Journal of the Royal Society of Western Australia, 92: 111–127, 2009

The ongoing influence of the Leeuwin Current on economically important fish and invertebrates off temperate Western Australia – has it changed?

R C Lenanton, N Caputi, M Kangas & M Craine

Department of Fisheries (Western Australia),
Western Australian Fisheries & Marine Research Laboratories,
PO Box 20, North Beach, WA 6920
Corresponding author: ✉ Rod.Lenanton@fish.wa.gov.au

Manuscript received August 2008; accepted April 2009

Abstract

Earlier reviews have identified that the strength of the Leeuwin Current is a key factor associated with changing abundance of a number of key invertebrate and scalefish species harvested by on-shelf commercial fisheries off the Western Australian coast. This review of these relationships has revealed that the addition of more recent data has strengthened the relationship for western rock lobster, the only species whose larvae are primarily distributed in the area of the influence of the Leeuwin Current and its offshore eddies. For other species, particularly scallops and whitebait, while the addition of new data has weakened the LC relationships, other as yet unquantifiable factors now appear to be more important determinants of changing abundance. For a number of the scalefish species (*e.g.*, south coast Australian salmon), discontinuation of juvenile monitoring and the lack of ongoing records of comparable abundance data, primarily as a consequence of changes in the distribution of fishing, relative to the distribution of the stocks, has precluded ongoing exploration of earlier relationships. However preliminary data for some hitherto unreported relationships for other coastal scalefish species suggest that some physical and biological variables that are likely to be influenced by both the Leeuwin and Capes Currents may also be important. To help unravel these relationships, the underlying mechanism of the influence of the current, particularly the role of the northward flowing, mid-shelf Capes Current and salinity of shelf waters, and factors controlling the availability of nutrients to on-shelf primary productivity need to be better understood.

Keywords: Leeuwin Current, invertebrates abundance, scalefish abundance, time-series robustness

Introduction

The Leeuwin Current (LC) is a poleward flowing eastern boundary current that carries warm, low salinity water southward along the shelf break off the Western Australian (WA) coast (Cresswell & Golding 1980; Waite *et al.* 2007).

Mesoscale interannual and seasonal variability in the LC strength (Ridgeway & Condie, 2004), measured as coastal sea level height, has been shown to be related to the El Nino/Southern Oscillation (ENSO) cycle, with LC strength highly correlated with the Southern Oscillation Index (SOI); the current being weaker during ENSO events and stronger during La Nina events (Pearce & Phillips 1988, Caputi *et al.* 1996, Feng *et al.* 2003). While the LC strength is also correlated with temperature and salinity of outer shelf waters, air-sea heat flux processes rather than advection associated with the LC appear to be the key factors influencing the temperature and salinity of shallower coastal waters inshore of the current (Pearce *et al.* 2006).

Earlier reviews (Lenanton *et al.* 1991; Caputi *et al.* 1996; Pearce *et al.* 1998) have revealed that LC strength was correlated with the abundance and/or catchability of a number of target species taken in a range of on-shelf commercial fisheries off the coast of South-Western Australia (SWA) (Figure 1). For most of these species there are long-term data bases that either measure the abundance of settlement life history stages, or the abundance of adults. They include western rock lobster (WRL, *Panulirus cygnus*), Shark Bay scallops (*Amusium balloti*), Shark Bay king prawns (*Penaeus latisulcatus*), Australian salmon (*Arripis truttaceus*), Australian herring (*Arripis georgianus*), Albany pilchards (*Sardinops sagax neopilchardus*), and whitebait (*Hyperlophus vittatus*). All of these relationships with the LC strength were "invoked" from statistical correlations; they can be either positive (*e.g.* western rock lobster), or negative (*e.g.* Shark Bay scallops). Few of the underlying mechanisms have been empirically verified, although the timing of the period when the current affected the stock indicated that in most instances, the larval phase appeared to be the main life history stage influenced by the current. For example, the contention by Fletcher *et al.* (1994) that "loss" of larvae due to the LC reduces recruitment of pilchards two years later was supported by Gaughan *et al.* (2001) who found that the larvae of south coast pilchards could be transported up to 1000 km east, and in some cases well into South Australian waters, primarily under the influence of the LC. Increases in availability and resolution of oceanographic data (*e.g.* satellite derived steric height data to derive surface current patterns) have permitted advances in modeling of potential transport of the larval stages of WRL. However, there have been no

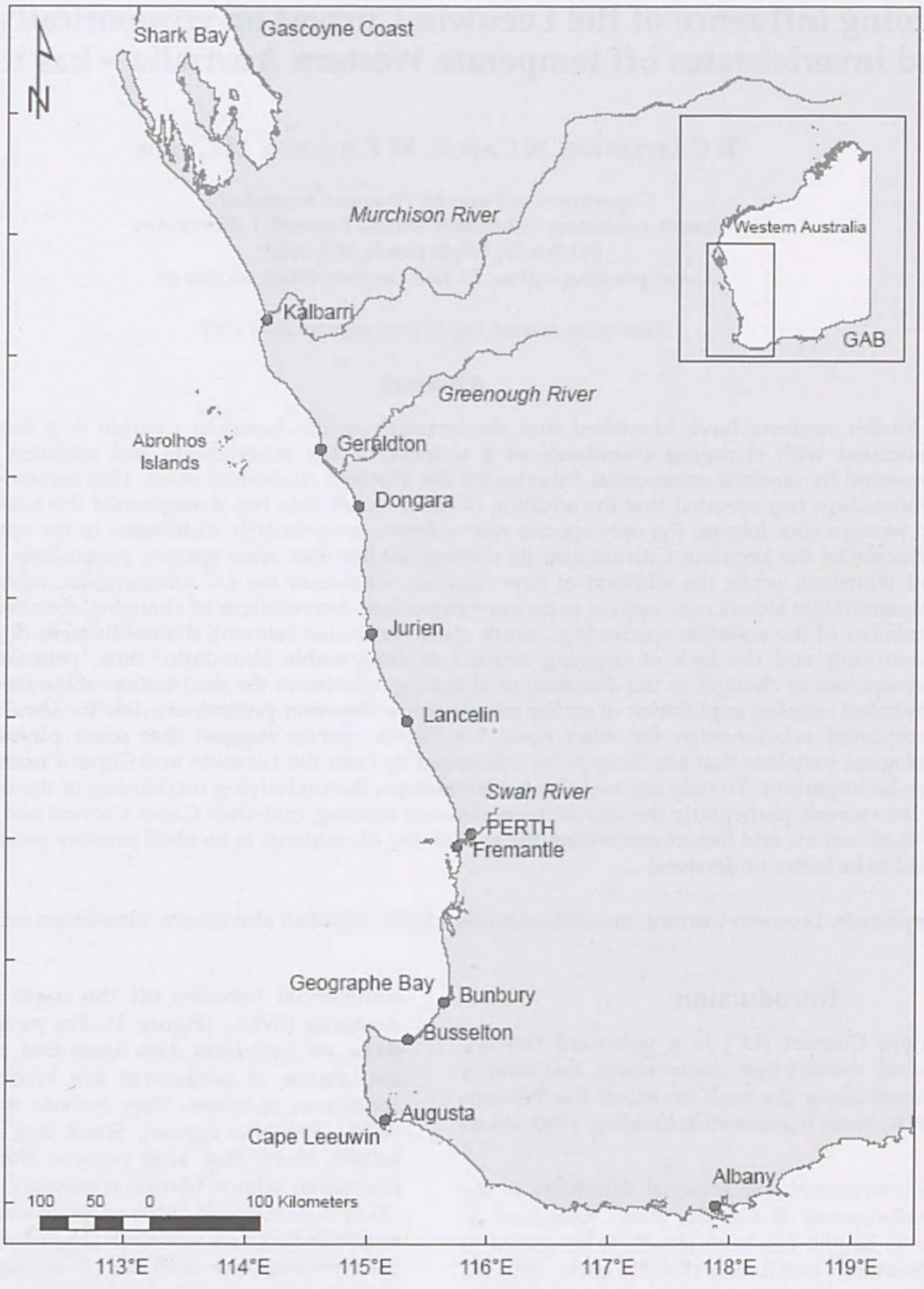

Figure 1. Key locations along the lower west and western south coasts of Western Australia.

other studies directed at determining the influence of oceanographic variability on transport or survival of the larval stages of marine species.

Ongoing research during the 30 years since the formal recognition of the existence of the LC (Golding & Symonds 1978; Cresswell & Golding 1980) has revealed that this surface flowing current is one of four major currents that comprise the Leeuwin Current System (LCS) (Batteen *et al.* 2007). Beneath the southerly surface-flowing LC, the Leeuwin Undercurrent (LUC) flows northward in subsurface waters, while the wind generated Capes and Ningaloo Currents flow respectively northward on the shelf shoreward of the LC off the lower west coast, and the Gascoyne coast, during the austral summer. Meso-scale features such as eddies and meanders are also associated with the LCS. The way in which this system influences the water column behaviour and biological productivity off the WA coast has recently been reviewed in greater detail (Waite *et al.* 2007). In addition to the LCS, global atmospheric changes are also contributing to the observed long-term temperature and salinity changes to continental shelf waters off Western Australia (Pearce & Feng 2007). However, as noted above, while such changes are acknowledged as factors that may further influence the complex interrelationships between the LCS and fisheries production, indices of such changes are broad, making it inherently difficult to empirically demonstrate conclusive causal relationships; something few studies undertaken thus far have been able to achieve. Given this dearth of studies focused on determining causal relationships, the aim of this paper is to review the ongoing robustness of the hitherto established relationships between interannual and seasonal variability in LC strength and species abundance in the regions of relevance to fisheries (*i.e.* fisheries production or recruitment), and highlight any further examples where the abundance of economically important species is being influenced by the LCS.

This review updates the previous assessments from earlier reviews, either building on hypotheses identified earlier or invoking plausible conceptualizations of causal links between the LC and species abundance. In the absence of information that can be used directly to ascribe mechanisms of influence, such hypotheses are framed around physical and biological effects linked to variability in the LCS and which may affect different life history stages of the various species. Physical effects could be changes in temperature to levels sub-optimal for growth, or transport of eggs or larvae (Muhling & Beckley 2007; Muhling *et al.* 2008a). Biological effects could include changes to nutrient regimes and broader patterns of primary productivity leading to variability in growth and survival.

Data sources

The relationships between 10 species/fisheries and the LCS are reviewed here, building on the seven covered in earlier reviews (Lenanton *et al.* 1991; Caputi *et al.* 1996). Details of the biological data used here, such as method of collection and any validations undertaken, are not dealt with here unless explicitly relevant. Rather, the pertinent data are mentioned as required to build the conceptual understandings and hypotheses relevant to progressing our knowledge of how the LCS affects fisheries production off the WA coast.

For each species or fishery the primary historical data consists of commercial catch and effort records, typically available since 1975. These compulsory catch and effort data are aggregated monthly by fishing method for each one degree by one-degree block (or to other spatial fishing zones for some fisheries), submitted to the Department of Fisheries, and stored in the Catch and Effort System (CAES) database.

The fisheries/species covered in this review are shown below. Further details of these fisheries can be found in the Department of Fisheries, Western Australia annual State of the Fisheries reports available from www.fish.wa.gov.au.

- western rock lobster (WRL, *Panulirus cygnus*)
- Shark Bay scallops (*Amusium balloti*)
- Shark Bay king prawns (*Penaeus latisulcatus*)
- Green or giant mud crabs (*Scylla serrata*) *
- Australian salmon (*Arripis truttaceus*)
- Australian herring (*Arripis georgianus*)
- Albany pilchards (*Sardinops sagax neopilchardus*)
- whitebait (*Hyperlophus vittatus*)
- tailor (*Pomatomus saltatrix*) *
- West Australian dhufish (*Glaucosoma hebraicum*) *

* species added since the last review.

Oceanography and meteorology

Below are the sources of monthly values of the physical variables that were used when exploring relationships with abundances indices of different species:

- Southern Oscillation Index (SOI): http:/ www.bom.gov.au/climate/current/soihtm.shtml);
- Fremantle Sea Level (FSL): National Tidal Centre in Adelaide;
- Sea surface temperatures (SST) on a 1° latitude/ longitude grid: Reynolds Global dataset (Reynolds & Smith 1994); and
- Rainfall: the Bureau of Meteorology (http:// www.bom.gov.au/silo/products/Rain.shtml).

Monthly at-sea measurements of surface and bottom salinity and temperature have been made at four locations, Fremantle, Lancelin, Jurien and Dongara, across four depths, <10, 10–20, 20–30, and >30 fm during the WRL fishing season (15 November to 30 June) each financial year since 1971/72 (Caputi *et al.* 2009; Lenanton *et al.* 2009).

Recruitment Indices

The tailor recruitment index was expressed as a catch rate, calculated as the average number of 0+ and 1+ yr old tailor caught per standard angling hour over the period February to April at a representative Perth Metropolitan site (Ayvazian *et al.* in prep.).

The dhufish recruitment index was derived from the current age structure, back-calculated to estimate the abundance of the each age cohort during the year of its birth (St John unpublished).

The Australian salmon recruitment index is the standardized catch rate of 0+ individuals settling in nursery areas off the lower west coast between September and December each year, and is derived from data collected during an ongoing coastal scalefish recruitment index survey (Gaughan *et al.* 2006).

Results and Discussion

Western Rock Lobster

While adults are confined to the shelf, larval stages are distributed throughout oceanic waters adjacent to the continental shelf off the coast of SWA (Phillips 1981). The final larval stage (puerulus) actively swims from oceanic waters across the shelf to settle in shallow coastal habitats. There are long-term databases recording indices of the annual abundance of settling puerulus, environmental variables such as LC strength (April Fremantle sea level), satellite derived sea surface temperature (SST February–April), and westerly wind during peak settlement (October to November)(rainfall index of storm fronts). Correlations using data since the

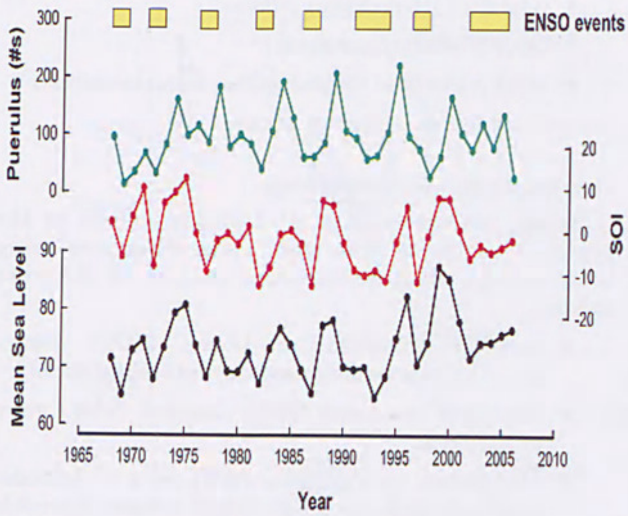

Figure 2. Annual mean values of the Southern Oscillation Index, Fremantle mean sea level, and puerulus settlement at Seven-Mile Beach Dongara Western Australia (Updated from Pearce and Phillips 1986).

late 1960s have revealed a strong positive relationship between puerulus settlement, mean Fremantle sea level and the SOI (Figure 2) (Pearce & Phillips 1988). Further, there is also a strong positive relationship between mean monthly SST (February to April) and puerulus settlement, with strongest settlement often occurring during years exhibiting high SST levels combined with the strongest rainfall index (*i.e.* periods of strongest westerly winds) (Figure 3).

It seems that in years of strong LC, the survival and growth of WRL early stage larvae is enhanced, either via retention of larvae in anticyclonic warm core eddies, and/or as a result of improved growth and survival as a consequence of warmer temperatures and/or higher productivity (chlorophyll A) during late autumn/winter. Potential sources of nutrients include upwelling associated with eddy formation, advection from the shallower nutricline further north, and seasonal cooling and storms which promotes convective mixing of the water column and shoaling of the nutricline (Koslow *et al.* 2008). Understanding the causal mechanism of the effect of the LC is an area of ongoing research.

Research has also demonstrated that strong LC in the second half of the year (June–December) which is near the period of peak settlement (August–December) has an advection effect as it distributes puerulus further south (Figure 4) (Caputi 2008).

Thus annual puerulus settlement (abundance), LC strength (Fremantle sea level), SST, productivity (chlorophyll A), and eddy kinetic energy are all positively correlated (Caputi *et al.* 2001; Feng *et al.* 2005), with the more southerly distribution of higher puerulus settlement also positively correlated with LC strength (Caputi 2008). However the frequency of ENSO events (weak LC) over the last 16 years (1991–2006) has been greater than in the previous 20 years (1971–1990). If this trend continues, is there likely to be a continuing trend in average to low puerulus settlement; or will the influence of global climate change (increasing SST of the WA coast, particularly the lower west coast) to some extent counter the negative influence of weak LC?

There has also been considerable effort expended exploring the effect of long-term temperature increases

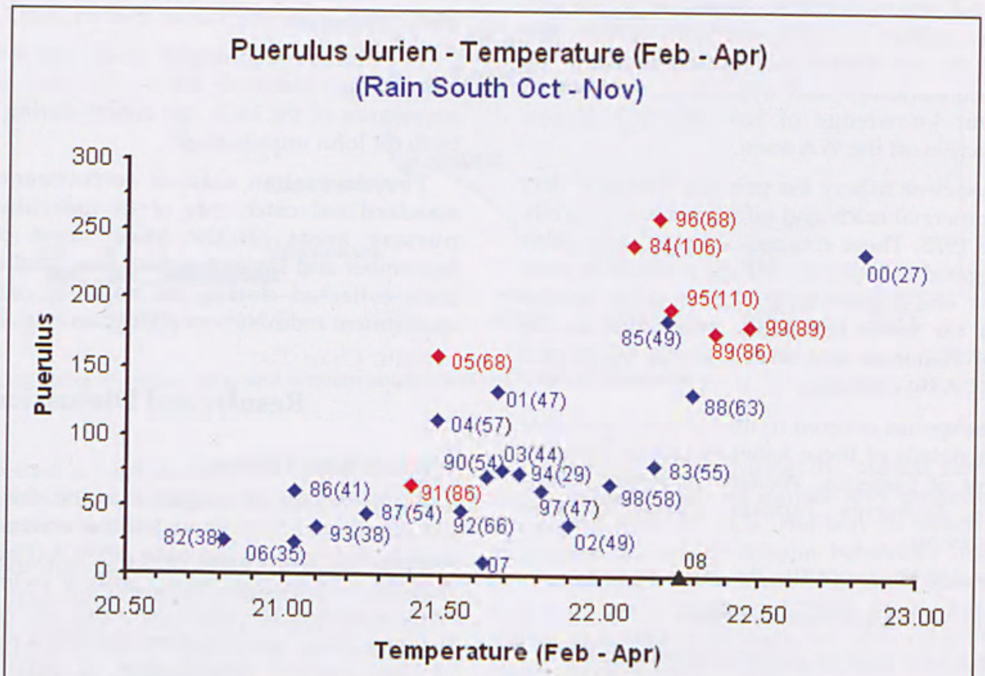

Figure 3. Relationship between the annual puerulus settlement (mean number per collector) at Jurien, and sea surface temperature, at two levels of rainfall (red data points >, and blue data points < than 80 mm, an index of the strength of westerly winds) in October–November, off the lower west coast of Western Australia (updated from Caputi *et al.* 1996). The predicted level of puerulus settlement for 2008 is presented. The multiple correlation is 0.82 (p<0.001) for 1982–2006 data.

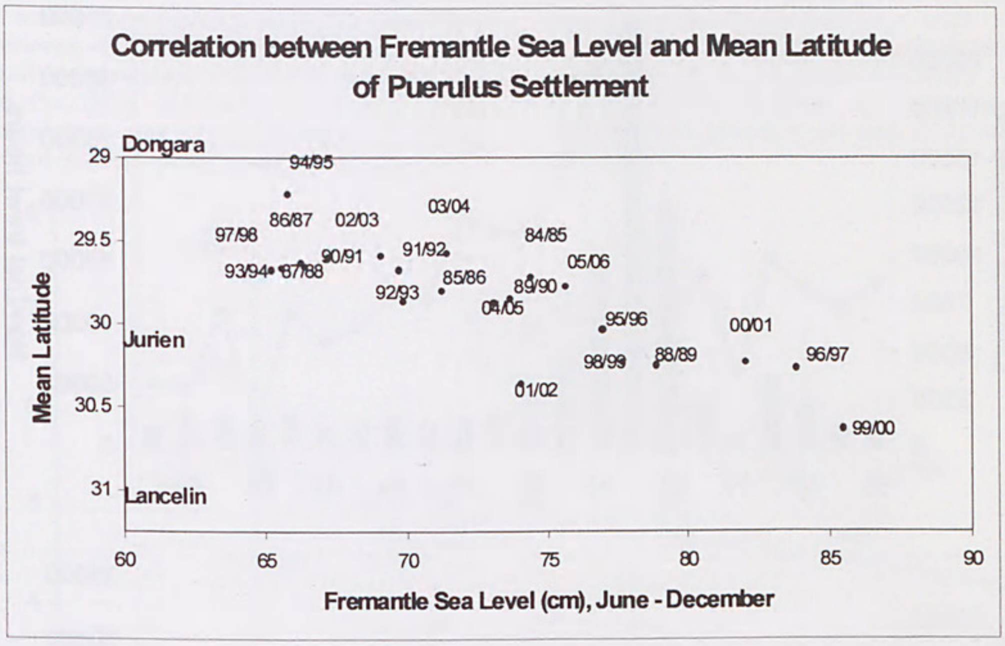

Figure 4. Relationship between the Leeuwin Current strength (measured by Fremantle sea level) over June to December, and the annual mean latitude of puerulus settlement at sites along the lower west coast of Western Australia (r=0.86, p<0.001 Caputi 2008).

(Pearce & Feng 2007) on growth, size at migration, size at maturity, catchability, and timing of moulting (thus peak catch rates) of WRL (Caputi *et al.* in prep.).

Scallops

Scallop recruitment is highly variable (Joll 1994; Joll & Caputi 1995). In WA, this is seen by widely varied annual commercial scallop catches in the main scallop fisheries, which occur at Shark Bay, the Abrolhos Island (Mid-west Trawl Fishery) and off the south coast (South Coast Trawl fishery). The Shark Bay scallop fishery has historically been the most productive fishery in WA, with annual catches ranging between 600 to 22,000 tonnes (whole weight). However, in 2003 and 2005 the Mid-West Trawl fishery recorded higher annual landings for scallops and in 2000 the South Coast Trawl fishery recorded the highest scallop catches in the state for that year (Figure 5).

Scallops are broadcast spawners (Kailola *et al.* 1993) with a larval duration of about two to three weeks (Rose *et al.* 1988). During this period larvae are susceptible to being passively transported by tides and currents whilst in the water column. Larval survival is affected by food availability and predator abundance, and the length of the larval period (assuming survival is enhanced by reducing time in the plankton community) can also be influenced by water temperature.

Annual scallop surveys, conducted between October and December, have been undertaken in Shark Bay since 1983, and provide size class and abundance information from over 90 trawl sites within the bay. These data are used to determine an index of recruitment strength during that year (individuals derived from the current years spawning) and provide the basis for predicting the catch the following year. They also provide an index of the size of the residual stock (older scallops remaining from the year before and possibly 2 years before, noting the life span is 2–3 years). For the Abrolhos Islands, a regular pre-season survey has also been undertaken in October since 1997, and as for Shark Bay, a catch prediction for the following season can be made using the survey abundance index derived from the pre-season survey.

The pattern of settlement in both Shark Bay and the Abrolhos Islands is variable between years and settlement patterns are patchier in the Abrolhos Islands compared to Shark Bay. The patchiness may reflect the habitat and/or the water current circulation pattern and eddies that occur at the Abrolhos Islands. However key areas where settlement may occur in any one year are now reasonably well known for both fisheries. No fishery independent surveys are conducted on the south coast. Normally in this region, one boat is elected to 'survey' potential settlement sites (derived using fishers knowledge) and if an encouraging "showing" of scallops is located, the other boats (only four licenses issued in the South Coast Trawl fishery) may elect to fish during the season.

Leeuwin Current correlation with recruitment of *Amusium balloti*

Shark Bay

In the 1980s in Shark Bay, a good correlation was observed between scallop recruitment strength and the strength of the Leeuwin Current (Joll & Caputi 1995). The proxy used for the LC is the height of the Fremantle Sea Level (FSL) during May to August, lagged by 1 month from the peak scallop spawning period of April to July to account for the latitudinal difference between Shark Bay and Fremantle. It was apparent that in years of weaker LC flow, higher recruitment success was observed and vice versa. A more recent analysis of LC

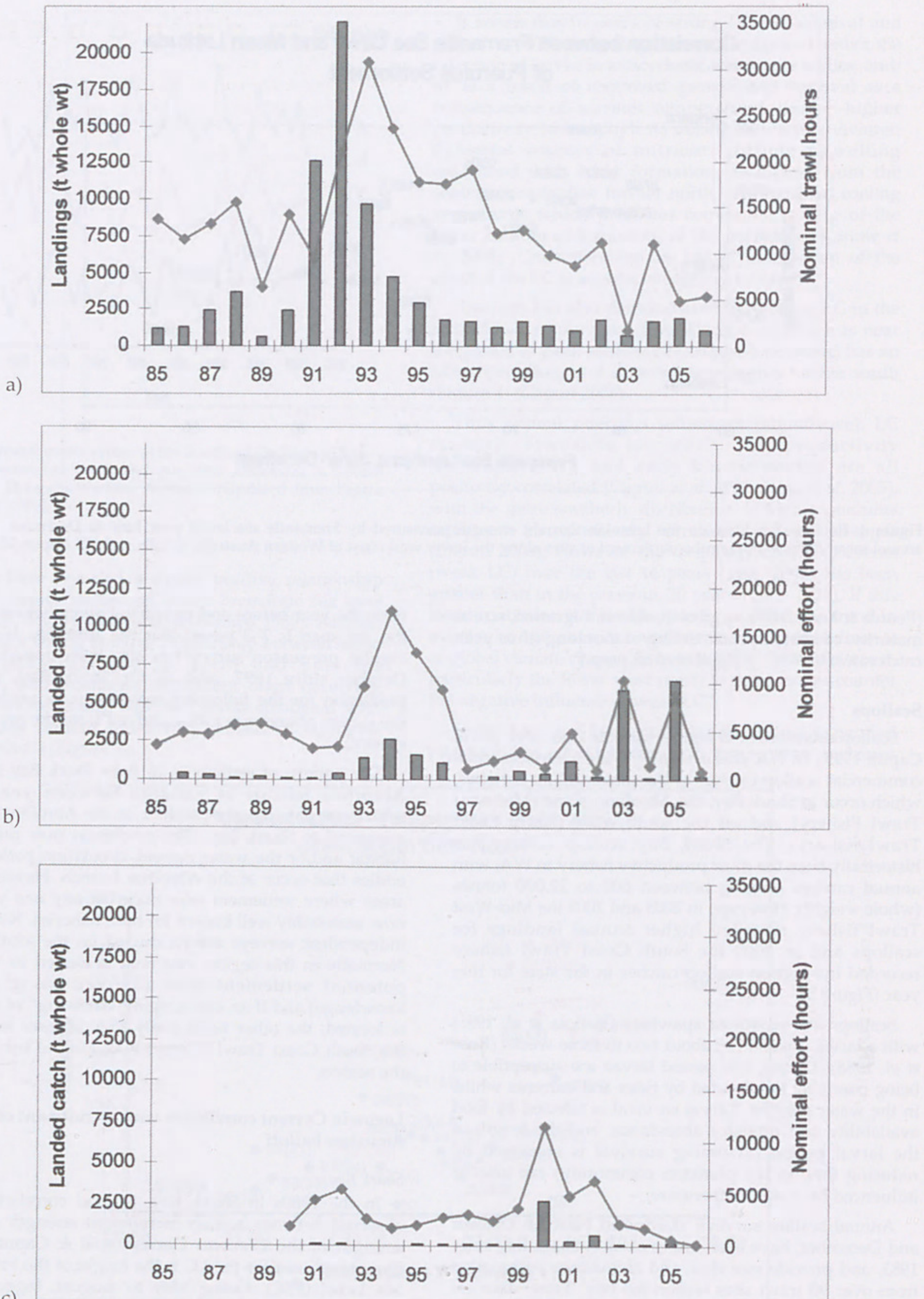

Figure 5. Annual scallop landings (tonnes whole weight – bar histograms) and nominal hours of trawling (line graph) in a) Shark Bay, b) Abrolhos Islands and c) South Coast trawl fisheries

strength and scallop recruitment in Shark Bay using data collected between 1983 and 2006 indicates a much weaker negative correlation (Figure 6) than the one reported for the 1980s. Similarly, a relatively weak negative correlation was observed between scallop recruitment and surface water temperature (Figure 7). There is some indication that a weak LC flow and/or cooler water temperatures benefit recruitment but not sufficient in themselves to always result in good recruitment. Other factors (*e.g.* water current movements during larval phase) must also be strongly influencing recruitment.

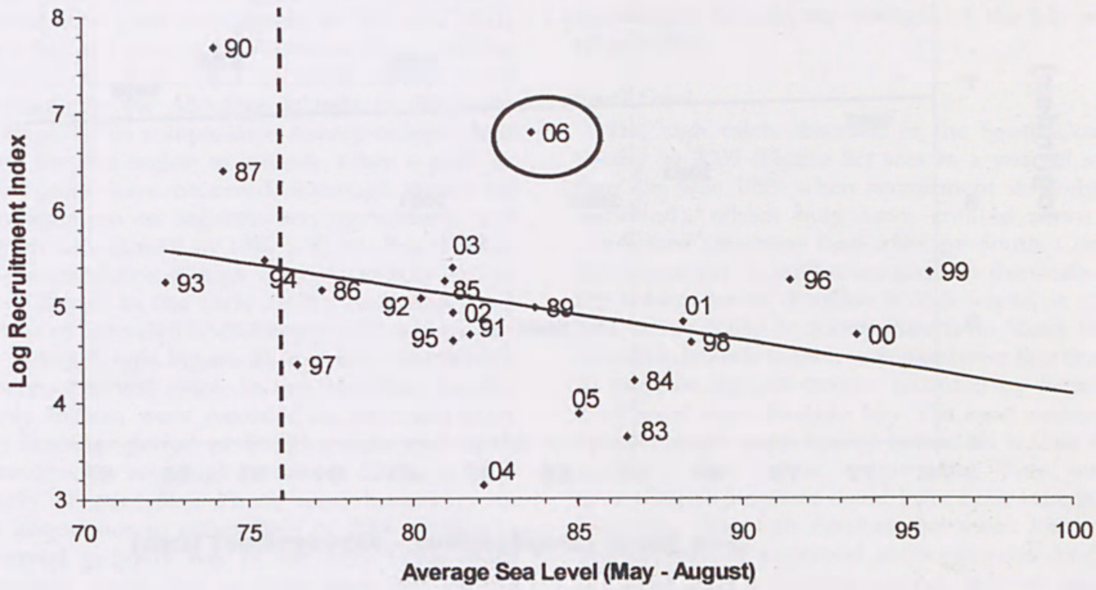

Figure 6. Correlation (log (Recruitment) = 9.6- 0.06FSL, R^2 = 0.14) between recruitment index in the Shark Bay scallop fishery (northern ground) and Leeuwin Current strength (FSL) between May and August (1983–2006). Dashed line indicates low average FSL conditions where some recruitment was observed to be high. Note 2006 is highlighted as a year with higher recruitment even though FSL was average.

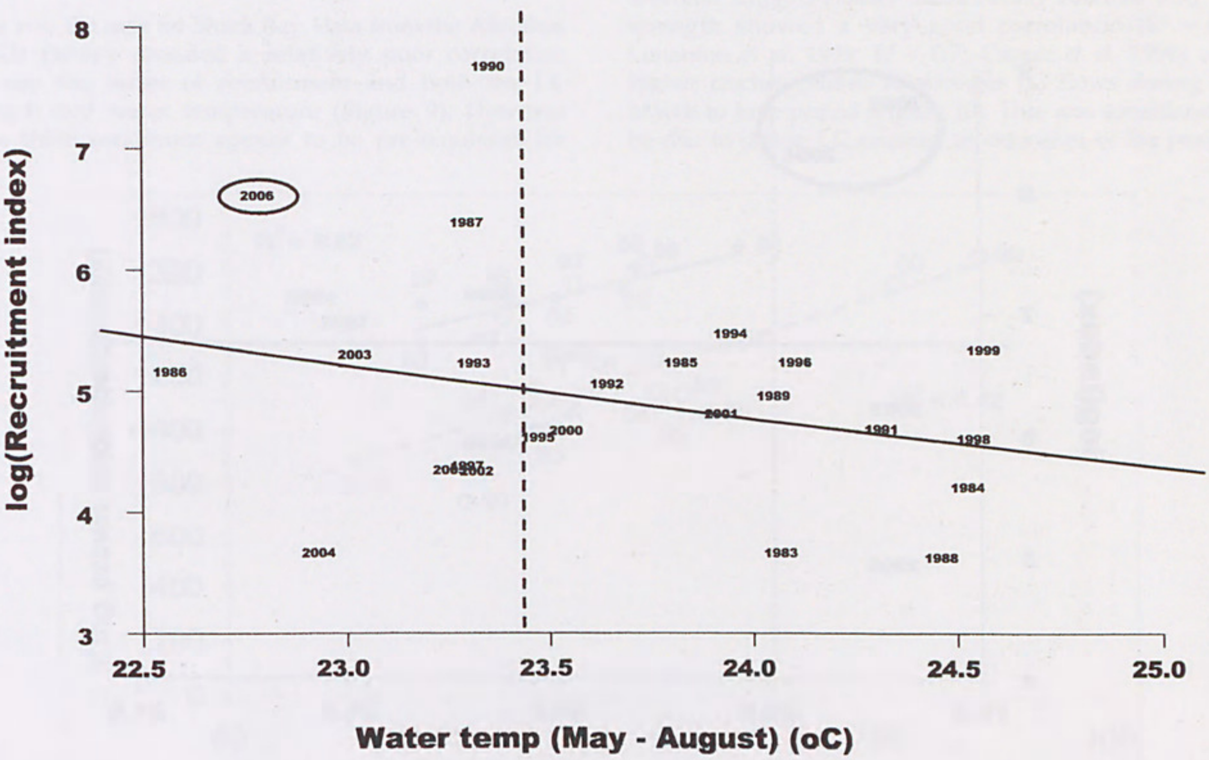

Figure 7. Correlation (log (Recruitment) = 15.8–0.46 SST, R^2 = 0.08) between recruitment index in the Shark Bay scallop fishery and surface water temperature (°C) between May and August (1983–2006). The dashed line indicates years when higher recruitment has been observed when Reynolds water temperature in waters of Shark Bay have been less than 23.5°C on average between May and August (when larvae in water column). Also 2006 is highlighted, as high recruitment when LC flow was stronger than for 1987 or 1990.

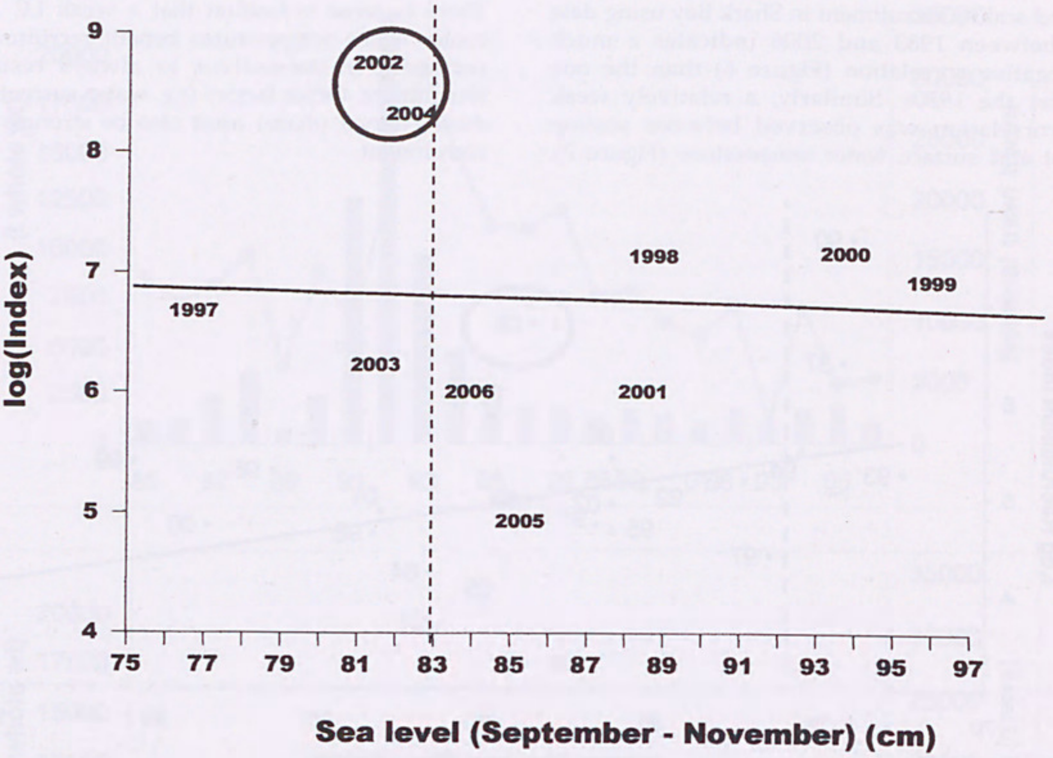

Figure 8. Correlation (log (Index) = 2.02–0.0013FSL, R^2 = 0.0022) between recruitment index in the Abrolhos Islands scallop fishery and Leeuwin Current strength (FSL) between September and November (1997–2006). The 2002 and 2004 are highlighted as years of high survey abundances during relatively low FSL resulting in high catches in 2003 and 2005.

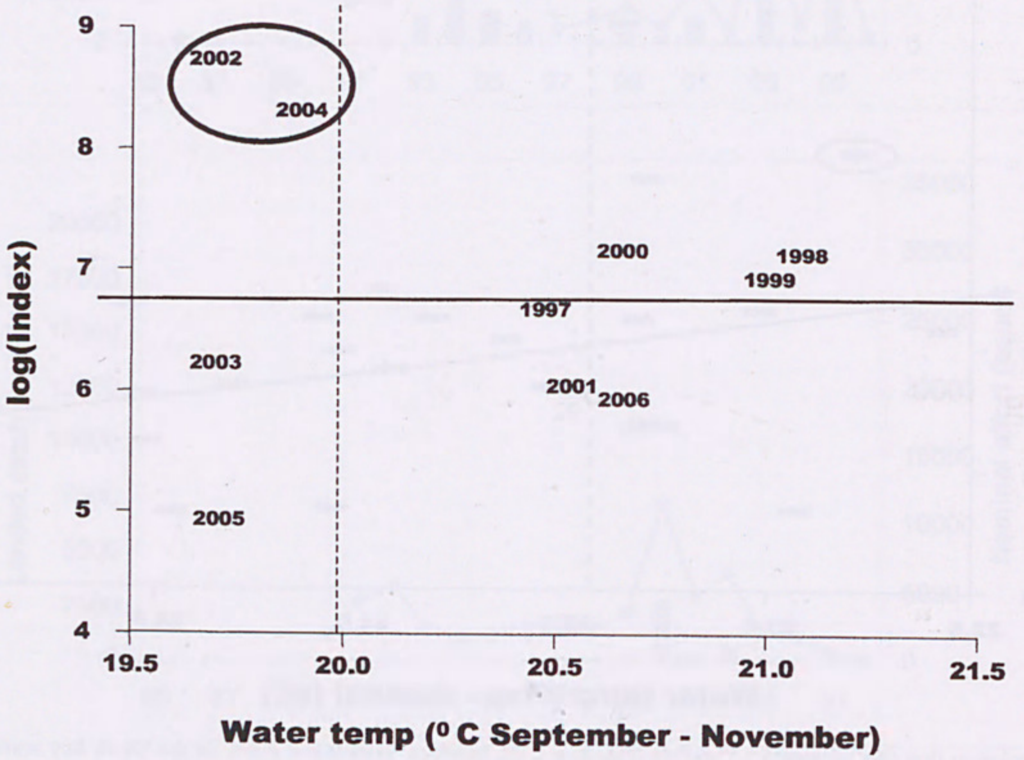

Figure 9. Correlation (log(Index) = 1.89 + 0.0010SST, R^2 = 1.156E-5) between recruitment index in the Abrolhos Islands scallop fishery and Surface Seawater Temperature (SST) between September and November (1997–2006). The 2002 and 2004 are highlighted as years of high survey abundances during relatively low FSL resulting in high catches in 2003 and 2005.

Abrolhos Islands

The high recruitment observed in Shark Bay in 1990 and 1992 (mainly in Denham Sound) resulted in four years of good catches between 1991 and 1994, in particular exceptional catches in 1992 (Joll 1994) (Figure 5a). In the Abrolhos Islands, the peak in catches occurred in 1993 and 1994 (Figure 5b) which would have resulted from good recruitment in 1992 and 1993, indicating a lag of a year or two between these and the high catches in Shark Bay. Standardised surveys were not undertaken in the Abrolhos Islands in the early 1990s so there is no comparative fishery-independent information for this region to indicate when a peak in recruitment may have occurred, although based on current information on lag between recruitment and catch, a good recruitment in 1992 and possibly 1993 is likely. The coincidence of high catches (with a lag) in these two fisheries in the early 1990s were associated with a period of extended ENSO events and subsequent weak LC strength (see Figure 2) and this coincidence has not been observed since. In the Abrolhos Islands, high survey indices were recorded in 2002 and 2004 (Figure 8) (another period of ENSO events and weak LC) and resulted in very high catches in 2003 and 2005 respectively (Figure 5b). There was, however, no carryover abundance in either 2004 or 2006 similar to those observed in Shark Bay in the early 1990s, even though records show that scallops were left on the grounds at the end of each fishing season. This may be due to differences in the timing of spawning resulting in the scallops at the Abrolhos Islands generally being six to twelve months older at the time of harvesting compared to those in Shark Bay.

As was the case for Shark Bay, data from the Abrolhos Islands fishery revealed a relatively poor correlation between the index of recruitment and both the LC strength and water temperature (Figure 9). However again these conditions appear to be pre-requisites for strong recruitment as years of high settlement have occurred under conditions of low LC flow and lower water temperatures (Figures 8 and 9). Another good recruitment occurred in 2007, and was associated with below average FSL and water temperature. These assessments indicate that there are other significant environmental variables that contribute to the success of recruitment besides the strength of the LC and water temperature.

South Coast

The high catch observed in the South Coast Trawl fishery in 2000 (Figure 5c) was in a year of strong LC flow (as was 1999 when recruitment is likely to have occurred), which may have created more optimal conditions (warmer than average South Coast water temperatures) for scallop survival on the south coast. As the scallop larval duration is 2–3 weeks, it is unlikely that larvae could be transported from Shark Bay or the Abrolhos Islands to the south coast over that time period. In fact, the highest catches recorded by fishers during 2000 were from Israelite Bay, the most eastern area of suitable south coast scallop habitat. It is thus extremely unlikely that larvae originating from west coast spawning populations could have been transported that far east. The high catches are more likely to be a consequence of improved environmental conditions on the south coast enhancing survival of larvae produced by the local populations in two successive years.

Shark Bay Western King prawns

Earlier work during the 1980s and 1990s relating western king (*Penaeus latisulcatus*) catches and LC strength showed a very good correlation (R^2 = 0.6, Lenanton *et al.* 1991: R^2 = 0.7; Caputi *et al.* 1996) with higher catches related to stronger LC flows during the March to June period (Figure 10). This was considered to be due to strong LC causing an extension of the peak in

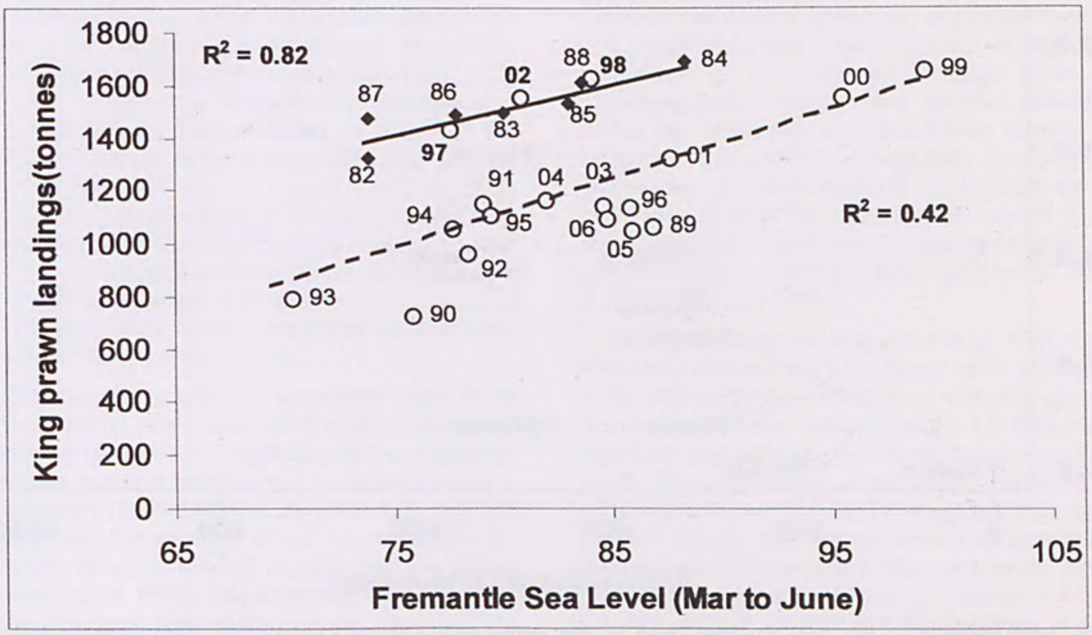

Figure 10. Average Fremantle sea level height between March to June each year and annual western king (*Penaeus latisulcatus*) catches in the Shark Bay prawn fishery between 1982 and 2006. The years highlighted in open circles (from 89 onwards) are included in the dashed line relationship.

the annual temperature cycle to match the main March to June fishing season at a time when king prawns are recruiting onto fishing trawl grounds from the nursery and/or shallow inshore areas. Higher catches were thought to be related to improved catchability, growth and survival (Caputi *et al.* 1996). The updated relationship (Figure 10) reveals that this positive correlation has persisted, but is now much weaker (overall R^2 =0.37). Interestingly, while the relationship is still positive for the years since 1989 (R^2 = 0.42), there has been an overall reduction in total prawn landings (Figure 10). The average landings have reduced from between 1400 and 1600 tonnes annually between 1982 and 1988, to between 1000 and 1200 between 1989 and 2005. The reasons for the lower landings may be related to different targeting and harvesting strategies since the early 1990s, where fishers have tried to save fuel and reduce costs by focusing less effort on larger more valuable prawns as the price of small prawns decreased due to the development of the prawn aquaculture industry.

Mud crabs

In Western Australia, there are numerous examples of the capture of tropical finfish and invertebrates well south of their historical distribution range (Hutchins 1991; Lenanton *et al.* 1991; Hutchins & Pearce 1994). The LC is the mechanism usually invoked as the vector transporting pelagic larvae well south of the normal range of distribution. Exceptionally strong LC during 1999 and 2000 distributed mud crab larvae as far south as Wilson Inlet just west of Albany (Figure 1) on the south coast (Bellchambers 2002; Gopurenko *et al.* 2003). These recruits survived and grew into mature individuals and during subsequent years, were caught by both commercial and recreational fishers. However they appeared not to have successfully bred in the lower west and south coast locations. Thus although they persisted in these more southerly locations for a few years, they did not establish a permanent population. The series of weaker LC since 2000 as a result of ENSO or neutral conditions may not have provided additional recruitment from further north nor the right water temperatures for successful breeding. However, mud crab populations have become established further south of their historical distribution (Shark Bay), perhaps made possible by slight elevations in ambient water temperature as a consequence of warming water temperatures due to "climate change" (Pearce & Feng 2007). One conclusive example is mud crabs having extended its southerly range to include the Murchison, and the Greenough Rivers (Figure 1).

Australian salmon

The western species of Australian salmon is distributed from southwestern WA eastwards to the gulf systems in South Australia (SA). The major part of the breeding stock does not reside along the southwestern coast but undertakes an annual migration from the east in autumn to spawn in this region, with adults then returning to the east. Progeny return to nursery areas in

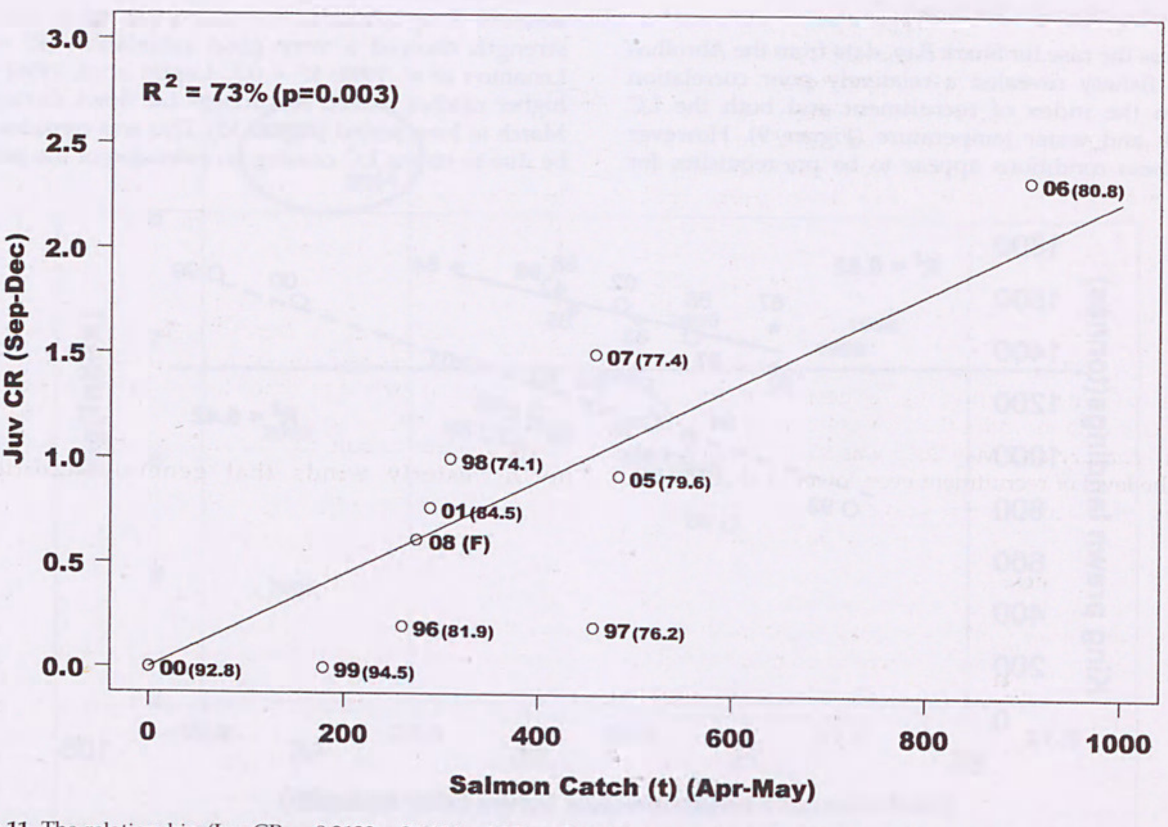

Figure 11. The relationship (Juv CR= - 0.2123 + 2.6414 x 10^{-3} catch (t)) between the annual index of the West Coast Australian Salmon breeding stock (April to May catch), and the annual index of juvenile (0+ yr class) recruitment (measured between September and December of the same year). Mean Fremantle sea level (February to May) is presented in parenthesis after each annual data point. Note that recruitment data were not collected between 2002 and 2004. Recruitment forecast for 2008 is also presented (F).

SA: larvae are thought to be transported east under the influence of the LC (Lenanton *et al.* 1991; Gaughan 2007), and juveniles are assumed to actively swim to nursery areas once able to do so. Historical catch information indicates that relatively few adults and juveniles reside in the south-west region throughout the year.

The strong negative relationships between the south coast commercial log book catch per hour of beach observation [up to 1980s], and LC (Albany sea level in February to April; Lenanton *et al.* 1991) is unable to be updated because a continuing lack of demand for the product and the changing nature of the fishery, has meant the beach-based catches no longer provide a good relative index of adult abundance. However, this is not the case on the lower west coast where a number of fishing teams queue to fish off the same few beaches, where they are afforded seasonal priority of access. Here on the lower west coast, despite reduced demand for the product, the hours of beach observation is believed to have remained relatively constant, and thus catch is still considered to provide a reasonable index of stock abundance. An annual index of recruitment (standardised catch rate of 0+ individuals) of juveniles settling in nursery areas off the lower west coast (the western extremity of the species distribution) (Gaughan *et al.* 2006) is available from research surveys conducted since 1996.

Preliminary analyses have revealed a strong relationship ($R^2 = 0.73$) between the April to May catch (annual index of the breeding stock), and the index of subsequent recruitment to the lower west coast (measured between September and December of the same year) (Figure 11). While the strength of the LC (average monthly FSL between February and May) appears to contribute little to this relationship, the data does reveal that no 0+ yr old recruits were recorded in the West Coast (WC) nursery areas during each of the very strong LC years of 1999 and 2000 (FSL > 92). Elevated indices of recruitment were recorded in both 2006 (2.59) and 2007 (6.91), the most recent (FSL respectively 80.8 and 77.4) of a series of seven weaker LC years experienced off the lower west coast since 2001. FSL was consistently below 85 in all years since 2000. While the breeding stock-recruitment relationship predicts the 2008 recruitment index is likely to be markedly lower than the index measured in 2007 (Figure 11), the extremely strong LC experienced in 2008 (preliminary data indicates that the average monthly FSL between February and May 2008 was 95) is predicted to reduce the level of recruitment even lower. It should also be noted that recruitment surveys were suspended between 2002 and 2004. Thus recruitment indices were not available for those years.

These preliminary results are consistent with those obtained from earlier work conducted at the eastern end of the species range in South Australia, that as expected, shows a strong positive relationship between the index of 0+ recruitment [1979–1989] of juvenile fish into SA nursery areas and the strength of the LC, measured by sea level height in one of the key nursery areas in the SA Gulfs (Lenanton *et al.* 1991). Unfortunately it has not been possible to progress this earlier work, because the juvenile sampling used as a basis for determination of the annual recruitment index in SA has since been discontinued.

Australian herring

Australian herring spawn off the south-west corner of Western Australia between April and May, with a relatively restricted peak in May. Juveniles recruit and settle into coastal and marine embayment habitats along the WA, SA and western Victorian coastlines (Ayvazian *et al.* 2000; Dimmlich *et al.* 2000). Monthly seine netting for 0+ juveniles at numerous locations between Perth and Adelaide was carried out during 1996, 1997 and 1998. These data were used to develop indices of annual recruitment. In order to assess the annual variation in juvenile recruitment, the indices of recruitment were used to model juvenile transport to explain the movement of juveniles from spawning areas to nursery areas. The factors that appear to determine the degree of recruitment success (strength of index of recruitment) are oceanic (the LC) and wind-induced currents and the swimming ability of the juvenile fish. In general, the transport model (Dimmlich *et al.* 2000) indicated that in years of stronger transport, there is a greater recruitment and settlement of juvenile Australian herring east of the Great Australian Bight (GAB) (Figure 1), while in years of weaker current, there was a stronger pulse of juveniles collected from west of the GAB. It seems that the LC was the dominant vector off WA, whilst a wind-driven current dominated off SA. Herring larvae are neustonic. The fact that they experience a single spawning event makes the transported larvae very vulnerable to episodic environment events (such as storms). Also, variable market demand for Australian herring in WA precludes the use of commercial catch and effort data needed to demonstrate links between strong recruitment to SA, and large catch three years later in WA.

Pilchard

Pilchard is the only teleost species from SWA for which there is a reasonable understanding of the dispersal of eggs and larvae. Fletcher *et al.* (1994) showed that winter spawning of pilchard off southern WA resulted in eastward transport of eggs under the influence of the LC, while eggs from summer spawning were transported shorter distances west under the influence of wind-driven surface currents. Gaughan *et al.* (2001) subsequently provided evidence that winter spawned pilchard larvae from the southern WA coast could be transported up to a 1000 km eastwards due to both the LC and seasonally dominant north-westerly winds that generate additional eastward surface drift.

Data was presented (Lenanton *et al.* 1991; Caputi *et al.* 1996) that showed the abundance of 2+ pilchard recruits in the Albany purse-seine fishery was strongly negatively correlated with the strength of the LC (FSL) during the June/July (spawning period) two years earlier [1985–1992]. The potential of considerable eastward transport of pilchard larvae by the LC suggests that such loss of progeny can have a serious impact on recruitment. This relationship deteriorated subsequent to the 1996 review, probably due to other factors becoming more important for pilchard recruitment and thus masking any LC affect. Firstly, pilchard recruitment on the south coast of WA was very low for several years in the mid-1990s, independent of the mass mortality mentioned below.

Secondly, the relationship was affected by a reduction in the overall stock size off Albany as a result of two significant mass mortalities of adult fish, the first in 1995 (Fletcher *et al.* 1997; Hyatt *et al.* 1997) and a second more severe mass event in 1998/99 (Gaughan *et al.* 2000). This has led to dramatic changes in the abundance of mature pilchards and also to their spatial dynamics (Gaughan 2003), relative to the area of influence of the LC.

Whitebait

Annual variation in the catch from a 3-year moving average of catch as an annual index of recruitment variation was positively correlated with LC (FSL) lagged one year [1977–1994] (Gaughan *et al.* 1996; Caputi *et al.* 1996). This promising relationship was updated to include years from 1995 until 2007. Demand for the product has remained strong so annual fluctuations in catch are still considered a good index of abundance, and the residuals (difference between the moving average and the annual catch) still provides a good reflection of the annual variations in recruitment. While there is still a positive relationship between the catch residuals and the FSL during the previous year (Figure 12), the addition of the more recent data weakened the relationship (R^2=0.29), implicating causative factors other than LC.

Dhufish and tailor

Dhufish and tailor are iconic angling species in marine waters off south-western Australia, with the former also a highly valued commercial species. For both species spatial dynamics of their life history are poorly understood. Dhufish spawn in deeper shelf waters while tailor possibly spawn in the vicinity of exposed reefs, usually those some distance off the coast. The larval life history of each is very poorly understood. Similarly, little is known about dhufish juveniles except that they recruit to deep (>10 m) reefs (Hesp & Potter 2000; Hesp *et al.* 2002) whereas juvenile tailor recruit to estuaries and shallow inshore waters where they are frequently caught (Lenanton *et al.* 1996).

Annual indices of recruitment are available for both species. For dhufish, they are derived from the current (2004–2007) age structure, with the numbers in each fully recruited year class back-calculated (taking into consideration mortality and selectivity) to the abundance during the year of initial settlement. Indices have been calculated for each year between 1986 and 2002 (St John unpublished). For tailor, an annual recruitment index has been calculated using data collected from the lower reaches of the Swan River during late summer/autumn months (February to April) that have been shown to be a robust indicator of the abundance of the 0+ and 1+ year classes off the lower west coast of WA (Ayvazian *et al.* in prep.). The abundance of the 0+ year class only has been used in these analyses. These data are available between 1995 and 2008.

Initial comparisons revealed no obvious relationship between LC strength (FSL) and sea surface temperature (SST), and the recruitment indices for dhufish in the waters off the lower west coast of WA. However a strong positive relationship (R^2=0.78) was apparent between recruitment strength, and the average sea surface salinity (measured between November and June, which encompasses the months of spawning and recruitment of

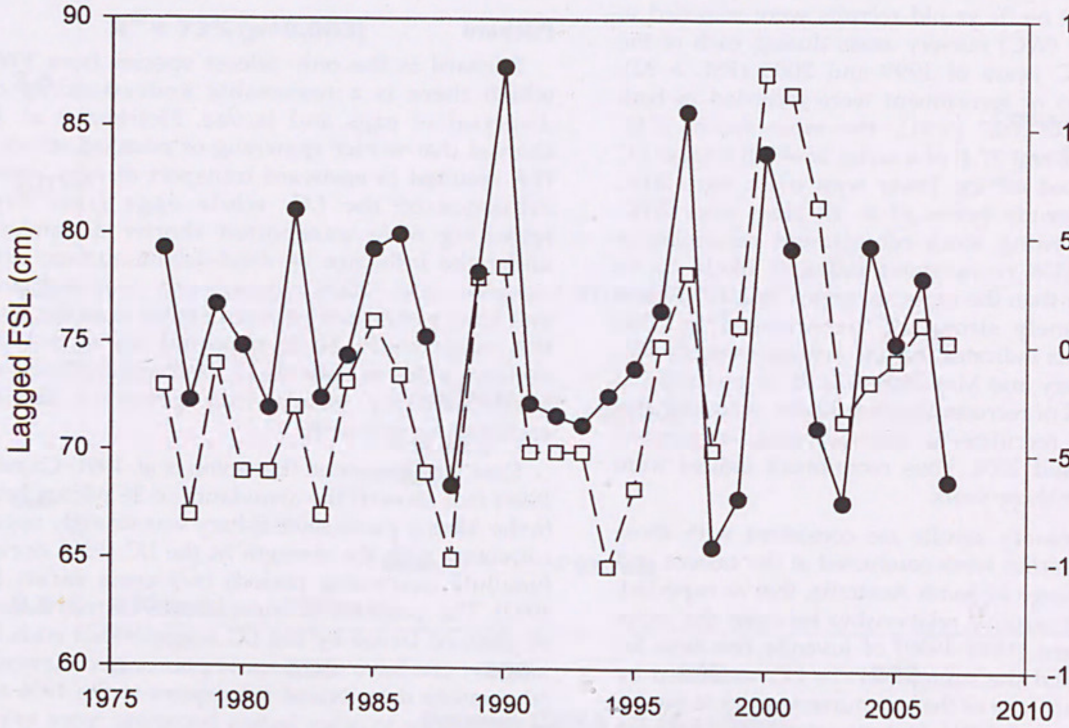

Figure 12. Time series of the residuals of whitebait catches (●), which takes into account the trend in the time series, and sea-level (FSL) time series lagged 1 year (□).

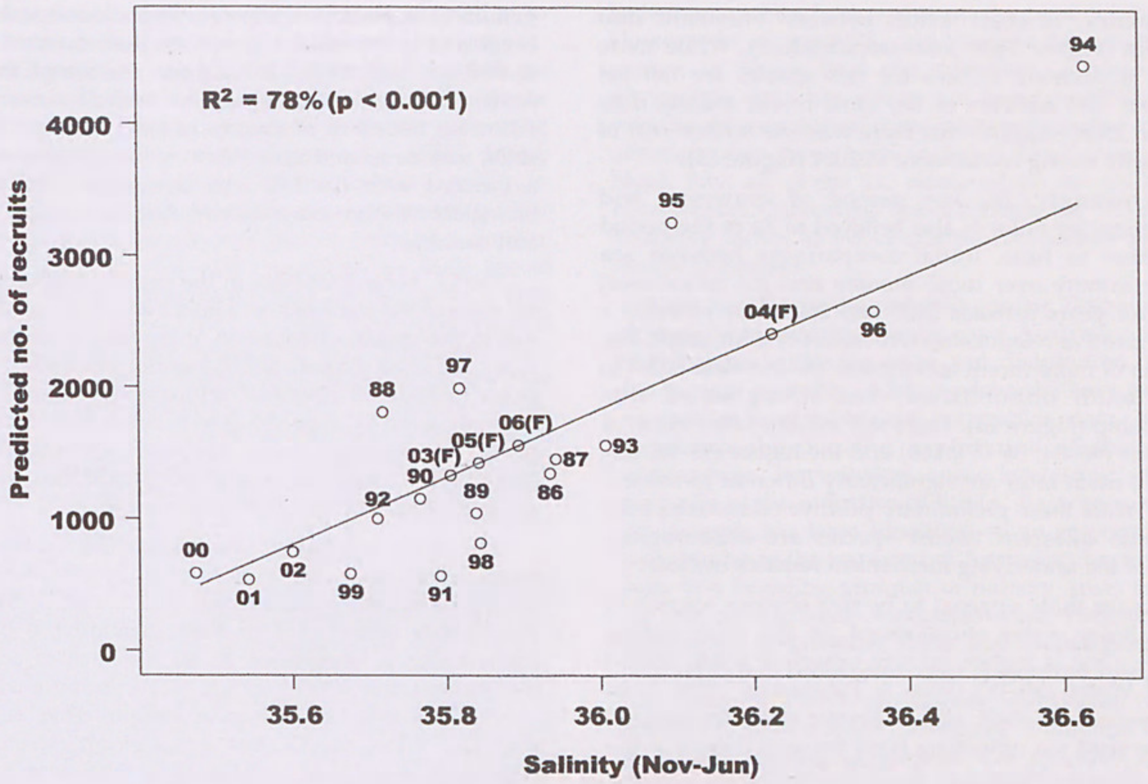

Figure 13. The relationship (Predicted no. of recruits = -82867 + 2348.5 Salinity) between the annual back calculated indices of dhufish recruitment (0+ year class), and the average sea surface salinity (ppt; 35.3‰ = Salinity = 36.7 ‰) of continental shelf waters between Fremantle and Dongara measured between November and May each year. Recruitment forecasts for the years beyond 2002 are shown in parentheses (F).

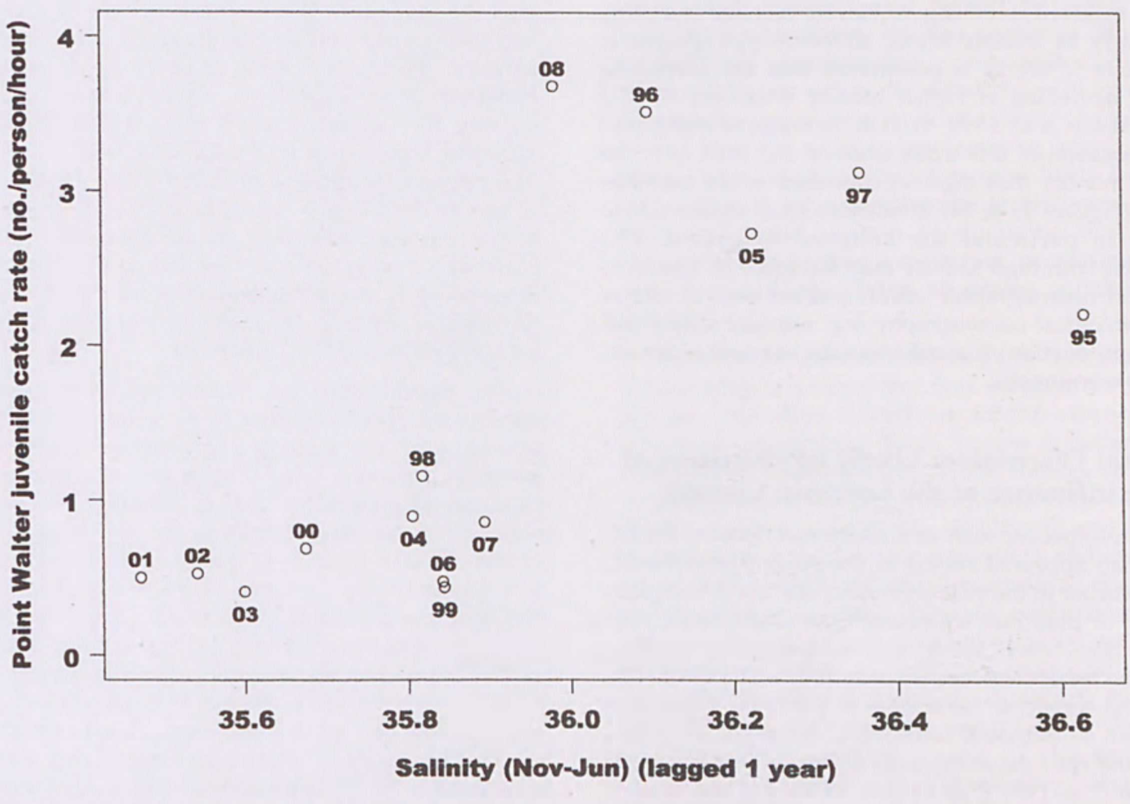

Figure 14. The relationship between the annual index of recruitment of tailor (measured between February and April each year), and the mean salinity of continental shelf waters between Fremantle and Dongara measured between November and May lagged by one year.

this species) of shelf waters between Fremantle and Dongara (Figure 1)(St John unpublished). While more recent recruitment indices for this species are not yet available, the addition of the most recent salinity data (2003 to 2008) suggests that there was one further year of potentially strong recruitment in 2004 (Figure 13).

Interestingly, the key period of spawning and recruitment for tailor is also believed to lie in the period November to June. Initial comparisons between sea surface salinity over those months and the recruitment index, for years between 1995 and 2004, also revealed a strong positive relationship (Ayvazian *et al.* in prep). The addition of more recent recruitment indices data (2005 to 2008, Smith unpublished) has strengthened this relationship (Figure 14). The t-test indicates that mean of the lower (98–04, 06–07)(0.66) and the higher (95–98, 05–08)(3.05) catch rates are significantly different (p-value $<$ 0.001). While these preliminary positive relationships for two quite different teleost species are encouraging, details of the underlying mechanism remains unclear.

However there appears to be two obvious sources of high salinity water encountered on the shelf during summer. One is higher salinity upwelled South Indian Central Water (SICW) (Woo & Pattiaratchi 2008) from areas beyond the shelf, and/or deeper water transported onto the shelf via upwelling from the mixed layer at the base of the LC (Hanson *et al.* 2005; Twomey *et al.* 2007). This latter source of upwelled water is believed to be associated with the Capes Current (Gersbach *et al.* 1999; Pearce & Pattiaratchi 1999). The other is as a consequence of higher rates of evaporation, particularly in inner-shelf regions during years of weak LC (Pearce & Feng 2007; Hanson *et al.* 2005; Waite *et al.* 2007). While evaporation alone is believed to be able to elevate on-shelf salinities, particularly in inshore areas, above 36 ppt (Pearce & Pattiaratchi 1999), it is postulated that the combined effect of upwelling of higher salinity water (up to 35.9 ppt: Gersbach *et al.* 1999; Woo & Pattiaratchi 2008), and the evaporation of this water once on the shelf over the summer months, may together contribute to the salinities >36 ppt (Figures 13 & 14) in offshore shelf waters where dhufish in particular are believed to spawn. The correlation with high salinity may therefore be linked to a physical oceanographic effect, and/or onward effects on the biological oceanography (*e.g.* nutrient status and primary production) that enhances the survival of larvae, and thus recruitment.

General Discussion: Likely mechanisms of the influence of the Leeuwin Current

For some species, such as western rock lobster, the LC relationship appeared robust to the point where the LC strength earlier in the year (Feb–Apr) was used to explain the trend in puerulus settlement later in the same year (peak in Sep–Nov), which was subsequently used to predict the fishery catches three to four years later. The spatial and temporal variability of peak LC flows was also shown to influence catchability of adults of certain species, and thus the magnitude of the commercial catch (Lenanton *et al.* 1991; Caputi *et al.* 1996). On the basis of our current understanding of the behaviour of the LC, and the biology of the species discussed in this paper, WRL appears to be the only species whose larvae genuinely depend on water conditions found at the shelf-break and in the adjacent ocean for their survival (Pearce & Phillips 1988, 1994). It has been postulated that high settlement rates of puerulus into on-shelf nursery areas following their 9 to 11 months of larval life spent off the shelf, may be related to retention within persistent eddies associated with the LC, and favourable physical and biological offshore environment that encourages growth and survival.

The LC behaviour later in the year (Jun–Dec) close to the time of the puerulus settlement also has an advection role in the spatial distribution of the puerulus settlement along the coast. Caputi (2008) has demonstrated that the mean latitude of puerulus settlement is related to the strength of the LC near the time of settlement. Thus WRL could be expected to be the only species of those considered to date that would likely exhibit a sustained and robust relationship with LC strength.

This study highlights the importance of long time series when assessing factors such as environmental conditions affecting recruitment. Relationships based on short times series of data may provide the basis of establishing a hypothesis as to the factors affecting recruitment but confirmation of the relationship can only be established when a longer time series is available. While the LC has a significant effect on the WRL stocks based on a relative long time series of data, it is not the only environmental factor that affects the stock given that it has a long (9–11 mo.) larval phase over a large spatial area. For example, the strength of the westerly winds in winter/spring has also been identified as affecting the puerulus settlement (Caputi *et al.* 2001) and no doubt there are other factors that may be relevant. While these other environmental variables remain within historic ranges, the relationship between the LC and WRL is likely to be maintained. However if we experience environmental conditions outside the historic ranges then it can result in an apparent breakdown in the LC and WRL relationship. The puerulus settlement in 2008/09 may be an example of this as the LC was strong in 2008 and an average or above average settlement would have been expected. However a very low settlement was achieved. An assessment is currently underway as to other factors (biological and/or environmental) that may have contributed to this low settlement.

The reproductive life history stages of most other commercial species appear to be confined to the shelf waters, and are thus to a greater or lesser degree, generally believed to be distributed shoreward of the main area of influence of the LC. Although tongues of LC water can penetrate the shelf for periods of up to several months (Pearce *et al.* 2006), details of the finer-scale shelf behaviour of the LC are still poorly understood. Nevertheless it has been postulated (Gaughan 2007) that under conditions of strong LC flow, large mesoscale eddies can entrain and remove large numbers of pelagic larvae of on-shelf teleost species from the shelf and away from suitable on-shelf nursery areas, thereby contributing to episodes of low annual recruitment, and ultimately contributing to the large annual recruitment variability observed in a number of these teleost stocks. There is however no evidence of an overall negative effect of lobster larvae entrained in these eddies. The very long larval duration of WRL may in fact be an adaptation to cope with entrainment and offshore movement. Depending on its strength at the time when pelagic larvae are present, the LC can also transport larvae considerable distances alongshore from the spawning location (Fletcher *et al.* 1994; Caputi *et al.* 1996), where their ultimate survival will depend on their ability to locate and settle into suitable nursery habitats. For pelagic species whose larvae do not settle to a benthic habitat and that may have a relatively long larval duration, the distance transported can be up to a 1000 km (Gaughan *et al.* 2001), with these advectional processes ultimately being the key determinant of recruitment success (Muhling *et al.* 2008b). Ultimately the effect of alongshore transport by the LC at a whole-of-population level is likely to be different to that at local levels relevant to fishery management boundaries, and the location of fishing grounds. This broad- *versus* local-effect has yet to be considered but would likely differ for species with different larval durations.

Compared to other eastern boundary current coastlines, the coastal waters off SWA have historically been regarded as being characterized by low levels of dissolved nutrients, and as a consequence, were believed to have typically experienced low plankton productivity in the water column (Pearce 1991; Hanson *et al.* 2005; Gaughan 2007). However recent research has shown that nitrate-rich deep water which is located under the LC, can be injected into the euphotic zone and thus generate higher within-water column productivity via upwelling events that extend across the continental shelf. These can occur off the mid-west coast in late autumn and winter (Koslow *et al.* 2008). Localized, but sporadic upwelling events can also be associated with the Capes (Gersbach *et al.* 1999; Twomey *et al.* 2007) and Ningaloo (Hanson *et al.* 2007) Currents during the summer months. Thus it appears that the activity of the Capes and Ningaloo Currents, both of which are components of the LCS, can also influence the composition of the on-shelf larval teleost assemblages (Muhling & Beckley 2007; Muhling *et al.* 2008a), the abundance of individual larval teleosts species, and the levels of recruitment to the fishable stocks of economically important species in coastal waters off SWA. Indeed, ongoing investigations have now revealed that a combination of mean wind speed at Cape Naturaliste and mean salinities measured at four locations along the west coast, and not just salinity (see under Data Sources, and Results and Discussion) during the main spawning period of dhufish were the best available indicators of the activity of the Capes Current, and that these variables were shown to have a positive influence on the annual year class strength of dhufish (Lenanton *et al.* 2009). Similar extensions to the work on tailor are also planned.

As such, the climactic patterns that generate the northern wind stress responsible for generating the Capes and Ningaloo Currents may well be crucial for sustaining stocks of fish in this region.

Summary and Conclusions

Prior to this review, significant correlation between species abundance (juveniles and/or adults) and LC strength could be demonstrated for seven economically important species from water off the west coast of WA. However in all but WRL, and possibly the western king prawn in Shark Bay, the addition of more recent compatible data has either not been possible, or has considerably weakened these relationships. For example, although data have been included from areas outside Shark Bay, all of the LC relationships for scallops are now weaker, indicating that although the LC is still a causative factor, as yet unquantifiable factors appear to also be important.

For a number of the scalefish species, discontinuation of juvenile monitoring (south coast Australian salmon), and changes in the structure and distribution of stocks due to mass mortality (Albany pilchards) have prevented the provision of additional compatible data, and thus precluded the ongoing exploration of these initial relationships. Nevertheless, some interesting additional examples of the influence of the LC have been revealed. LC strength has been identified as an important factor contributing to the transport of Australian herring larvae from WA breeding grounds to nursery areas further to the east off the South Australian coast. Further, a short time series of breeding stock and recruitment indices data from the lower west coast Australian salmon stock have revealed a stock-recruitment relationship where LC appears to have a major "threshold" influence. While no Australian salmon recruitment was recorded along the lower west coast during the two very strong years of LC (1999 and 2000), these unusually strong current events did distribute larvae of a tropical mud crab to lower west and south coast locations well beyond the normal southern distribution of this tropical species.

Two additional interesting relationships (West Australian dhufish and tailor) between juvenile abundance and salinity are also presented. However the underlying mechanisms responsible for these relationships are still in the initial stages of investigation. Because the actual magnitude of salinity change over the period that the relationships cover is very unlikely to exert a physiological effect, it is most likely that salinity is a surrogate for some physical or biological factor *e.g.* increased water column productivity, that enhances survival via increasing growth rate, decreasing mortality and/or increasing ability to access suitable nursery habitat.

From recent research it seems likely that water column productivity is a factor that may enhance the survival of larvae, and thus contribute to the strength of the observed correlations. There is now a better, and still developing, understanding of the sources of variability in pelagic nutrient regimes associated with the waters of the LC in the region of the shelf-break and in adjacent oceanic waters (eddies and meanders), and in nearshore/inner shelf waters (detached macrophyte and terrestrial runoff nutrient sources). However, while there is a broad understanding of the relationships between spatio-temporal variability in nutrient supply and subsequent phytoplankton and zooplankton dynamics, the dynamics of primary production for mid to outer shelf benthic communities in which many of the economically important finfish reside, regrettably, remains poorly understood.

Correlative relationships can continue to provide insight to variability of stock recruitment and fisheries production that is directly relevant to making management decisions. Poor knowledge of the causative agents (single or multiple) may well dictate that fisheries management continues to use plausible hypotheses as an additional source of information for developing scientific advice.

Acknowledgements: We would like to thank Alan Pearce (Curtin University of Technology) for access to his database on Fremantle sea level, and Dr Kim Smith for access to the recruitment indices data for tailor and A. salmon. We also owe a debt of gratitude to our many other colleagues from the Research Laboratories who collectively contributed to data analysis and the production of the manuscript, as well as those who provided constructive criticism of the manuscript, in particular Dr Daniel Gaughan, Adrian Thompson, Carli Johnson, Josh Brown, Ian Keay and Sue Turner.

References

Ayvazian S G, Craine M D Lenanton R C & Brown J I in prep. A novel approach to assessing the juvenile-recruitment relationship for the commercial tailor (*Pomatomus saltatrix*) fishery in the Swan River estuary, Western Australia.

Ayvazian S G, Jones K K, Fairclough D, Potter I C, Wise B S & Dimmlich W F 2000 Stock assessment of Australian herring. FRDC Final Report. Project 96/105: 223 pp.

Batteen M L, Kennedy Jr R A & Miller H A 2007 A process-orientated numerical study of currents, eddies and meanders in the Leeuwin Current System. Deep-Sea Research II 54: 859–883.

Bellchambers L 2002 Mud crabs on the move. Western Fisheries, Winter, 12–14.

Caputi N 2008 Impact of the Leeuwin Current on the spatial distribution of puerulus settlement on the western rock lobster (*Panulirus cygnus*) and the implications for the fishery off Western Australia. Fisheries Oceanography 17(2): 147–152.

Caputi N, Chubb C F & Pearce A 2001 Environmental effects on recruitment of the western rock lobster, *Panulirus cygnus*. Marine & Freshwater Research 52:1167–1175.

Caputi N, Fletcher W J, Pearce A F & Chubb C F 1996 Effect of the Leeuwin Current on the recruitment of fish and invertebrates along the Western Australian coast. Marine & Freshwater Research 47: 147–155.

Caputi N, de Lestang S, Feng M & Pearce A 2009 Seasonal variation in the long-term warming trend in water temperature off the Western Australian coast. Marine & Freshwater Research 60: 129–139.

Caputi N, Melville-Smith R, de Lestang S, Pearce A & Feng M in prep. The effect of climate change on the western rock lobster fishery of Western Australia.

Cresswell G R & Golding T J 1980 Observations of a south flowing current in the south eastern Indian Ocean. Deep-Sea Research 27A: 449–466.

Dimmlich W F, Ayvazian S G, Allison R & Fleer D 2000 Development of an exploratory model of larval and juvenile Australian herring (*Arripis georgiana*) transport from Western Australian spawning grounds to coastal nursery habitats. *In*: Stock assessment of Australian herring (eds S G Ayvazian, K K Jones, D Fairclough, I C Potter, B S Wise & W F Dimmlich). FRDC Final Report. Project 96/105: 223 pp.

Feng M, Meyers G, Pearce A & Wijffels S 2003 Annual and interannual variations of the Leeuwin Current at 32°S. Journal of Geophysical Research 108 (C11): 3355, doi:1029/2002JC 001763, 203.

Feng M S, Wijffels S, Godfrey G & Meyers 2005 Do eddies play a role in the momentum balance of the Leeuwin Current? Journal of Physical Oceanography 35(6): 964–975.

Fletcher W J, Tregonning R J & Sant G J 1994 Interseasonal variation in the transport of pilchard eggs and larvae off southern Western Australia. Marine Ecology Progress Series 111: 209–24.

Fletcher W J, Jones B, Pearce A F & Hosja W 1997 Environmental and biological aspects of the mass mortality of pilchards (Autumn 1995) in Western Australia. Fisheries Research Report 106: 1–65.

Gaughan D J 2003 Is there a place for aquatic protected areas in the management of small pelagic in coastal waters? *In:* Aquatic protected areas – what works best and how do we know? (eds J P Beumer, A Grant & D C Smith). World Congress on Aquatic Protected Areas proceedings. Cairns, Queensland, 32–40. University of Queensland Printery, Queensland. 689 p.

Gaughan D J 2007 Potential mechanisms of influence of the Leeuwin Current eddy system on teleost recruitment to the Western Australian continental shelf. Deep-Sea Research (II) 54: 1129–1140.

Gaughan D J, Mitchell R W & Blight S J 2000 Impact of mortality, possibly due to *Herpesvirus sp.*, on pilchard *Sardinops sagax* stocks along the south coast of Western Australia 1998–1999. Marine & Freshwater Research 51: 601–612.

Gaughan D J, White K V & Fletcher W J 2001 Links between functionally distinct adult assemblages of *Sardinops sagax*: larval advection across management boundaries. ICES Journal of Marine Science 58(3): 597–606.

Gaughan D J, Fletcher W J, Tregonning R J & Goh J 1996 Aspects of the biology and stock assessment of whitebait *Hyperlophus vittatus* (Clupeidae), in south-western Australia. Fisheries Research Report Fisheries Western Australia 108: 1–127.

Gaughan D, Ayvazian S, Nowara G, Craine M & Brown J 2006 The development of a rigorous sampling program for a long-term annual index of recruitment for finfish species from south-western Australia. Fisheries Research Report 154: 1–135.

Gersbach G H, Pattiaratchi C, Ivey G N & Creswell G R 1999 Upwelling on the south-west coast of Australia – source of the Capes Current? Continental Shelf Research 19: 363–400.

Golding T J & Symonds G 1978 Some surface circulation features off Western Australia during 1973–76. Australian Journal of Marine & Freshwater Research 29: 187–191.

Gopurenko D, Hughes J M & Bellchambers L 2003 Colonisation of the south-western Australian coastline by mud crabs: evidence for a recent range expansion or human-induced translocation. Marine & Freshwater Research 54: 833–840.

Hanson C E, Pattiaratchi C B & Waite A M 2005 Seasonal production regimes off south-western Australia: influence of the Capes and Leeuwin currents on phytoplankton dynamics. Marine & Freshwater Research 56: 1011–1026.

Hanson C E, Waite A M, Thompson P A & Pattiaratchi C B 2007 Phytoplankton community structure and nitrogen nutrition in Leeuwin current and coastal waters off the Gascoyne region of Western Australia. Deep-Sea Research II 54: 202–924.

Hesp S A & Potter I C 2000 Determination of biological parameters required for managing the fishery for Western Australian dhufish FRDC Final Report No. 96/103: 54pp.

Hesp S A, Potter I C & Hall N G 2002 Age and size composition, growth rate, reproductive biology, and habitats of the Western Australian dhufish (*Glaucosoma hebraicum*) and their relevance to the management of this species Fishery Bulletin 100: 214–227.

Hutchins J B 1991 Dispersal of tropical fishes to temperate seas in the southern hemisphere. Journal of the Royal Society of Western Australia 74: 79–84.

Hutchins J B & Pearce A F 1994 Influence of the Leeuwin Current on recruitment of tropical reef fishes at Rottnest Island, Western Australia. Bulletin of Marine Science 54: 245–255.

Hyatt A D, Hine P M, Jones J B, Whittington R J, Kearns C, Wise T G, Crane M S & Williams L M 1997 Epizootic mortality in the pilchard *Sardinops sagax neopilchardus* in Australia and New Zealand in 1995 II Identification of a herpesvirus within the gill epithelium. Diseases of Aquatic Organisms 28: 17–29.

Joll L M 1994 Unusually large recruitment in the Shark Bay (*Amusium balloti*) fishery. Memoirs of the Queensland Museum 36: 261–267.

Joll L M & Caputi N 1995 Environmental influences on recruitment in the saucer scallop (*Amusium balloti*) fishery of Shark Bay, Western Australia. ICES Marine Science Symposia 199: 47–53.

Kailola P J, Williams M J, Stewart P C, Reichelt R E, McNee A & Grieve C 1993 Australian Fisheries Resources. Bureau of Resource Sciences and the Fisheries Research and Development Corporation, Canberra: 422 pp.

Koslow J A, Pesant S, Feng M, Pearce A, Fearns P, Moore T, Matear R & Waite A 2008 The effect of the Leuwin Current on phytoplankton biomass and production off Southwestern Australia. Journal of Geophysical Research 113: 1–19.

Lenanton R C J, Joll L, Penn J W & Jones K 1991 The influence of the Leeuwin Current on coastal fisheries in Western Australia. Journal of the Royal Society of Western Australia 74: 101–114.

Lenanton R C, Ayvazian S G, Pearce A F, Steckis R A & Young G C 1996 Tailor (*Pomatomus saltatrix*) off western Australia: where does it spawn and how are the larvae distributed? Marine & Freshwater Research 47: 337–346.

Lenanton R C, St John J, Keay I, Wakefield C, Jackson G, Wise B, Gaughan D (eds) 2009 Spatial scales of exploitation among populations of demersal scalefish: implications for management. Part 2: Stock structure and biology of two key demersal fishes, Western Australian dhufish (*Glaucosoma hebraicum*) and snapper (*Pagrus auratus*), in the West Coast Bioregion. Final report to Fisheries Research and Development Corporation on Project No 2003/052. Fisheries Research Report No 174. Department of Fisheries, Western Australia: 187 pp.

Muhling B A & Beckley L E 2007 Seasonal variation in horizontal and vertical structure of larval fish assemblages off south-western Australia, with implications for larval transport. Journal of Plankton Research 29 (11): 967–983.

Muhling B A, Beckley L G, Koslow J A & Pearce A F 2008a Larval fish assemblages and water mass structure of the oligotrophic south-western Australian coast. Fisheries Oceanography 17 (1): 16–31.

Muhling B A, Beckley L E, Gaughan D J, Jones C M, Miskiewicz A G & Hesp S A 2008b Spawning, larval abundance and growth rate of *Sardinops sagax* off southwestern Australia: influence of an anomalous eastern boundary current. Marine Ecology Progress Series 364: 157–167.

Pearce A F 1991 Eastern boundary currents of the southern hemisphere. Journal of the Royal Society of Western Australia. 74: 35–45.

Pearce A F & Feng M 2007 Observations of warming in the Western Australian continental shelf. Marine & Freshwater Research 58: 914–920.

Pearce A F & Pattiaratchi C B 1999 The Capes Current: a summer countercurrent flowing past Cape Leeuwin and Cape Naturaliste, Western Australia Continental Shelf Research 19: 401–420.

Pearce A F & Phillips B F 1988 ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. Journel du Conseil 45: 13–21.

Pearce A F & Phillips B F 1994 Oceanic processes, puerulus settlement, and recruitment of the western rock lobster (*Panulirus cygnus*) *In:* The bio-physics of marine larval dispersal (eds P W Sammarco & M L Heron). American Geophysical Union, Coastal & Estuarine Studies 45 Washington DC: 279–303.

Pearce A F, Caputi N & Suber K 1998 Effects of season and interannual variability of the ocean environment on recruitment to the fisheries of Western Australia. FRDC Final Report. Project 94/032: 67pp.

Pearce A F, Lynch M J & Hanson C E 2006 The Hillarys Transect (1): Seasonal and cross-shelf variability of physical and chemical water properties off Perth, Western Australia, 1996–98. Continental Shelf Research 26: 1689–1729.

Phillips B F 1981 The circulation of the southeastern Indian Ocean and the planktonic life of the western rock lobster. Oceanography & Marine Biology Annual Review 19: 11–39.

Reynolds R W & Smith T M 1994 Improved global sea surface temperature analyses using optimal interpolation. Journal of Climate 7: 929–948

Ridgway K R & Condie S A 2004 The 5500-km-long boundary flow off western and southern Australia. Journal of Geophysical Research C: Oceans 109 (4): C04017.

Rose R A, Campbell G B & Sanders S G 1988 Larval development of the saucer scallop *Amusium balloti*, Bernardi (Mollusca:Pectinidae). Australian Journal of Marine & Freshwater Research 39: 133–160.

Twomey L J, Waite A M, Pez V & Pattiaratchi C B 2007 Variability in nitrogen uptake and fixation in the oligotrophic waters off the south west coast of Australia Deep-Sea Research II 54: 925–942.

Waite A M, Thompson S, Pesant M, Feng M, Beckley L E, Domingues C M, Gaughan D, Hanson C E, Holl C M, Koslow T, Meuleners M, Monyoya J P, Moore T, Muhling B A, Paterson H, Rennie S, Strzelecki J & Twomey L 2007 The Leeuwin Current and its eddies: an introductory overview. Deep-Sea Research II 54: 789–796.

Woo M & Pattiaratchi C 2008 Hydrography and water masses off the Western Australian coast. Deep-Sea Research I 55: 1090–1104.