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The influence of the Leeuwin Current on coastal fisheries of Western Australia

R C Lenanton[1], L Joll[1], J Penn[1] and K Jones[2]

[1]Western Australian Marine Research Laboratories, PO Box 20, North Beach, WA 6020, Australia
[2]South Australian Department of Fisheries, GPO Box 1025, Adelaide, SA 5001, Australia

Abstract

The fisheries of the three major southern hemisphere eastern boundary currents are briefly reviewed. In all three systems, physical environmental variables influence fish catches in a major way. Both the Benguela and Humboldt Currents create highly productive and dynamic upwelling ecosystems that are characterised by a succession of dominant finfish species, which can individually support substantial commercial fisheries. By contrast, the Leeuwin Current waters off the west coast of Australia are characterised by low biological productivity. Although a group of finfish species, almost identical to those of the Benguela and Humboldt Current ecosystems is represented in the Leeuwin Current ecosystem, the collective Western Australian catches of these species are insignificant by world standards. Indeed the major commercial species of this region are demersal invertebrates, some of which (*eg* rock lobster) support fisheries of international significance. Thus the Leeuwin Current does exert a major influence on the overall ecology of this unique region, and affects the production of both economically important finfish and invertebrate species.

Introduction

Historically four major eastern boundary current systems were recognised in the world oceans (Wooster & Reid 1963). They comprise very large spatial systems which exhibit unique bathymetry, circulation, biological productivity and trophodynamic relationships of populations. Two of these, the California and Canary Currents, are located in the northern hemisphere, while the other two, the Humboldt and Benguela, are located in the southern hemisphere (Parrish *et al.* 1983, Weaver 1990).

Both the Humboldt and Benguela eastern boundary currents are part of oceanic-scale wind-driven anticyclonic gyres in the southern hemisphere. Because the equatorward flow of water is in the same direction as the prevailing wind, upwelling is associated with these coastal currents (Cushing 1971, Shannon 1985, Bohle-Carbonell 1989). In recent years, however, a fifth and uniquely different eastern boundary current system has been recognised (Golding & Symonds 1978, Cresswell & Golding 1980, Pearce & Phillips 1988, Pearce & Prata 1989). In contrast to the other four eastern boundary current systems, the Leeuwin Current is driven poleward by a deep alongshore density gradient, whose existence is partly dependent on the flow of warm western equatorial Pacific water through the Indonesian Archipelago (Weaver 1990). The lack of upwelling associated with this current is because of the eastward flow of Indian Ocean water despite the prevailing southerly winds (Godfrey & Ridgway 1985).

The life history characteristics, such as spawning, migration, recruitment and feeding patterns, and ultimately the overall production of many ecologically important finfish species have evolved under the influence of such current systems.

For example, the upwelling of cool nutrient-rich water, which is a most important characteristic of the Humboldt/Benguela systems leads to high rates of primary production *ie* high biomass of phytoplankton and zooplankton (Cushing 1971, Armstrong *et al.* 1987, Chavez *et al.* 1989). This accounts for the substantial populations of pelagic planktivorous fishes found in both of these upwelling systems (Crawford *et al.* 1983, Parrish *et al.* 1983, Crawford *et al.* 1987, Crawford 1987). Indeed the commercial catches of pelagic species from these regions are very significant in the context of world fish production (FAO 1988).

By contrast, the Leeuwin Current consists of warm low nutrient water flowing into continental shelf waters,

Table 1

The prominent families of finfish which comprised the commercial catch from southern hemisphere eastern boundary currents systems during the 1980's.

Finfish Families	Southern Hemisphere Eastern Boundary Current Systems		
	Humboldt	**Benguela**	**Leeuwin**
Clupeidae (true herrings)	Sardine	Pilchard Round herring Sardinella	Pilchard Round herring (maray) Sardinella
Engraulididae (anchovy)	Anchoveta	Anchovy	Anchovy
Carangidae (trevally)	Horse mackerel	Horse mackerel	= Jack mackerel (or scad)
Scombridae (mackerel)	Mackerel Bonito	Mackerel Bonito	Mackerel Bonito
Merluccidae (hake)	Hake	Hake	?(offshore)
Gemplylidae (snoek)		Snoek	Barracouta (or snoek)
OVERALL ANNUAL CATCH (Million tonnes)	<1-13*	<1-4*	<0.001+

Source * FAO, 1988, Crawford *et al*, 1987
+ Anon. 1990

which, by Humboldt/Benguela standards, are already low in nutrients (Rochford 1980, 1988, Pearce *et al*. 1985). Although similar pelagic planktivorous fish species are represented in the Leeuwin Current system, the commercial catches of these species are far smaller than those of similar species taken from the Benguela and Humboldt upwelling regions (Table 1). Indeed, demersal species (particularly rock lobster and prawns), that are dependent on benthic production dominate commercial catches taken from the Leeuwin current (Anon. 1990).

Effect of the Humboldt and Benguela Currents on Associated Fisheries

Environmental change, rather than factors such as recruitment overfishing, predation or pollution, has been identified as the major variable controlling large scale changes in fish abundance in all eastern boundary currents (Sherman 1987).

Understanding the complex processes through which, in an overriding sense, climate (Cushing 1982, Sharp 1987) and more specifically the physical environmental properties of the current systems can ultimately affect commercial fish catches is of major importance to the managers of such fisheries.

Principal abiotic properties of the current environment that can lead directly to changes in fish abundance (and therefore catches) include: current strength and direction, current motion (or turbulence), water temperature, water salinity, and dissolved oxygen. For example, temperature, turbulence and transport patterns influence the location of spawning grounds and the breeding period of anchovies and pilchards in those eastern boundary currents characterised by upwelling (Parrish *et al.* 1983).

Certainly, instances of strong recruitment for neritic stocks in the southern Benguela system have been linked to environmental anomalies (Crawford *et al.* 1983). Specifically, sea surface temperature and anchovy recruitment have been positively correlated (Boyd 1979). Sea temperature has also been shown to influence directly the survival of pilchard and anchovy eggs (King 1977).

Furthermore, a shift of the predominant species from anchoveta to sardine between 1970 and 1983 resulted in a dramatic increase in the yield of sardine off Chile and Peru (Cushing 1982). This has been partially attributed to El Niño producing higher sea surface temperatures which in turn reduced the anchoveta habitat size (Muck 1989a), and thereby made them more vulnerable to fishing pressure (Cushing 1982, Csirke 1989).

The above abiotic factors can also indirectly affect abundance of important commercial fish species by influencing their food supply, competitors and predators (Wooster & Bailey 1989).

For example, high sea surface temperatures associated with El Niño events can indirectly reduce anchoveta abundance by increasing the density-dependent mortality on eggs and larvae, increasing metabolic cost and reducing food availability (Muck 1989a). Moreover, the intrusion of warm oxygen-rich waters from the north into the Humboldt upwelling system during El Niño events, led to hake extending further south, and thus invading the main anchoveta area. This allowed increased anchoveta predation of hake eggs (Muck 1989b).

Effect of the Leeuwin Current on Fisheries Productivity

The continental shelf waters off Western Australia are relatively low in nutrients (Pearce *et al.* 1985) and relatively clear. As a result of the Leeuwin Current, the overall temperature range in the region of its influence is also relatively small. Temperatures are therefore appreciably warmer than at comparable latitudes in other eastern boundary current regions (Pearce 1991).

Because of the shape of the Western Australian coastline, and in particular variation in the width of the continental shelf, the impact of the Leeuwin Current appears to be greater on some sections of the shelf than others. Satellite imagery has suggested that the current approaches the coastline between North-West Cape and Shark Bay, in the Geographe Bay/Cape Naturaliste/Cape Leeuwin region, and along the south coast from Pt. D'Entrecasteaux to about Albany (Pearce 1985). In addition, islands near the edge of the shelf, such as the Abrolhos Islands and Rottnest Island, are particularly affected by the warm current waters (Hatcher 1991, Hutchins 1991).

Because upwelling is not a feature of the current system, nutrient levels in the coastal waters are largely dependent on terrestrial inputs. Run-off from the largely arid hinterland is particularly low, with the limited river outflow mostly from the south-western region of the State being confined almost entirely to winter/spring (Lenanton & Hodgkin 1985). The relatively clear coastal waters landward of the Leeuwin Current, which include the large marine embayments of Shark Bay and Geographe Bay, are typified by extensive seagrass meadows and macroalgae dominated coastal reef systems (Kirkman 1985, Walker 1991). Coastal finfish resources of the state are generally confined within these water masses landward of the main current and are largely dependent on the relatively productive estuarine and protected coastal marine ecosystems (Lenanton 1982, Robertson & Lenanton 1984, Lenanton & Potter 1987).

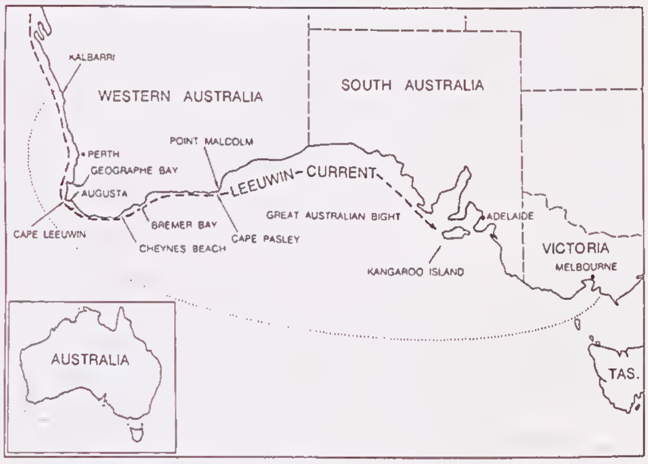

Figure 1 The limits of distribution of the Western Australian salmon. Hatching indicates the region of most intensive spawning. In addition to these major fisheries, there are also tropical species appearing in the commercial and recreational catch off the west coast which are dependent on the seasonal flow of the Leeuwin Current (Maxwell & Cresswell 1981, Hutchins 1991).

The major invertebrate resources of Western Australia, the western rock lobster *Panulirus cygnus* (Phillips & Brown 1989), and penaeid prawns *Penaeus esculentus* and *Penaeus latisulcatus* (Penn 1981), are similarly dependent on the extensive inshore and relatively productive macrophyte zones.

Fisheries Affected by the Leeuwin Current

Almost all of the major economically important fish stocks in waters off the western and southern coasts of Western Australia are influenced to some extent by the Leeuwin Current. As will be shown below, fisheries which are specifically affected by the current are (i) the Western Australian salmon and herring fisheries off the south and lower west coasts; (ii) the pilchard purse seine fishery off the south coast; (iii) the western rock lobster fishery off the west coast; (iv) the saucer scallop fisheries in Shark Bay and other areas off the west and

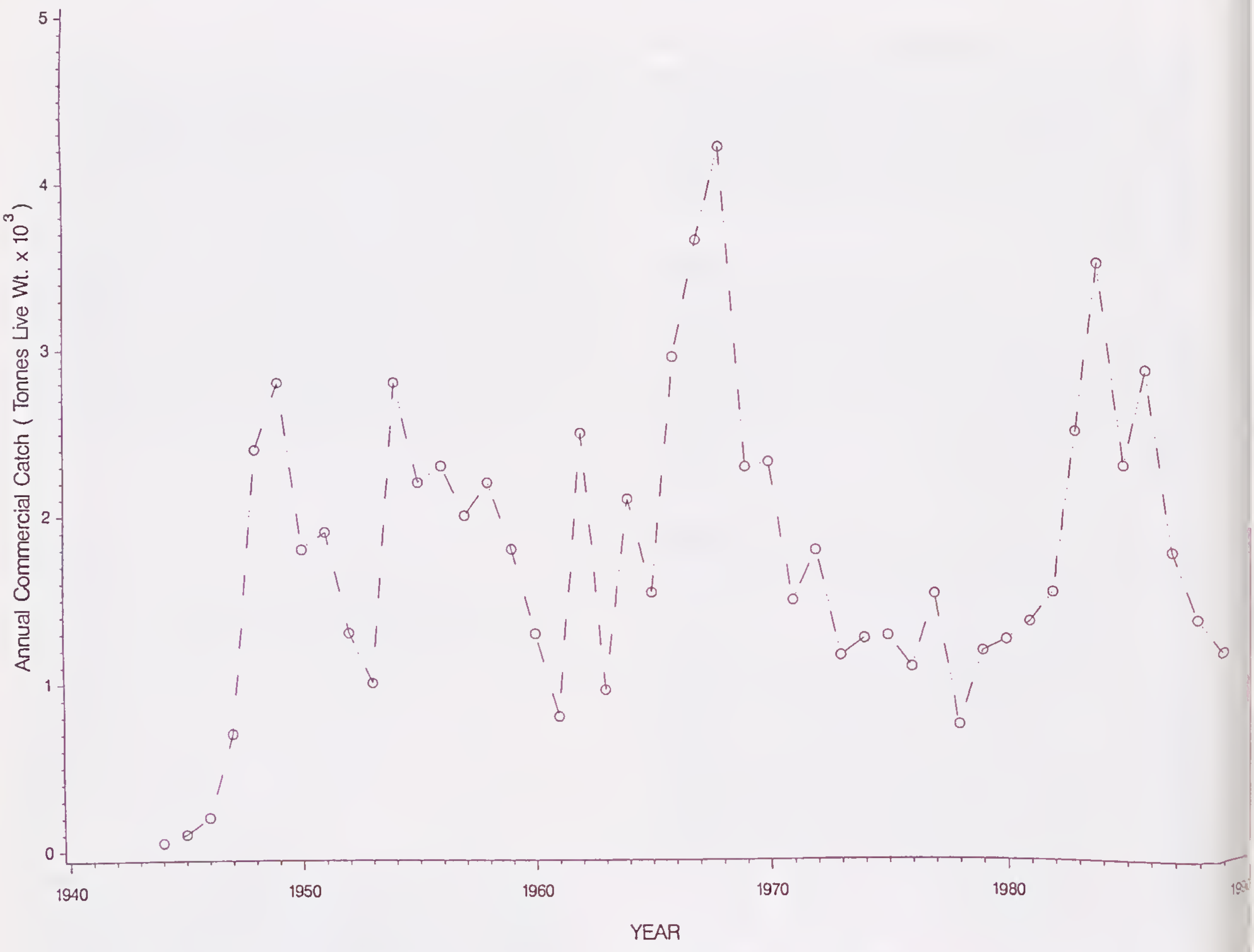

Figure 2 The annual Western Australian commercial catch of Western Australian salmon between 1944 and 1989.

south coasts; and (v) the penaeid prawn fishery in Shark Bay.

They include scaly mackerel (*Sardinella lemura)*, dusky (bronze) whaler shark (*Carcharhinus obscurus*), spanish mackerel (*Scomberomorus* spp.) and baldchin groper (*Choerodon rubescens)* in marine waters; and bar-tailed flathead (*Platycephalus endrachtensis)* and giant herring (*Elops machnata)* in the Swan river system.

A large component of the finfish catch from the Abrolhos Islands is also made up of tropical species such as narrow-barred spanish mackerel (*Scomberomorus commerson*), cod (*Epinephelus spp.*), coral trout (*Plectropomus* spp.) and baldchin groper.

Western Australian salmon fishery

Western Australian salmon (*Arripis truttaceus*) is a large pelagic inshore schooling species (Malcolm 1960). It is distributed from Kalbarri on the mid-west coast of Western Australia to about Victoria and western Tasmania on the south coast of Australia (Fig. 1) (Stanley 1980a, Hutchins & Swainston 1986) where it supports substantial commercial net and recreational angling fisheries (Stanley 1980a, Walker 1982, Cappo 1987).

The major Western Australian fishery for salmon is located off the beaches between Geographe Bay and just east of Bremer Bay (Stanley 1980a, Walker 1982). All fish located east of the western Great Australian Bight are immature (Malcolm 1960, Stanley 1980a, 1980b), while all the mature fish are located in Western Australian waters.

Spawning commences during March, and reaches a peak during early April (Malcolm 1960, Nicholls 1973). It is postulated that large numbers of fertilised eggs and larvae are transported east by the Leeuwin Current to inshore protected nursery grounds located between the western Bight and Victoria (Cresswell 1986, Malcolm 1960, Robertson 1982).

Juveniles first appear in the Western Australian nursery grounds in April (Lenanton 1977, 1982), and in

South Australia, nursery grounds in June (Jones *et al.* unpublished). Although juveniles are first fished commercially as 1 year old fish in South Australia (Stanley 1979, Cappo 1987), there is very little commercial exploitation of juveniles in Western Australia (Walker 1982). Fish tend to mature according to size rather than age, and grow much faster in Western Australia than in eastern Australia (Nicholls 1973, Stanley 1979, 1980b).

At about the end of January/early February, mature and maturing fish migrate from waters adjacent to their nursery grounds west to spawn off the lower west and south coasts of Western Australia (Malcolm 1960, Stanley 1980a). These fish form the basis of the Western Australian commercial and recreational fishery (Walker 1982, Cappo 1987).

At the beginning of each season, the Western Australian catch comprises mainly larger resident fish (Malcolm 1960, Stanley 1980a). By about mid March, smaller new recruits dominate the catch (Stanley 1980b, Cappo 1987).

Preliminary modelling of the Western Australian salmon fisheries has revealed that stock abundance appears to be dependent mostly on the magnitude of annual recruitment. Major peaks in annual Western Australian catch, in particular those in the late 1960's and early 1980's (Fig.2) are thought to be related to periods of strong recruitment from Western Australian nursery areas (C. Walters, R.C.J. Lenanton and M. Cappo, unpublished). Furthermore environmental change influenced by the Leeuwin Current, rather than fishing, appears likely to be one of the main factors affecting recruitment.

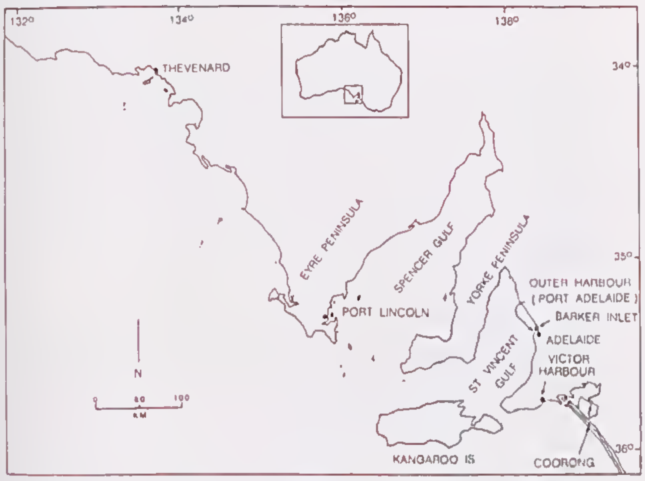

Figure 3 Central and western coastline of South Australia showing sites where sealevel is routinely monitored, together with sites where juvenile salmon abundance is measured.

Preliminary evidence from South Australia suggests that the Leeuwin Current assists the recruitment of salmon to South Australian nursery areas. First a significant positive correlation has been demonstrated between the Southern Oscillation Index (SOI) and mean annual sealevel at Thevenard ($r^2=0.42$, $0.025<P>0.05$), Port Lincoln ($r^2=0.35$, $0.0025<P>0.005$), Port Adelaide (Outer Harbour) ($r^2=0.46$, $0.005<P>0.025$) and Victor Harbor ($r^2=0.50$, $P=0.01$) (Fig. 3). In years of low SOI (and weak Leeuwin Current) (*eg* 1982), relatively low sealevels occurred during June to September when 0+ year old salmon are being distributed across the Great Australian Bight and entering the nursery areas of the west coast bays, South Australian Gulfs and the Coorong waters (Fig.4). In years of high SOI (and strong Leeuwin Current) (*eg* 1981), the sealevel during these months was relatively high.

An annual recruitment index (natural log numbers (ln n)) of 0+ year old salmon is available between 1980 and 1990 from the waters of Barker Inlet, adjacent to the Outer Harbour in South Australia (Fig.3) (G.K. Jones, G. Wright & K. Edyvane, unpublished). Further analysis revealed a significant positive correlation between sealevel in August (the usual month when salmon enter the South Australian nursery areas) at Outer Harbour, and the annual recruitment Index of salmon in Barker Inlet (Fig.5).

The commercial catch of salmon in waters of the Coorong comprises mainly 1+ year old fish (Cappo 1987). There is also a significant positive correlation between the commercial catches of 1+ year old salmon in the Coorong waters and the adjacent Victor Harbor August sealevel measured one year earlier (Fig.6).

Thus, there is strong circumstantial evidence for a direct, relatively short-term (up to 6 months) process of transportation of larvae from Western Australian spawning areas to South Australian nursery areas. Furthermore, there are indications that both current strength and timing of peak flow are likely to have an important influence on the strength of recruitment to South Australian nursery areas.

Attempts to relate mean sealevel at Albany at the time of spawning to the subsequent recruitment of maturing salmon into the Western Australian commercial fishery (*ie* between 4 to 6 years later) have to date been unsuccessful because of:

1) the complicated size-dependent recruitment process

2) variable annual rates of fishing and natural mortality during the relatively long period of four or more years leading up to recruitment into the fishery.

However, there are indications that commercial catches may be adversely affected in years of strong Leeuwin Current flow along the south coast of Western Australia. Preliminary analyses have revealed a negative correlation between the mean monthly sealevel at Albany over the period of the fishery (February - April) and the mean annual south coast log book catch per hour of beach observation in that same year (Fig.7). These data were treated as two separate

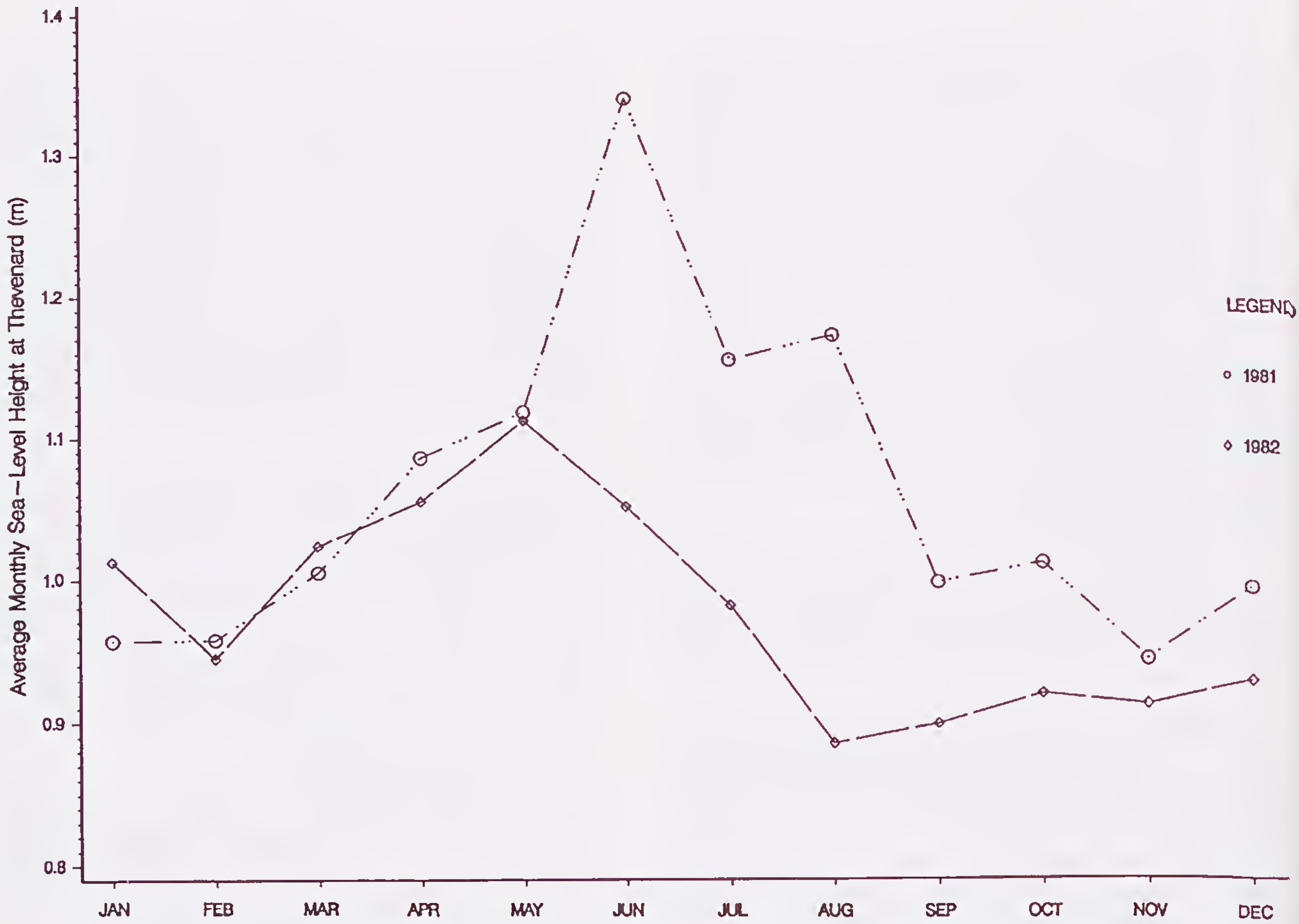

Figure 4 The average monthly sealevel at Thevenard, South Australia during years of weak (1982) and strong (1981) SOI.

groups: those from years of low catches (=abundance) and those from years of high catches.

The suggestion, supported by observations from commercial fishers, is that in years of strong Leeuwin Current flow, local storm events modify the pattern of the current flow, resulting in "patches" of warmer Leeuwin Current water adjacent to the shoreline. Thus, migrating salmon are forced offshore and deeper, in order to avoid these cells of warmer water, and at such times are not available for capture on beaches located along the affected shoreline. Thus during years of strong Leeuwin current flow the catchability of the stock is reduced.

Indeed, log book records kept by two demersal shark gill net fishers (Table 2) show clearly that salmon occurred within 3 m (the approximate depth of the nets) of the bottom in water depths of up to 57 m. Further, a by-catch of salmon has consistently been recorded in the monthly catch and effort returns of a number of demersal gill net fishers who operate in a variety of areas between Geographe Bay and Cheynes Beach (Fig.1).

Although the above data suggest that the Leeuwin Current is the major factor influencing larval transport and distribution, the precise details of the process are not known. Observations by fishers suggests that salmon spawn close to the coast. However the Leeuwin Current usually flows along the shelf break. Thus if the current is in fact the medium of larval transport, then either the fish must spawn in locations where the current is close to the coast (*eg* in the Cape Naturaliste region), or other factors such as local weather conditions must contribute to the transport of fertilised eggs offshore into Leeuwin current waters.

If the timing of peak current flow coincided with peak spawning, maximum numbers of larvae could be expected to be transported via the current. Then there is the question of what factors influence the relative size of recruitment to the different shoreline nursery areas located off the southern Australian coast. Do local weather conditions play an important role? Are the larvae transported in a frontal system associated with the current? How are potential competitors/predators affected by the current? Clearly the processes involved are only just beginning to be understood.

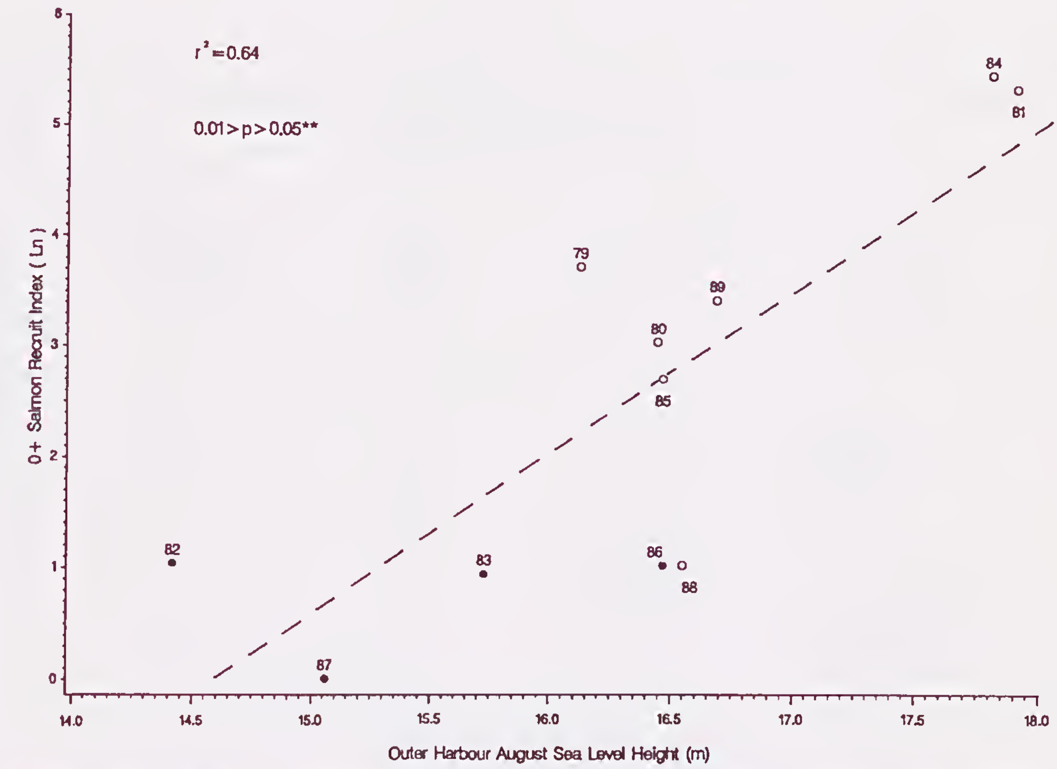

Figure 5 Relationship between the annual recruitment index (ln n) of salmon in Barker Inlet, and the sealevel in August at Outer Harbour over the period 1979-89 (83 = year of data; ● ENSO years ○ Non-ENSO years).

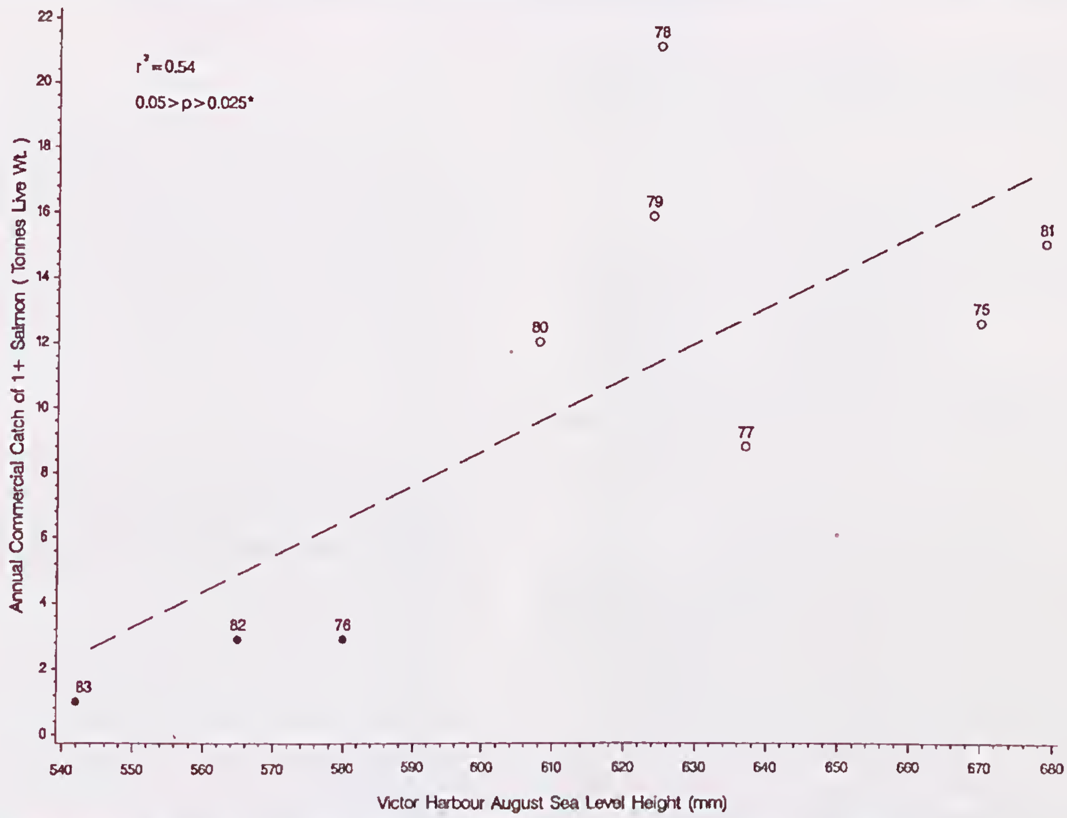

Figure 6 Relationship between the annual commercial catch of 0+ year old salmon caught in the Coorong between 1976/77 and 1984/85 and the Victor Harbor sealevel in August one year earlier (83 = year of data; ● ENSO years ○ Non-ENSO years).

Table 2

Western Australian salmon by-catch records extracted from log books kept by two demersal longline and demersal gill net limited entry fishers.

Date	Fishing area (see Fig. 1)	Location	Depth (m)	Surface water temp (°C)	WA salmon catch
1990					
290390	Augusta	34°43'S 115°18.4'E	50	20.1	500 kg
300390	Augusta	34°38.5'S 115°14.6'E	47	21.2	+
070490	Augusta	34°43'S 115°15.3'E	50	21.2	+
080490	Augusta	34°41.6'S 115°16.5'E	47	21.6	+
130490	Augusta	34°27'S 115°27.2'E	38	20.3	+
140490	Augusta	34°26.7'S 115° 27.7'E	38	20.5	+
1991					
210291	Cape Pasley/ Pt. Malcolm	33°49'S 124°0'E	57	20.8	7 fish
050391	Cape Pasley/ Pt. Malcolm	34°02'S 123°40'E	55	21.1	5 fish

\+ WA Salmon were caught but precise quantities were not recorded

Australian herring fishery

The stock of Australian herring (*Arripis georgianus*) occupies an almost identical range to salmon, extending from Kalbarri to South Australia and into Victoria (Fig. 1). Like salmon, herring spawn predominantly on the lower west and western south coasts of Western Australia (Lenanton 1978), while the juveniles extend through the Great Australian Bight into South Australia and Victoria. A pre-spawning migration to Western Australia occurs for the first time during the second year of life. The source of recruitment ranges from South Australia and the G.A.Bight region to local marine embayments, particularly Geographe Bay, where juveniles occur abundantly, associated with seagrass and drift macrophytes in the waters inshore of the Leeuwin Current (Lenanton 1982).

Ongoing research (G.K. Jones, unpublished) is providing preliminary evidence for a direct link between the abundance of juveniles in South Australia and the size of the spawning stock in Western Australia. Thus it is highly likely that the strong Leeuwin Current flow at the time of spawning in autumn is a critical factor in the transport of larvae across the G.A.Bight to South Australian and Victorian nursery areas.

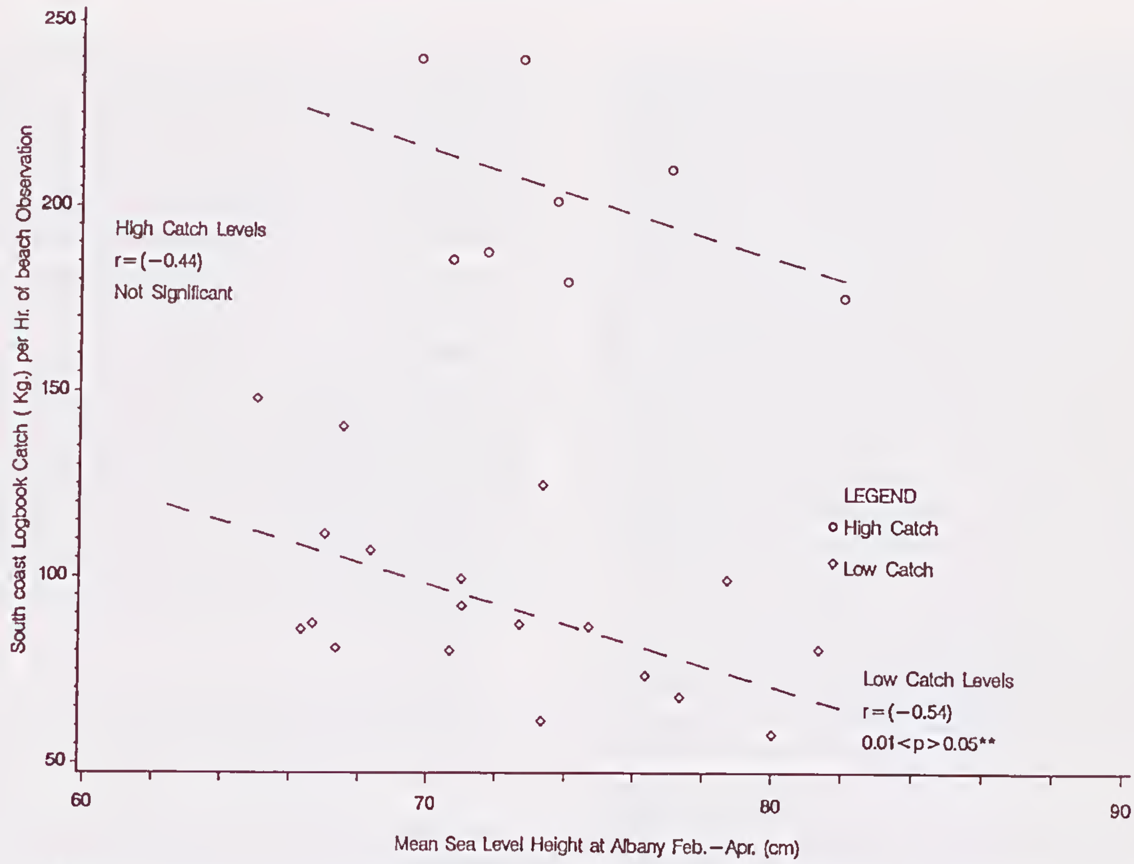

Figure 7 Relationship between the mean monthly Albany sealevel between February and April, and the mean annual south coast log book catch of salmon per hour of beach observation during years of low and high annual catch.

Pilchard purse seine fishery

The stock of pilchards (*Sardinops neopilchardus*) on the south coast, centred on King George Sound at Albany, provides Western Australia's largest single catch of finfish (Fletcher 1990). The fishery, which has developed over the past decade, reached a peak in catch of 8 300 tonnes in 1988, but has subsequently declined to less than 6 500 t annually (W.J. Fletcher, unpubl).

This species is either closely related to, or the same species as, the dominant *Sardinops* species in the Humboldt and Benguela Currents (Table 1, Parrish *et al.* 1989). However, catches in Western Australia to date indicate that maximum sustainable production is likely to be around 10 000 t which is orders of magnitude lower than catches of the same or similar planktivorous species in the other current systems (FAO 1988).

Survey data (W.J. Fletcher & R.J. Tregonning, unpublished) has shown that the species in Western Australia is found predominantly close inshore and therefore is taken only in bays, usually within the 50 m depth contour. Thus the Leeuwin Current significantly reduces the production of pilchards in this region compared to other boundary current systems. Furthermore, analyses of commercial catch rates, together with computer modeling (W.J. Fletcher, unpubl), suggest that yearly fluctuations in current strength are probably involved in the larger variations in the observed catch.

Western rock lobster fishery

The western rock lobster (*Panulirus cygnus*) stock supporting Australia's most valuable single species fishery is directly influenced by the Leeuwin Current and other environmental factors.

Phillips *et al.* (1991) and Pearce & Phillips (1992) deal in detail with the impact of the current on the recruitment of the puerulus stage of the life history. These studies have shown that the levels of puerulus settlement in the nursery grounds on the coast are highly correlated with sealevel changes which provide an index of the Leeuwin Current strength (Pearce & Phillips 1988), and with westerly storm conditions during the settlement period (Caputi & Brown 1989). Once settled, the juvenile lobsters remain for approximately 4 to 5 years on the coastal limestone reefs while feeding on the fauna and flora associated with seagrass beds (Joll & Phillips 1984). Thus the Leeuwin Current, which not only regulates recruitment to the stock but maintains the clear water environment essential to the development and survival of the extensive seagrass beds, is closely linked to the overall production of the fishery.

A second and possibly more critical influence of the Leeuwin Current on this important fishery is through its impact on the biology of the lobster at the Abrolhos Islands. In this location, the lobster stock matures at a smaller size than on coastal reefs, and spawns before reaching the minimum legal size for capture (C.F. Chubb, unpublished). The lobsters at the Abrolhos Islands account for about half the annual egg production (C.F. Chubb, unpublished) from the total stock, and are critical for the ongoing productivity of the fishery. While the specific effect of the Leeuwin Current on the spawning stock has yet to be precisely determined, evidence from aquarium experiments has shown that elevated water temperatures, such as those caused by the current at the Abrolhos Islands, increase reproductive activity (Chittleborough 1976). A further important aspect of the fishery involving the Leeuwin Current is the effect on catchability of the lobsters through the influence on temperature and salinity. Furthermore, Morgan (1974) has shown that both temperature and salinity variations at the Abrolhos Islands, (again related to the current), have significant effects on the catchability of the rock lobster. Thus, the Leeuwin Current has a major influence on most stages of the life history of the lobster and the catch ultimately achieved by the fishery (Phillips 1986).

Saucer scallop fishery

The distribution of the saucer scallop (*Amusium balloti*) extends considerably further south on the western coast of Australia than on the eastern coast. On the western coast it extends as far south as 35°S (off Albany) and east along the southern coast to Esperance (122°E) (Gwyther *et al.* 1991), whereas on the eastern coast it extends only as far as 27°S (Moreton Bay) (Dredge 1985). This extension of the range on the western side of the continent almost certainly results from the warming influence of the Leeuwin Current.

Scallop populations throughout the world are acknowledged as having highly variable recruitment as a result of the influence of environmental factors (Caddy 1989). In the Shark Bay scallop fishery catches of *A. balloti* have shown a greater than five-fold variation over the period 1983 - 1990, primarily as a result of inter-annual variations in recruitment (Joll & Caputi 1991). Examination of satellite imagery of Shark Bay suggested that the Leeuwin Current may be the environmental factor responsible for this recruitment variation. The imagery showed tongues of warmer water, derived from the south-flowing Leeuwin Current, entering the bay during the spawning season (April to December (Joll 1987)) and possibly affecting recruitment. Populations at locations further south (*eg* the Abrolhos Islands) spawn at different times of the year (Joll 1989) and are probably less vulnerable to any environmental influences of the Leeuwin Current.

Surveys to measure recruitment in Shark Bay have been conducted in November each year since 1983. Growth data from tagged scallops (Joll 1987) showed that scallops from size classes as small as 30-39 mm in November reach a size of around 90 mm by March of the following year, at which size they are acceptable for commercial harvest. Trawling surveys in November, therefore, are capable of estimating the abundance of recruits from the current spawning season which will reach sizes appropriate to enter the fishery in the following year.

Data on landings of scallops by vessels operating in the scallop fishery are provided voluntarily by fishermen in their research logbooks and these are checked against wholesale buyers' receival records. In all years except 1983 the fishery has ceased before the legal closing date when catches have fallen to levels which are not commercially viable. With the exception of 1984, therefore, the catch in each year has been dominated by the new recruits from the previous year's spawning.

The strength of the Leeuwin Current is reflected in the coastal sealevel (Reid & Mantyla 1976, Pearce & Phillips 1988), so that data from the Fremantle tide gauge are a useful index of the flow of the Leeuwin Current. The sealevel at Carnarvon may have more accurately reflected the influence of the Leeuwin Current in the Shark Bay area, but these data were not available for the whole of the period of this study.

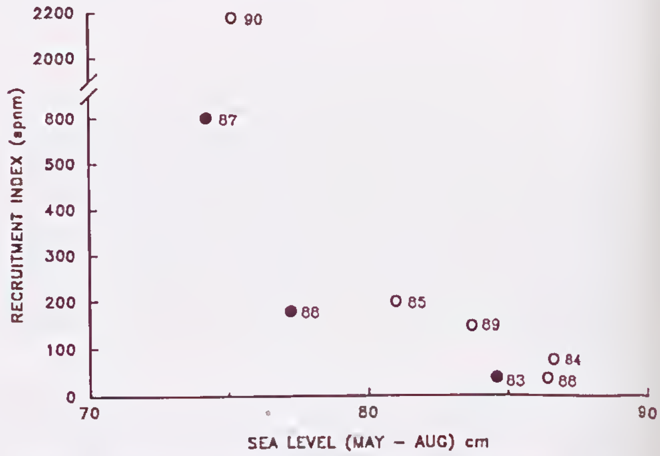

Figure 8 Relationship between the recruitment index for saucer scallops (*Amusium balloti*) in Shark Bay over the period 1983 - 1990 and the mean sealevel at Fremantle over the period May to August of the same year. (83 = year of data; ● ENSO years; ○ Non-ENSO years) (spnm = scallops per nautical mile).

Spawning activity, which results in recruits detectable in the November survey and which subsequently contribute to the recruitment to the fishery in the following year, occurs mainly in the period, April to July (Joll & Caputi 1991). Therefore, in considering the effects of the Leeuwin Current on scallop recruitment, it is the strength of the current in these months which is likely to be of greatest importance. As the peak in the sealevel at Fremantle due to the current occurs about a month after the peak at Carnarvon, the sealevel over the months of May to August at Fremantle was used as the environmental variable to examine the influence of the Leeuwin Current on spawning / recruitment success in Shark Bay over the period April to July.

Over the period 1983-1990, average Fremantle sealevel for the months May to August was negatively correlated with the abundance of recruits measured in the November survey of that year (Fig.8). Similarly, there was a negative correlation between the Fremantle sealevel over the months May to August and the catch of the fishery in the following year (Fig. 9). The catch for 1991 indicated in Fig. 9 is a conservatively estimated figure based on the very high recruitment index recorded in November 1990. By the end of June 1990 the catch of the fishery was over 1 000 tonnes.

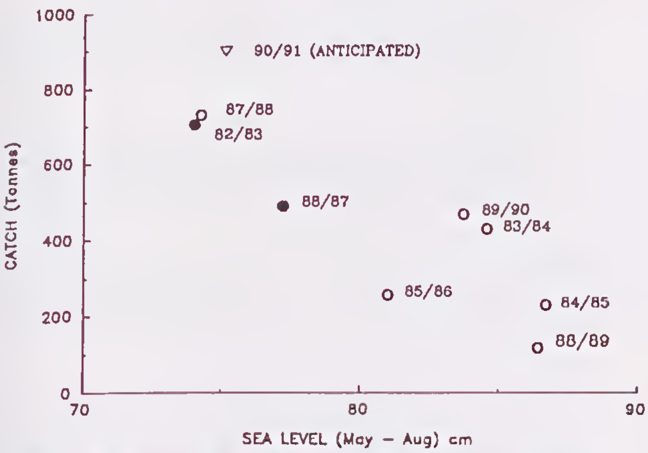

Figure 9 Relationship between the annual catch of saucer scallops (*Amusium balloti*) from Shark Bay over the period 1983 to 1991 and the mean sealevel at Fremantle over the period May to August of the previous year. (83/84 = year of sealevel data / year of catch data; ● ENSO years; ○ Non-ENSO years). (1991 catch data are anticipated).

The mechanism by which the Leeuwin Current influences recruitment success in *Amusium balloti* in Shark Bay has not been determined. However, the data suggest very strongly that in years of a weak Leeuwin Current, both recruitment success and the catch in the following year will be high. The Leeuwin Current is known to be weakest when El Niño/Southern Oscillation (ENSO) events occur (Pearce & Phillips 1988), so that good recruitment could also be expected to be associated with these events. Massive increases in the abundance of the Chilean scallop (*Argopecten purpuratus*) were noted to be associated with the ENSO event of 1982/83 by Arntz (1984) and Wolff (1987).

While the mechanism of action of the environment on recruitment success of *Amusium balloti* has not been positively identified, hydrological flushing in years of strong Leeuwin Currents seems a strong possibility. Both Dickie (1955) and Caddy (1979,1989) noted the importance of hydrological flushing in recruitment success of the Atlantic sea scallop (*Placopecten magellanicus*). Strong Leeuwin Currents also bring warm, low-nutrient waters into Shark Bay. Thus, other possibilities for the mechanism of action may be negative effects of increased temperatures on spawning or the success of fertilization or a reduction in primary production leading to an inadequate food supply for the larvae. Whichever mechanism or combination of mechanisms is responsible for the observed influence of the Leeuwin Current, it is clear that the effect of the current is to depress fisheries production in an embayment which is otherwise capable of high productivity.

Penaeid prawn fishery of Shark Bay

The largest Western Australian fishery for western king (*Penaeus latisulcatus*) and brown tiger (*Penaeus esculentus*) prawns is located in Shark Bay (Penn *et al.* 1989), a sector of the coast frequently influenced by the Leeuwin Current.

The current has two major effects on the prawn fishery particularly the major western king prawn stock. It firstly radically changes the annual temperature cycle on the trawl grounds (Penn 1988) from that found in the more usual annual cycle in inshore waters which are unaffected by the current. The winter Leeuwin Current flow results in the temperature of the shelf water peaking later, usually in May; and a period of lower temperatures extending through spring, when the warm current declines and cooler local inshore waters dominate. This unusual temperature regime alters the burrowing behaviour of western king prawns (Penn 1984) and thereby influences the catches of prawns. The resulting changes in catchability produce high catches and maximum exploitation rates from the start of each season in March through to May/June of each year, followed by significantly lower catches and exploitation rates for the remainder of the year. Alterations in the annual temperature cycle, particularly the timing of the temperature decline in May/June that is almost certainly related to the timing of the current peak, have been simulated in a computer model (N.G. Hall & J.S. Andrews, pers. comm.) which predicts catch variations in the order of 20% with a one month alteration in the time of the temperature decline.

Secondly, within each season, there is also a significant correlation (r=0.6) between recruitment catches each year, and the strength of the Leeuwin Current expressed as the mean monthly Fremantle sealevel over the period April to August of that same year. Since the spawning season for king prawns recruited in a particular year is during winter/spring of the preceeding year, the above correlation suggests that the current is having an effect on the survival, or growth, of recruits, once the year class has migrated out into the main trawl ground in the northern region of Shark Bay (Penn *et al.* 1989).

As a result of the generally positive relationship between the current strength and prawn catches, and the negative effect of the current on the scallop recruitment to the same trawl fishery, the cycles in prawn and scallop catches are often out of phase. Furthermore, the relatively infrequent occurrence of weak Leeuwin Current years results in consistent, relatively large king prawn catches and on average low scallop catches with occasional very high catches resulting from strong recruitment.

Summary

In conclusion, under the influence of the Leeuwin Current, a more tropical coastal water environment has evolved off south-western Australia. This situation contrasts markedly with those of other environments characteristic of eastern boundary currents. The oceanic sources of nutrients which support extensive plankton-based food chains on other western continental shorelines where upwelling occurs are not available off Western Australian. Fisheries production in these waters is therefore heavily dependent on benthic-based food webs in near-shore waters, rather than on those associated with oceanic ecosystems.

Thus inshore demersal invertebrate fisheries such as rock lobster, rather than pelagic finfish resources, dominate fisheries production in Western Australia.

Both the strength and timing of the peak current flow also appear to influence significantly the annual catches of most of the economically important finfish and invertebrate resources of the west and south coasts of Western Australia. Depending on the species being considered, strong current flows can either adversely or favourably affect catches. The precise mechanisms however, are in many instances still poorly understood, although larval dispersal and catchability variations are thought to be the most likely factors.

Long-term studies into the important interaction between the Leeuwin Current and Western Australia's major fisheries are ongoing with a view to increasing the level of understanding of the mechanisms underlying the effects of the current.

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