June and July); those that arrived in the 'middle' of the season (August and September); and the 'late' arrivals (October and November).

The second type of simulation involved forward model runs aimed at predicting where larvae would be transported, having originated at particular sites and then advected for nominated periods. We seeded the model at the 2 places that have recently been identified as spawning sites through the analysis of samples of adult fish (Fowler et al. 1999, Fowler et al. in press). These were Hardwicke Bay, the large bay located in the southeastern corner of Spencer Gulf, and the northwest coast of Kangaroo Island (Fig. 1). In both forward runs the larvae were released through the peak spawning time of April/May (Fowler et al. 1999), and the estimates of larval duration covered the range of 105 to 125 d.

## RESULTS

### Biological characteristics

#### Comparison of recruitment rates

A total of 4684 post-larvae were captured at the 4 sites on the sample occasions in July, September and October. Post-larvae were not evenly distributed amongst sites or occasions, and the pattern of temporal variation was not consistent amongst sites. In July, catches were low and did not differ between sites (Fig. 2). In September, catches were significantly higher at the 2 gulf sites than on the west coast. In October, the catch at Barker Inlet was significantly higher than at the other 3 sites. The October catches at both Barker Inlet and Coffin Bay increased relative to those in September, whereas those at Franklin Harbor and Streaky Bay were less.

Comparison of size structures amongst sites and sampling occasions demonstrated substantial differences. Where post-larvae caught in Barker Inlet in July were small, the size structures of samples taken in the latter months were complex, and had a high proportion

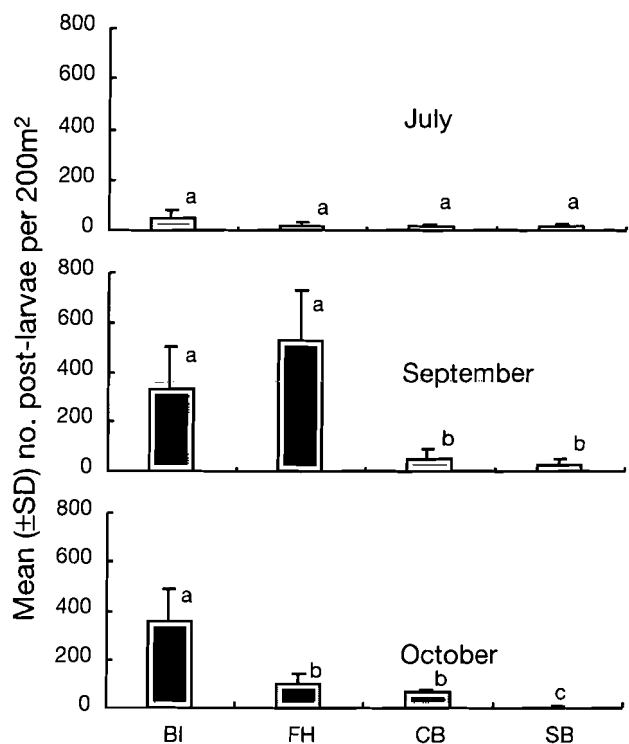


Fig. 2. Mean catch rate of post-larvae per transect on the 3 sample occasions. BI, Barker Inlet; FH, Franklin Harbor; CB, Coffin Bay; SB, Streaky Bay. Letters above histograms indicate the results of Student-Newman-Keuls tests comparing amongst sites for each occasion (means with the same letter are not significantly different)

of 'large' individuals, suggesting that numerous cohorts were represented in both later catches (Fig. 3). Most fish captured in Franklin Harbor in both July and September were 'small', whilst those in the October sample displayed numerous modes both of 'small' and 'large' fish (Fig. 3). Catches in Coffin Bay consisted of the smallest post-larvae of any site. Most taken in July were <15 mm SL, and those captured in September were also classified as 'small' (Fig. 3). The October sample was multimodal but the presence of very small fish indicates that recent recruitment had still occurred. Whilst few fish taken at Streaky Bay in July and September were small, the October sample was entirely 'large', indicating no recent recruitment.

#### Comparison of early life-history characteristics

For the analysis of estimates of age of the smallest post-larvae caught on the 3 occasions we excluded the October sample from Streaky Bay because of the lack of recent recruits. There was a general increase in mean age amongst sampling occasions, that was consistent across sites (Fig. 4). This substantial temporal effect accounted for 34.5% of the total variation in the data. Nevertheless, despite this, the post-larvae from both sites on the west coast were generally younger than those from the 2 gulf sites, with those from Coffin Bay slightly younger than those from Streaky Bay (Fig. 4).

The sub-samples of small post-larvae selected for age analysis were measured prior to dissection for otolith removal. For each occasion the post-larvae from the west coast were significantly smaller than those from the gulfs, whilst those from Coffin Bay were significantly smaller than those from Streaky Bay (Fig. 4). This spatial difference was the dominant effect and accounted for 63.4% of the total variation in size, as compared to the 2.0% attributable to temporal variation.

The estimates of size and age were used to calculate average growth rate (Fig. 4). These also demonstrated substantial variation, with the dominant effect being the substantial decrease that occurred at each site between the first and the 2 subsequent sampling occasions. This temporal effect accounted for >50% of the total variation. Only on the third sampling occasion did the *a posteriori* tests identify a significant difference amongst growth rates at the different sites (Fig. 4).

Hatch dates also differed amongst sites and occasions (Fig. 5). The smallest post-larvae from the 2 west

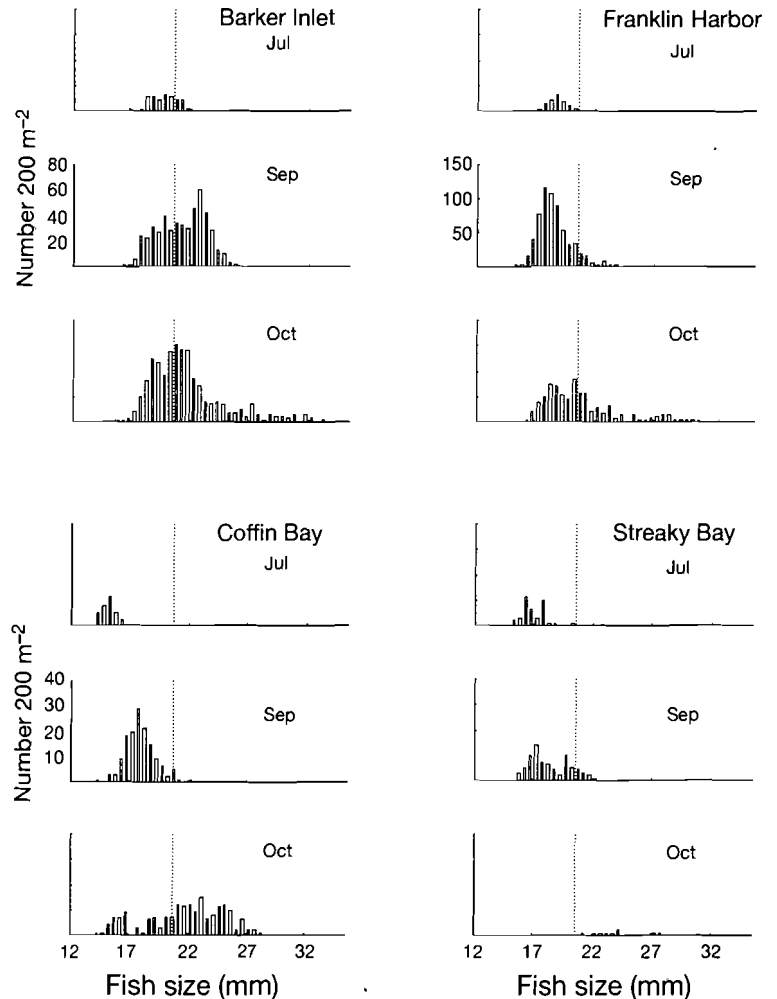


Fig. 3. Size frequency distributions of the catch at each site on each occasion. The dotted line indicates the size of 20.5 mm, and separates the catch into 'small' and 'large' (see 'Results')

coast sites hatched on a significantly later date than those collected from the gulfs at approximately the same time (Fig. 5). In July the minimum difference between median dates was 17 d, whilst in September the median hatch dates were at least 13 d later than those from the 2 gulfs. In October the median hatch date for Coffin Bay was 12 d later than that from the gulfs.

## Numerical modelling

### Reverse simulations

*Barker Inlet.* In total, 220 post-larvae were aged from the 10 sampling occasions at Barker Inlet across the 5 mo period. The estimates of age increased

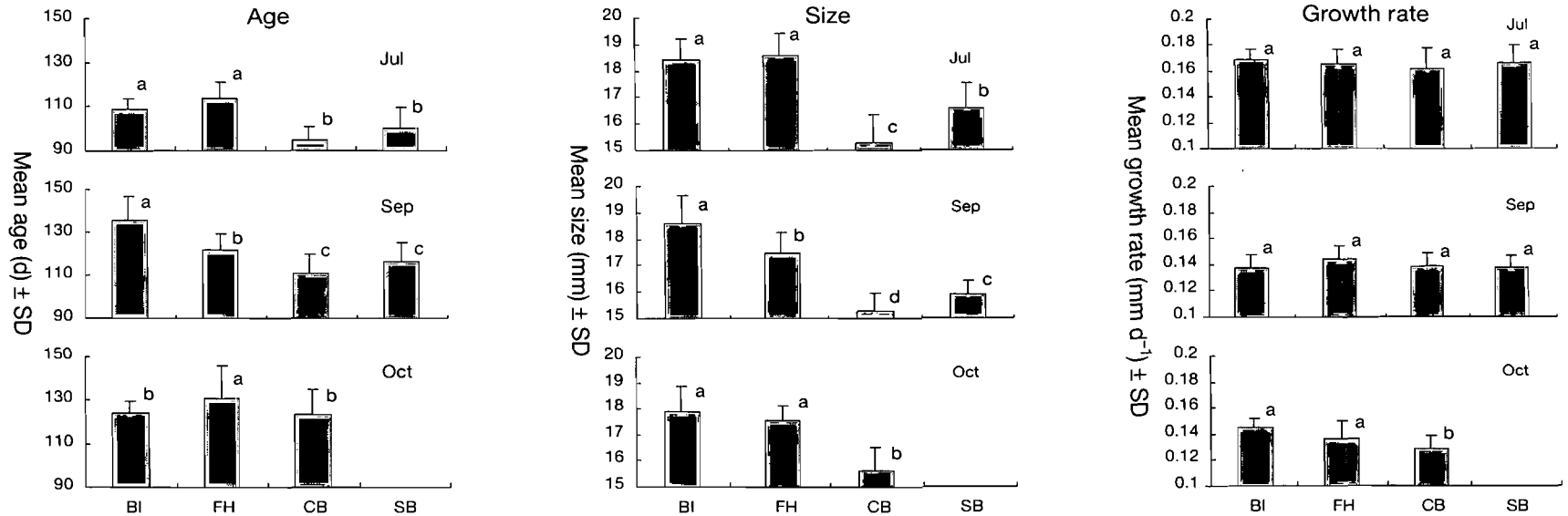


Fig. 4. Mean age, size and growth rates of the smallest post-larvae caught at each site on each sampling occasion. Letters above histograms indicate the results of Student-Newman-Keuls tests comparing amongst sites for each occasion (means with the same letter are not significantly different)

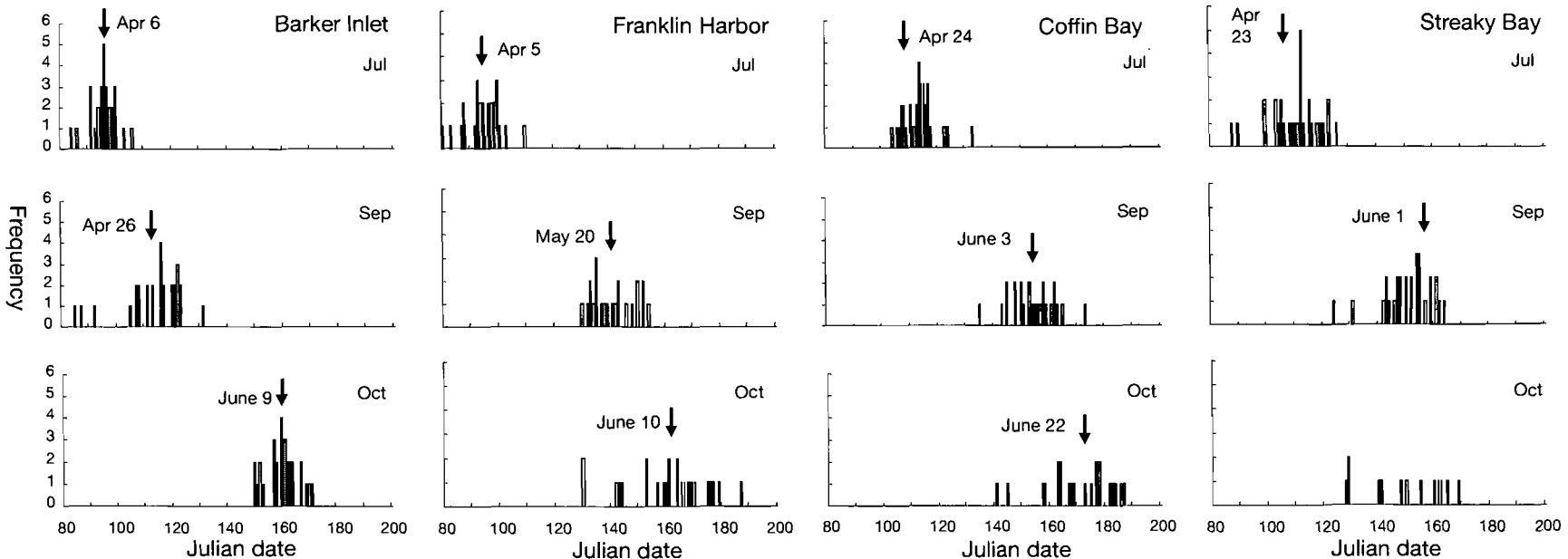


Fig. 5. Frequency histograms showing the number of post-larvae from each sample that hatched on the nominated Julian date. The median hatch date is shown for each sample site and date

systematically over time, even though post-larval size did not present the same temporal variation (Table 1). The simulation for 'early' recruits predicted that the region where larvae originated was in the western and southwestern coastal areas of Gulf St. Vincent, and along the southeastern shore of Yorke Peninsula, with the areas of highest density located only 50 to 120 km from Barker Inlet (Fig. 6). The results for post-larvae that arrived during the 'middle' part of the season showed a decrease in density of larvae originating in Gulf St. Vincent, with the high density region now located around southern Yorke Peninsula, 50 to 150 km away from the nursery area (Fig. 6). The probability distribution for the 'late' recruits to Barker Inlet covered a much broader area, which extended into southern Spencer Gulf. Several hotspots were located in the central and northern parts of Gulf St. Vincent only 40 to 60 km from Barker Inlet, and another around the southern tip of Yorke Peninsula extending into southern Spencer Gulf.

**Franklin Harbor.** A total of 70 post-larvae were aged from the 3 sampling occasions, and mean age estimates increased amongst successive occasions (Fig. 4). The main predicted spawning region was the inshore coastal area along the southwestern shore of Spencer Gulf from 30 to 130 km from the harbour entrance (Fig. 7). The predicted densities decreased off-shore towards the central and northern parts of the gulf. This model output also indicated the possibility that some post-larvae originated along the southern shore of Eyre Peninsula.

**Coffin Bay.** A total of 73 post-larvae were aged from the 3 sampling occasions and the age estimates increased amongst successive occasions (Fig. 4). The hydrodynamic model predicted that the total area from which larvae may originate, extended 140 km to the northwest along the coast and 70 km off-shore. However, the high density area included only the first

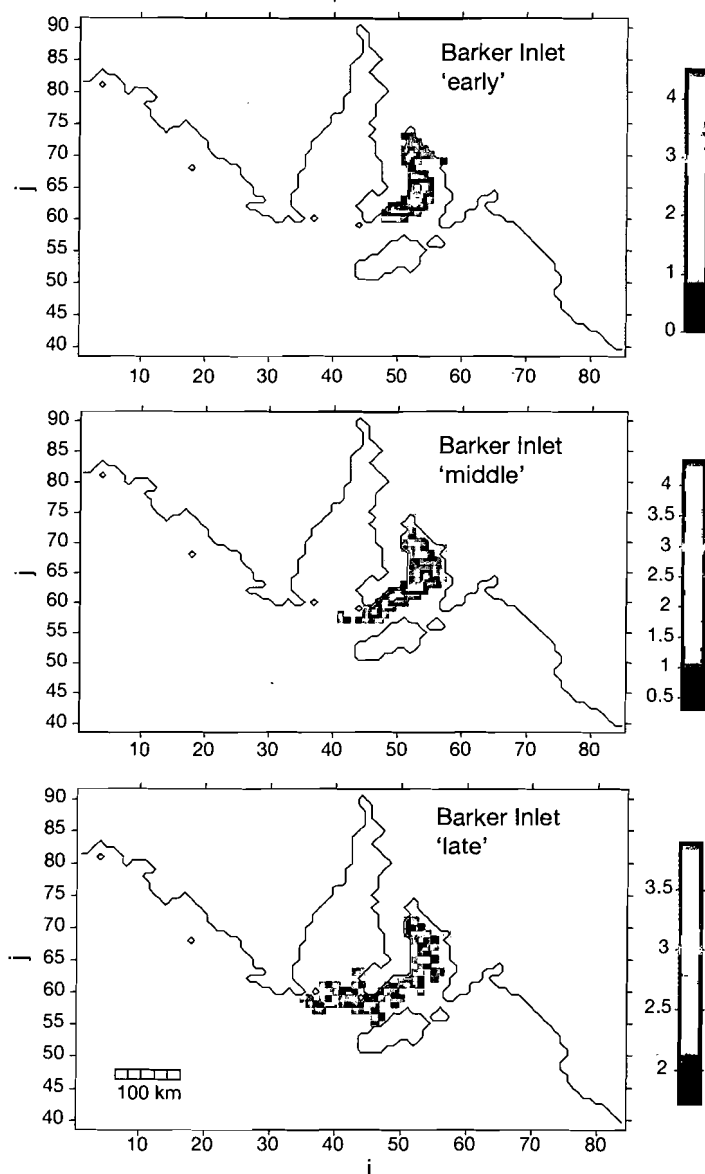


Fig. 6. Predicted spawning area for post-larvae collected from Barker Inlet during the 'early', 'middle' and 'late' parts of the 1994 recruitment season. Scale bar: log particle density; 'i': grid cell number from west to east; 'j': grid cell number from south to north

Table 1. Summary of results of size and age for post-larvae aged from the 10 sampling occasions in Barker Inlet in 1994

Sample date	No. post-larvae aged	Mean age (d)	SD	Mean SL (mm)	SD
10 Jun	6	79.7	3.72	17.5	0.84
28 Jun	14	95.4	8.38	19.1	1.24
14 Jul	23	104.6	6.07	18.2	0.76
24 Jul	28	109.2	4.57	18.9	0.73
8 Aug	30	120.1	6.25	18.7	0.6
22 Aug	30	124.2	8.42	18.1	0.77
9 Sep	28	135.8	0.81	18.6	1.04
11 Oct	29	124	5.84	17.9	0.96
2 Nov	21	144.8	13.49	20.1	0.99
16 Nov	11	144.7	12.1	18.8	0.77

60 km northwest from outside the mouth of the bay (Fig. 7).

**Streaky Bay.** Estimates of age could only be used to approximate pre-settlement duration for 2 sampling occasions for Streaky Bay (Fig. 4). This site is located near the western boundary of the model, and the reverse simulation indicated that some post-larvae came from outside the model area. Nevertheless, it still suggested the existence of a high density area at approximately 80 km directly west of Streaky Bay (Fig. 7).



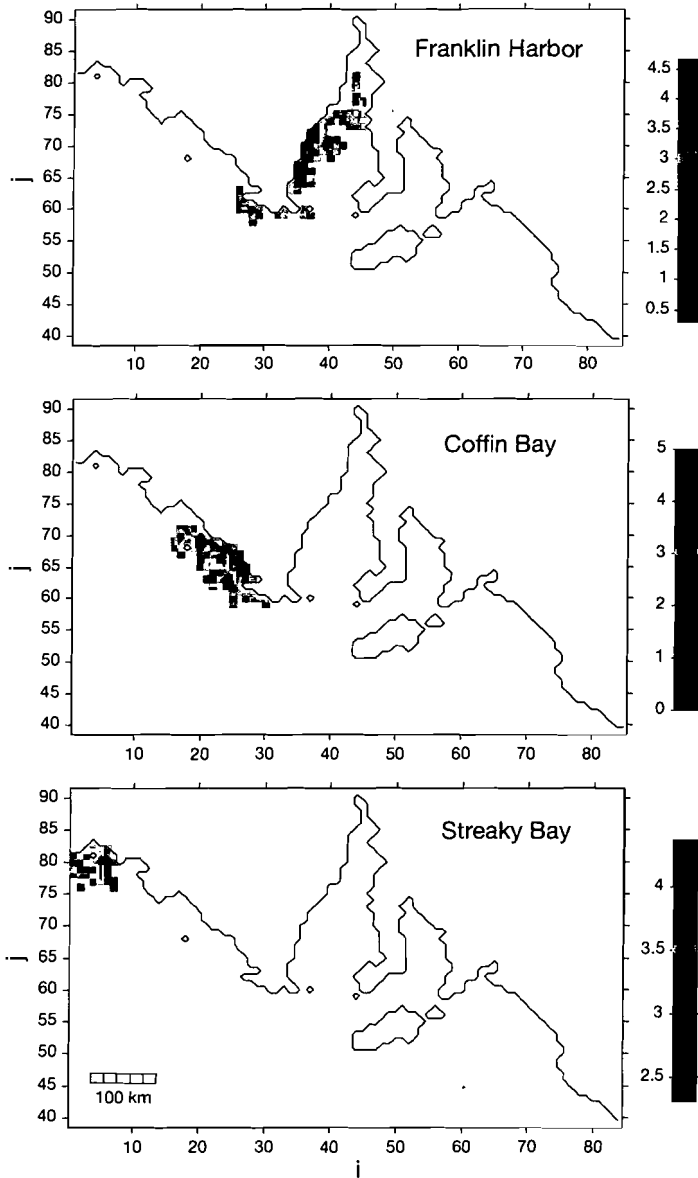


Fig. 7. Predicted spawning areas for post-larvae collected from Franklin Harbor, Coffin Bay and Streaky Bay during the 1994 recruitment season. Scale bar: log particle density; 'i': grid cell number from west to east; 'j': grid cell number from south to north

Forward model runs

*North coast of Kangaroo Island.* The model was seeded adjacent to the coastline at approximately mid-way along the north coast of the Kangaroo Island (Fig. 1), a known spawning site. The result predicted that most larvae would be transported eastwards through Backstairs Passage, and ultimately end up between 100 and 275 km from the spawning area (Fig. 8). There was a low probability that some post-

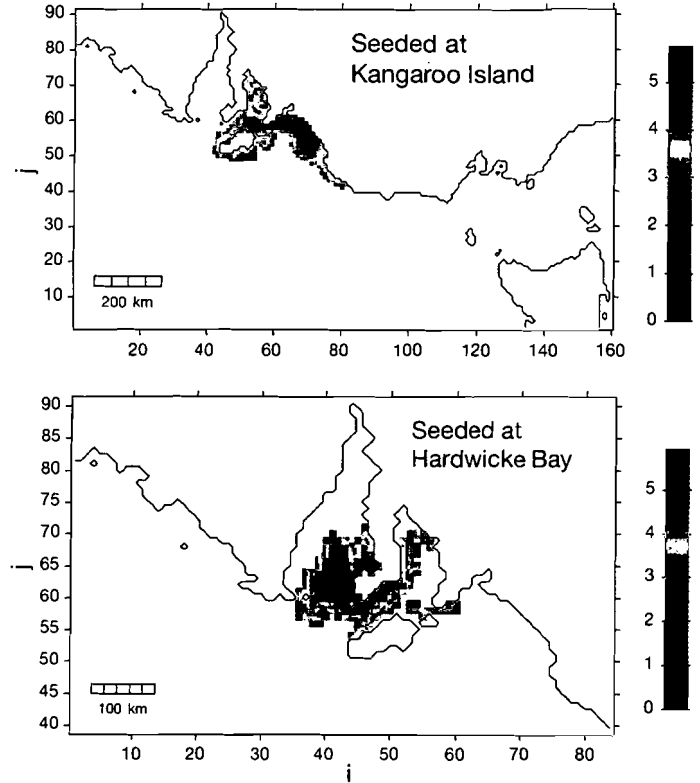


Fig. 8. Results of forward model runs showing predicted locations where larvae would end up, having originated either on the northwest coast of Kangaroo Island or in Hardwicke Bay, southeastern Spencer Gulf. Scale bar: log particle density; 'i': grid cell number from west to east; 'j': grid cell number from south to north

larvae would be located up to 400 km east of the spawn site, along the southeast coast of South Australia. The model also predicted that some larvae would be transported into, and distributed throughout Gulf St. Vincent. It did not, however, suggest any possibility of post-larvae being transported either into Spencer Gulf or west of Eyre Peninsula.

*Southeastern Spencer Gulf.* The model was seeded in Hardwicke Bay. The predicted locations for larvae after 105 to 125 d were primarily distributed throughout the southeastern part of Spencer Gulf and near the southwestern tip of Yorke Peninsula (Fig. 8). There was also a low probability that some would be transported through the northern part of Investigator Strait and up the western coast of Gulf St. Vincent. This suggests the interesting scenario of a higher chance that larvae would be transported from the southeastern part of Spencer Gulf into Gulf St. Vincent than to the northern part of Spencer Gulf. There was also no indication of larvae being transported from Spencer Gulf to the west coast.

## DISCUSSION

This study was concerned with the structural dynamics (Bailey 1997) of King George whiting in South Australia, particularly the spatial scale of larval advection, the relationship between spawning grounds and nursery areas, and the size of stock units. It was aimed at discriminating between 2 hypotheses regarding the origins of larvae that recruit to South Australian nursery areas. The first hypothesis was that larvae are derived from a spawning region located possibly as far west as Western Australia, which would imply that South Australian populations represent a single large stock. The alternative was that larvae originate from several different spawning grounds located within only 100 to 200 km of several nursery areas. Here, population structure would be represented by numerous, small, self-recruiting populations.

### Biological characteristics

#### Recruitment rates

The biological data were not definitive in distinguishing between the 2 hypotheses, but nevertheless were supportive of the second. There was no systematic temporal variation in the recruitment rates and size structures amongst sites. In fact, site-specific recruitment rates appeared largely independent of each other. Such lack of spatial conformity would suggest that recruitment rates were more likely the consequence of local events than of processes operating at a large spatial scale.

Our conclusion from this sampling program is necessarily limited because only 1 site was sampled in each area. This sampling in 1994 was actually a pilot study to more comprehensive recruitment monitoring that was done between 1995 and 1997. The more extensive program included the 4 sites considered here, as well as several others, which were all sampled at several places following a hierarchical protocol. The conclusion from this more extensive study was the same as that presented here—recruitment rates showed little conformity amongst sites (Fowler & McGarvey 1997). This consequently implicates the influence of local rather than large-scale events.

#### Early life-history

Recruits to west coast bays experienced a shorter larval duration, settled at a younger age and therefore were spawned and hatched at significantly later dates than those caught at the same time in the 2 gulfs. They

were also substantially smaller on arrival in the bays, a consequence of being younger. On first consideration such systematic spatial differences in size and age appear consistent with the hypothesis that the post-larvae were delivered to South Australian nursery areas from a westerly located spawning region. This is because the post-larvae would reach the west coast bays first because of their eastward transport, whilst those reaching the gulfs would be older and larger by virtue of the greater distance travelled from the west. The main argument against this, however, is that since there is a minimum of 200 km between Streaky and Coffin Bays the post-larvae would be expected to arrive at the latter bay marginally older and larger than those that arrive at the former. In fact, however, the opposite to this occurred, i.e., the post-larvae from Coffin Bay were the smallest and youngest of the 4 sites.

Recruits to the west coast bays experienced a shorter larval duration than did those captured in the 2 gulfs. In contrast, growth rate throughout the larval period was approximately the same, irrespective of where caught. There was, however, a substantial reduction in growth rate through the recruitment season. This phenomenon was previously documented for post-larvae collected from Barker Inlet in 1993, and attributed to the variation in water temperature regimes that larvae experience at different times through the recruitment season (Fowler & Short 1996). The current study has determined that such systematic, within-season variation in growth rates is a general phenomenon across South Australian waters.

### Numerical modelling

The numerical hydrodynamic modelling done for the year of 1994 in South Australia provided unambiguous support for the hypothesis that recruits originated from spawning grounds located only relatively short distances from each respective nursery area. Spawning locations assigned the highest particle densities by the model were generally located from 40 to 150 km from each respective bay or harbour, and were abutted against the nearest coastline that was located either to the south or west of the nursery area.

The predicted spawning locations were virtually non-overlapping between the 4 sites. Model output indicated the unlikelyhood that post-larvae from Franklin Harbor had originated from outside Spencer Gulf, whilst those caught in Coffin and Streaky Bays were unlikely to have originated in either Investigator Strait or southern Spencer Gulf. The simulations for Barker Inlet indicated that as the season progressed, there was an increased probability that post-larvae originated at greater distances from the nursery area, pos-

sibly reflecting the increase in larval duration. Nevertheless, the spatial scale of larval advection for even the late-arriving post-larvae, i.e., those with the longest pre-settlement duration, was restricted. This indicates there was a low possibility of input from southern Spencer Gulf, but none from the west coast.

These findings differ from those of Jenkins et al. (2000), who applied the same hydrodynamic modelling to a geographic region located approximately 1000 km to the east for the same year (1994), as well as 1989 and 1995. That study indicated the likely existence of a single large spawning region approximately 300 to 700 km west of the nursery areas. There were no substantial differences in the estimates of biological parameters between the 2 studies that could account for this difference. Rather, the differences in model output were most likely related to different hydrographic processes at the different places along the southern Australian coastline. The current velocities and direction predicted by the model for 1994 suggested that currents around the 2 gulfs were weak, but in southwestern Victoria were stronger and clearly directed from west to east. In each of the 3 years of 1989, 1994 and 1995 the strongest currents were in the Bass Strait region near the southern Victorian coast (Fig. 6 in Jenkins et al. 2000).

## CONCLUSIONS

This study has suggested that larval movement in South Australia in 1994 was highly restricted. The lack of conformity or systematic differences in the characteristics of recruitment to 4 distant nursery areas, suggested that recruitment was likely the consequence of local processes. The hydrodynamic modelling provided strong evidence that larvae were transported only over relatively short distances of 100 to 200 km, due to the weak near-shore currents typical of this region. Such weak near-shore currents were also obtained for this region in both 1989 and 1995 (Fig. 6 in Jenkins et al. 2000), thus conferring onto this result some generality. Under such oceanographic conditions there would be minimal exchange of larvae amongst sub-populations. The results also suggest that in such years major geographic features such as Eyre and Yorke Peninsulas may constitute significant barriers to larval transport, because of gyres that form in these areas. Frontal zones that form at the entrances to the 2 gulfs may also contribute to restricting larval movement (Petrusevics 1993).

In contrast, in Victoria the hydrodynamic modelling in 1989, 1994 and 1995 indicated that larvae were transported over far greater distances, and populations conformed to the concept of a single unit stock (Jen-

kins et al. 1997, 1998, 2000). Based on the oceanographic regimes for 1989, 1994 and 1995 the implications of the observed difference in population structure are substantial both for the spatial scale over which the population dynamics work and for fishery management. In South Australia population dynamics may be largely regulated on a small spatial scale, with such populations consequently vulnerable to local over-fishing or recruitment over-fishing. Alternatively, recruitment in Victoria in such years will be independent of local stock size, varying inter-annually as a consequence of large-scale environmental influences on current regimes. Such contrasting scenarios suggest that the spatial scale at which fishery management practises are applied must necessarily differ between the 2 regions. Yet, consideration should also be given to the possible further complexity of inter-annual variability in ocean currents patterns, which in other years would create different conditions for larval dispersal.

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