Effects of seasonal and interannual variability of the ocean environment on recruitment to the fisheries of Western Australia

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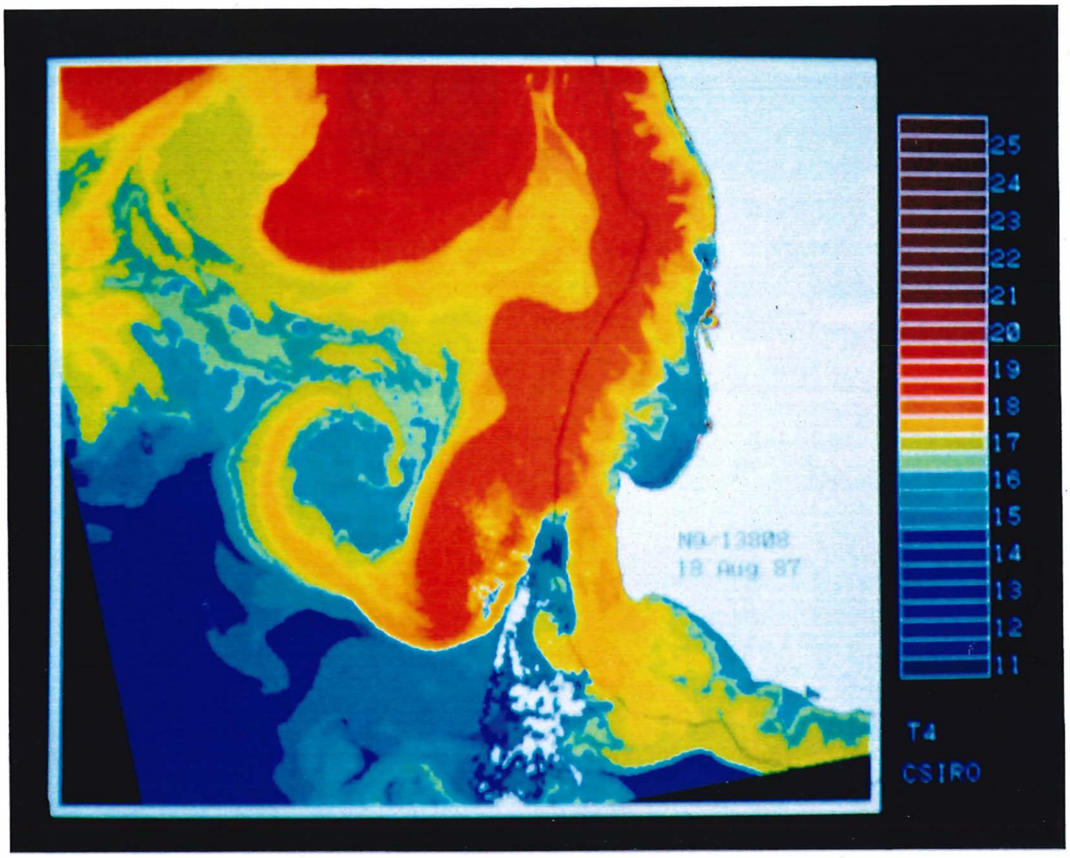

Frontispiece: NOAA AVHRR image of southwestern Australia in August 1987. Warmest water (shown in red) represents the Leeuwin Current, cooling through yellow and green to the coolest water in blue. Mottled white areas are clouds. The black line marks the approximate edge of the continental shelf. Note the large warm and cool eddies peeling westwards from the Leeuwin Current, as well as the smaller-scale tongues of Leeuwin Current penetrating onto the continental shelf towards the coast in Geographe Bay. Image courtesy of the Western Australian Satellite Technology and Applications Consortium (WASTAC).

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OBJECTIVES

1. Establish a monthly climatology of sea-surface temperatures (and derived ocean current patterns) around Western Australia from 1982 to 1997 using NOAA-AVHRR satellite data.
2. Develop appropriate monthly indices of ocean variability and create a historical database of oceanic variables at selected sites, including coastal sea level, sea-surface temperature, salinity and wind.
3. Study relationships between oceanic processes and seasonal/interannual fluctuations in recruitment to the rock lobster, scallop, Australian salmon, pilchard and shark fisheries of Western Australia.

NON-TECHNICAL SUMMARY

The relatively high catch of invertebrate species in Western Australia compared to finfish is in sharp contrast to other regions of the world where finfish production usually dominates. This low level of finfish production is primarily due to the Leeuwin Current which brings warm, low nutrient waters southward along the edge of the continental shelf of the Western Australian coast. By contrast, the other eastern boundary currents in the Southern Hemisphere (the Humboldt and Benguela Currents off the west coasts of South America and southern Africa respectively) are associated with upwelling of cool, nutrient-rich waters flowing northward, resulting in high rates of primary production and a correspondingly large finfish production.

There is an increasing awareness of the importance of oceanic processes such as advection, water temperature, *etc.* for recruitment to both pelagic and benthic fisheries. Previous studies off Western Australia have demonstrated that the Leeuwin Current and winds both play a key role in the settlement of rock lobster pueruli, with important consequences for the fishery 3 to 4 years later, and there are also indications of environmental influences on many other commercial fisheries.

This project has compiled the first comprehensive set of environmental data off Western Australia to enable these relationships to be further examined: satellite-derived sea-surface temperatures (SST), local *in situ* temperatures and salinities, coastal sea levels, the Southern Oscillation Index, and winds. In the absence of direct current measurements, monthly and annual coastal sea levels are used as an approximate "index" of the strength of the Leeuwin Current. SST gradients from both global-scale (the Reynolds dataset) and locally-received satellite data have also been derived as potential complementary indices of the thermal structure of Western Australian waters, but difficulties with adequate cloud-clearing have hampered work with the local data.

The high resolution satellite imagery shows the surface structure and variability of the Leeuwin Current and its associated meanders and eddies in its passage southwards down the coast and then eastwards towards the Great Australian Bight, but we have not as yet been able to quantify this variability from the satellite data. In some areas, notably off Ningaloo (22°S), the Abrolhos Islands (29°S) and Cape Naturaliste (33°S), there is a wind-driven northwards countercurrent inshore of the (weaker) Leeuwin Current between about October and March. The satellite imagery shows that tongues of Leeuwin Current water can penetrate across the continental shelf towards the coast and also into Shark Bay, with potential consequences for cross-shelf mixing and larval exchange.

There is a highly significant relationship between monthly/annual mean sea levels at Fremantle and the Southern Oscillation Index (and hence with *El Nino* events). Sea levels are lower during ENSO periods, which is interpreted as a weakening of the Leeuwin Current, and conversely during non-ENSO times (so-called *La Nina*), coastal sea levels are raised and the Leeuwin Current strengthens. Sea level is also related to ocean temperature, but only weakly with open-ocean winds (this may be a reflection of the quality of the available wind data).

The major influence of the Leeuwin Current on fisheries recruitment is during the larval phase. The strength of the Current has a significant positive influence during the larval stage of the western rock lobster (*Panulirus cygnus*), but a negative influence on the larval life of the scallop *Amusium balloti* in Shark Bay and at the Abrolhos Islands. For pelagic finfish species, the Current has an adverse effect on larval survival of pilchards (*Sardinops sagax neopilchardus*), but a positive impact for whitebait (*Hyperlophus vittatus*) and also on recruitment of Western Australian salmon (*Arripis truttaceus*) and Australian herring (*Arripis georgianus*) to South Australia as they are dependent on spawning which occurs only off Western Australia in autumn when the Leeuwin Current is flowing strongly along both the west and south coasts. The Current appears to have a correspondingly negative impact on the recruitment of herring in the south-west of Western Australia. Possible mechanisms for the effect of the Current include transportation of larvae and temperature effects on spawning success as well as survival and growth of larvae. The present project has increased our understanding of recruitment variability, enabling improved prediction of the catches as well as assisting in the proper management of these fisheries.

Two new developments will aid future research in this area. Firstly, the advent of satellite altimeter data and improvements in numerical ocean modelling now enable the ocean circulation along the continental shelf and open ocean to be determined directly, reducing our reliance on coastal sea level as an approximate index of the strength of the Leeuwin Current; this is being addressed in a new FRDC project 97/139 which commenced in July 1997 and is due for completion in June 2000. Secondly, the availability of ocean colour data from the SeaWiFS satellite sensor will enable the spatial and temporal variability of chlorophyll to be measured; this is linked with the phytoplankton distribution and is therefore an indicator of ocean productivity. As the archive of remotely-sensed ocean colour data grows and the necessary techniques for correcting the (large) atmospheric component of the radiance have been developed for our local waters, the resulting chlorophyll distributions can be related to fish production.

KEYWORDS Oceanic processes, Leeuwin Current, recruitment

Background

It is now well-known that oceanic processes can play an important role in fluctuations in fish recruitment and catches (Cushing 1982, Harris *et al.* 1988, Lee *et al.* 1992, Bakun 1996, Cobb 1997). Local research has shown that the Leeuwin Current is responsible for the existence of coral reefs as far south as 29°S (Collins *et al.* 1991), while recruitment of tropical fish larvae at Rottnest Island and along the south coast has been attributed to transport in the Leeuwin Current (Maxwell and Cresswell 1981, Hutchins and Pearce 1994).

Similarly, the Leeuwin Current is known to playa a major role in recruitment to a number of local fisheries. Because of the southward-flowing warm Current, there is relatively large production of invertebrate species in Western Australia compared to finfish, in sharp contrast to other regions of the world where finfish production is usually dominant. Inter-annual fluctuations in the strength of the Leeuwin Current have a major influence on the catch of many commercial fisheries off Western Australia (Cresswell 1986; Lenanton *et al.* 1991), including the western rock lobster (*Panulirus cygnus*) (Pearce and Phillips 1988, 1994; Phillips *et al.* 1991; Caputi *et al.* 1995), scallops (*Amusium balloti*) in Shark Bay (Joll and Caputi 1995a), Australian salmon (*Arripis truttaceus*), western king prawns (*Penaeus latisulcatus*) in Shark Bay, whitebait (*Hyperlophus vittatus*) and pilchards (*Sardinops sagax neopilchardus*).

Sustainable management of these fisheries requires a good understanding of environmental effects on recruitment levels, to enable these effects to be distinguished from recruitment declines resulting from reduced breeding stock levels. In many cases, an understanding of the influences of the environment on recruitment is required before the impact of the breeding stock can be detected (Caputi 1993). Management of these fisheries also requires forecasts of recruitment (future catch) to set annual catch or effort limits.

For most Western Australian fisheries there are historical databases which can be used to measure breeding stock and recruitment levels. Until recently, however, there have been limited historical environmental data available in computerised database format to enable recruitment-environmental relationships to be investigated. This is particularly true off Western Australia because of the immense expanse of coastline and the lack of human and financial resources. As a result, any environmental component of seasonal and interannual fluctuations in fisheries recruitment has been restricted to utilising, for example, simple environmental variables such as sea level as an index of the Leeuwin Current.

The main purpose of this project is to construct an environmental history of Western Australian coastal waters, better understand the environmental processes involved, and develop causal relationships between environmental factors and recruitment to fish stocks in Western Australia waters. The availability of new datasets has enabled a detailed description and analysis of the "climatology" of the ocean waters off our coast to be prepared as a foundation both for the present project as well as for ongoing environmental studies into the future.

Western Australia extends from 14° to 35°S and so encompasses both tropical and subtropical regions. Most of the important commercial fisheries, however, lie between the latitudes of Exmouth

Gulf (22°S) and Albany (35°S), so our focus is on that area and little attention is given here to the North West Shelf. Because of the number of different fisheries involved, the methods and results/discussion for each are presented separately in numbered chapters (to aid cross-referencing), following a detailed description of the oceanography and meteorology of the region. For convenience, the Figures for each section have been placed immediately after the text in that section.

Need

Up to the present, there has been limited regular monitoring of environmental variability off Western Australia, due both to the immense expanse of coastline and the lack of human and financial resources. As a result, any environmental component of seasonal and interannual fluctuations in fisheries recruitment has been restricted, for example, to utilising imprecise environmental variables such as sea level as an index of the Leeuwin Current. The present project has used satellite remote sensing in conjunction with recently-available large-scale datasets and some routine *in situ* measurements to provide a detailed historical database of monthly oceanic variables reflecting conditions in the coastal waters of the State. Management (both short- and long-term) of the various commercial fisheries will benefit from the ready availability of such data and catch forecasting which can be used by management to improve yields from fisheries.

Non-technical updates on the research have been published in the Western Fisheries Magazine (which is widely distributed to the fishing industry) and have also been reported to the relevant fisheries management/advisory committees and fishermen's meetings covering all the fisheries involved. Scientific papers have been published as technical reports and in national/international journals, as well as being presented at scientific and fisheries conferences.

Objectives

1) Establish a monthly climatology of sea-surface temperatures (and derived ocean current patterns) around Western Australia from 1982 to 1997 using NOAA-AVHRR satellite data.

2) Develop appropriate monthly indices of ocean variability and create a historical database of oceanic variables at selected sites, including coastal sea level, sea-surface temperature, salinity and wind.

3) Study relationships between oceanic processes and seasonal/ interannual fluctuations in recruitment to the rock lobster, scallop, Australian salmon, pilchard and shark fisheries of Western Australia.

1. Oceanography and Meteorology (A. Pearce, K. Suber and N. Caputi)

Introduction

The dominant ocean current off Western Australia is the southward-flowing Leeuwin Current (Cresswell and Golding 1980). In contrast with the cool northward boundary currents along the west coasts of southern Africa (the Benguela Current) and South America (Humboldt or Peru Current), the Leeuwin Current brings low-salinity, warm tropical waters *south*wards along the Western Australian coast (Pearce 1991). Because of the net northwards wind stress off southern Africa and Peru during the summer months, wind-driven upwelling of nutrient-rich waters occurs and results in the very productive fisheries in those areas. Despite similar winds off Western Australia, there is no upwelling along our coast because of the Leeuwin Current, and our fisheries are therefore completely different, largely based on demersal invertebrate species rather than the finfish species found elsewhere (Lenanton *et al.* 1991, Caputi *et al.*1996b). The Leeuwin Current flows most strongly during the autumn and winter months (Godfrey and Ridgway 1985), and both satellite imagery and buoy trajectories have shown the complex meandering and eddying nature of the flow (Legeckis and Cresswell 1981, Pearce and Griffiths 1991).

The Leeuwin Current is driven by a meridional pressure gradient set up by the warm, low-density Pacific Ocean water flowing through the Indonesian Archipelago into the equatorial Indian Ocean (Godfrey and Ridgway 1985). The resulting north-south sea level slope causes a transport of water from the open Indian Ocean towards the Western Australian coast (Figure 1.1), and this inflow then deflects southwards along the continental margin to form the Leeuwin Current. Pearce and Phillips (1988, 1994) have shown that annual mean sea levels along the Western Australian coast are highly correlated with El Nino/Southern Oscillation (ENSO) events indicating some link between global-scale processes and regional oceanic variability.

The climate of southwestern Australia is largely controlled by the seasonal movement of the subtropical high-pressure belt which migrates southwards in summer and returns northwards during the winter months. The net winds off the southwest are therefore dominantly from the south in summer, and in winter are far more variable with the passage of storms. Rainfall is also highly seasonal, with much of the annual precipitation falling between about April and September.

Methods

This project has involved the compilation of databases of environmental data at monthly and annual time-scales, to seek relationships between oceanic processes and recruitment/catch. These datasets have included satellite data, coastal sea levels, water temperatures and winds at sites along the Western Australian coast (Figure 1.2). While some longer time-series data have been acquired, most of the results are for the period 1966 to 1996, with some recent (1997-98) data included where available. Emphasis has been placed on seasonal and interannual variability as most appropriate for the fisheries connections.

Southern Oscillation Index

The Southern Oscillation Index (SOI) is the standardised atmospheric pressure difference between the central Pacific and equatorial Indian Oceans (Troup 1965) and is used as a measure of the duration and intensity of *El Nino/Southern Oscillation* (ENSO) events. It is defined as (Bureau of Meteorology monthly DTDS):

SOI = (DP*Tahiti* - DP*Darwin*) * 10 / SD

where DP*Tahiti* is the monthly pressure anomaly at Tahiti,

DP*Darwin* is the monthly pressure anomaly at Darwin, and

SD is the monthly standard deviation of the difference.

Monthly values of the SOI are available from 1882 to the present, with minor gaps. Because of the variability introduced by the subtraction of small differences in pressure, SOI values are usually smoothed by a simple 5-month running mean to more clearly show the ENSO cycles (Bureau of Meteorology monthly DTDS).

Coastal sea levels

The longest available time-series of oceanic data are sea levels measured at a number of ports along the Western Australian coastline. Monthly mean sea levels, which average out all wave and tidal variability, represent a simple "index" of oceanic conditions integrating effects due to currents, winds, atmospheric pressure and water density (which involves both temperature and salinity). While the longest sea level series in Western Australia is from Fremantle where monthly data go back to 1897, high-quality sea levels from 8 other ports (Table 1.1, Figure 1.2) between 1966 and 1996 have been provided by the National Tidal Facility (NTF) in Adelaide. Over the years, there have been changes to sea level datum points at some ports, as well as missing values and, in some cases, duplicate values when tide gauge replacements have overlapped.

Table 1.1: List and positions of tide stations along the Western Australian coast, and the number of months coverage between January 1966 and December 1996.

Station	Latitude	Longitude	No. Months	% Total
Broome	18°00'S	122°13'E	284	76%
Port Hedland	20°18'S	118°35'E	331	89%
Dampier	20°38'S	116°45'E	344	92%
Carnarvon	24°53'S	113°37'E	285	77%
Geraldton	28°47'S	114°35'E	372	100%
Fremantle	32°03'S	115°44'E	372	100%
Bunbury	33°19'S	115°38'E	359	97%
Albany	35°02'S	117°53'E	369	99%
Esperance	33°52'S	121°54'E	368	99%

At Fremantle, there were two sets of data for 1967 and these have simply been averaged here. As will be shown below, there is a long-term trend in Fremantle sea level (FMSL), the regression relationship being:

FMSL = 61.36 + 0.0120358 * (month since Jan 1900)

This trend has been removed from the time-series, and monthly anomalies have been derived from the detrended annual cycle. These sea level anomalies have been smoothed with a 5-month running-mean filter to reduce short-term variability and illustrate the overall relationships more clearly. Although the 1998 Fremantle sea level data have not yet been released by the NTF, approximate monthly means for that year have been derived by applying an adjustment to the (near-realtime) Seaframe data recorded at Hillarys marina some 26 km north of Fremantle.

For the other Western Australian ports used in this project, datum changes have been made (by visual inspection, and comparison with adjacent ports) as follows:

Port Hedland: added 1000mm to all data before 1975

Dampier: added 540 mm prior to 1983

Esperance: added 150mm prior to April 1975

Data gaps have been left where the number of hourly observations in any month were less than 300 (out of the total 720 or 744 hours) as it was felt that these monthly averages may not be representative of the true monthly means. Gaps in the time-series of less than 3 months were then linearly interpolated; annual means and the annual cycles were computed for each site, and the anomalies from the annual cycles derived. For these 8 sites, any long-term trend over the 30-year period 1966 to 1996 has been ignored.

Near-realtime sea level data have recently become available via FTP (File Transfer Protocol) from the Fremantle Port Authority (FPA) as well as from the Seaframe tide/weather stations at Broome, Hillarys marina and Esperance which commenced in 1991/92. Hourly tide-heights are acquired by CSIRO directly from the FPA and the monthly means are computed and directly passed on to Fisheries WA. Hourly sea level, wind, temperature and pressure data from the Seaframe stations, which are operated by the National Tidal Facility (NTF), are also available soon after the end of each month. As would be anticipated, the monthly mean Fremantle sea levels acquired periodically from the NTF agree closely with the values derived directly from the FPA data, while the Hillarys monthly sea levels are presently somewhat lower than the Fremantle data but show the monthly sea level variations.

Monthly and annual sea levels in this analysis have not been adjusted for atmospheric pressure variations, as *cross-shelf* changes in air pressure (which would affect the sea level slope and hence the strength of the alongshore flow) would be very small on monthly to interannual time-scales. Examination of monthly mean atmospheric pressure data for a number of Western Australian coastal ports indicates that the annual range in atmospheric pressure is about 10 hPa while interannual variability is of order 1 to 2 hPa. The interannual fluctuations (particularly) are therefore small, representing only 1 to 2 cm sea level change compared with the interannual sea level changes of order 10 cm, and have been found to make negligible difference to the sea level - recruitment correlations.

Water temperature and salinity

Water temperature plays an important role in recruitment and catches for many fisheries, both for survival and growth of the larvae and for the exploitation phase. A number of temperature datasets have been obtained covering a variety of time and length scales to provide a full description of the ocean temperature environment around Western Australia.

Reynolds satellite-derived sea-surface temperatures

On the large scale, global SST data has been derived from NOAA-AVHRR satellite imagery complemented by buoy and other *in situ* measurements since 1982 (Reynolds and Smith 1994). The analysis blends the *in situ* observations with atmospherically-corrected satellite data and uses optimum interpolation to produce daily SST fields on a 1° latitude/ longitude grid (about 100 km by 100 km). Monthly mean SSTs are generated by averaging the daily data. The advantages of this dataset over the COADS data described below are that the satellite-derived SSTs cover the whole region each month and are being updated monthly on a web-page.

SSTs for the region 10° to 50°S, 90° to 130°E in the southeastern Indian Ocean have been extracted from the Reynolds global dataset for our analysis. In particular, monthly SSTs have been derived for the north coast at longitudes 122.5°E (north of Broome), 118.5°E (Port Hedland) and 114.5°E (Exmouth); the west coast at 22.5°S (Exmouth), 25.5°S (Shark Bay), 28.5°S (Abrolhos Islands), 31.5°S (Fremantle) and 34.5°S (Cape Leeuwin); and the south coast at 117.5°E (Albany), 123.5°E (Cape Pasley) and 128.5°E (Eucla). However, for economies of space here, only the transects off Fremantle and Albany are discussed in this report as representative of the west and south coasts. The spatial scale of about 100 km is well-suited to offshore waters but the coastal waters and the inner continental shelf may not be well resolved; the high resolution locally-received SST data are more appropriate for coastal waters

COADS

Monthly global sea-surface temperatures are also available in the Comprehensive Ocean-Atmosphere Data Set (COADS) in 2-degree latitude/longitude squares between 1854 and 1989, albeit with many data gaps especially during the earlier years, as well as 1-degree squares from 1945 to 1989. The dataset is based on observations from merchant vessels, more recently supplemented by surface temperatures from both moored and drifting ocean buoys, and represents "the most extensive collection of marine data available for the world ocean over the past century and a half" (Woodruff *et al.* 1993). The data have been quality-checked for outliers based on climatological limits, and an objective analysis technique has been used for smoothing and to fill gaps in the data coverage. Updates beyond 1989 are currently in preparation.

We have extracted the same standard area 10° to 50°S, 90° to 130°E from the 45-year 1-degree dataset for comparison with the Reynolds SST data.

CSIRO coastal monitoring network

Open-shelf water temperatures, salinities and nutrients were measured by CSIRO at a coastal monitoring site in 55 m water depth west of Rottnest Island as part of a national coastal sampling program established in the early 1940s (Rochford 1988, Pearce *et al.*. in prep.(a)). While most of the stations in the network have now been closed down, the Rottnest station operated between 1951 and 1956 and again from 1969 to the present. The other Western Australian sites are listed in Table 1.2. Sampling was at 10 m depth intervals between the sea surface and the seabed at about 3-weekly intervals. Water temperatures were measured using reversing thermometers, nominal accuracy ±0.02°C, and salinities were measured on a salinometer in the laboratory with an accuracy of ±0.003 ppt.

Because of the irregularity of the sampling periods, an optimal interpolation technique (Pearce *et al.* in prep.(a)) has been used to derive monthly mean temperatures and salinities at all the stations except Esperance (which was occupied too briefly to be useful) for the period since 1969. The data has been analysed to show seasonal and interannual variability along the continental shelf, as well as the vertical thermal structure of the water column.

Table 1.2: CSIRO coastal monitoring stations in Western Australian waters.

Station	Position	Period operational
Barrow Island	20°48'S/115°35'E	Feb. 1977 to Dec. 1979
Geraldton	28°46'S/114°23'E	Dec. 1978 to June 1986
Rottnest	32°2'S/115°24'E	April 1951 to Dec. 1956; April 1969 to present
Augusta	34°22'S/114°56'E	Nov. 1978 to June 1981
Albany	35°8'S/118°2'E	Jan. 1952 to Nov. 1956; Nov. 1977 to June 1983
Esperance	33°56'S/121°51'E	Dec.1979 to April 1981

Puerulus collector sites

Nearshore water temperatures are also being measured at about monthly intervals by Fisheries WA at the rock lobster puerulus collector sites along the coast. These measurements started in 1969/70 at Seven-Mile Beach, Jurien, Garden Island and Rat Island, and the number of sites was

Table 1.3: Nominal positions of the puerulus sampling sites where temperature and salinity measurements have been made, and periods of data analysed in this report. The monthly samples are taken at the time of puerulus collection, while the temperature loggers record at 15 minute intervals. Expanded and updated from Pearce *et al.* (1999) and Pearce (1998, unpublished).

Site	Latitude °S	Monthly samples	Tloggers
South Passage (SP)	26°08'	1984-95	1990-94
Horrocks (HOR)	28°23'	1984-91	
Rat Island (RAT)	28°42'	1970-76; 1984-95	1993-94
Seven Mile Beach (SMB)	29°10'	1969-76; 1984-95	1990-94
Cliff Head (CLF)	29°30'	1971-76	
Green Head (GH)*	30°00'		1990-94
Jurien (JUR)	30°19'	1969-76; 1984-95	1991-94
Cervantes (CER)	30°32'	1984-92	
Lancelin (LAN)	31°01'	1990-95	
Alkimos (ALK)	31°38'	1984-95	1990-94
Marmion (MAR)	31°51'		1990-94
Garden Island (GAR)	32°12'	1969-76	
Warnbro Sound (WAR)	32°21'	1984-95	1990-94
Cape Mentelle (MEN)	33°57'	1984-95	1990-94
Augusta (AUG)	34°19'	1987-89	

* The Green Head (offshore) mooring had near-surface and near-bottom loggers.

greatly increased in 1984 to cover the west coast from Shark Bay to Cape Mentelle; many of these sites are still operational (Table 1.3).

Temperatures were measured with a mercury thermometer (estimated accuracy ±0.2°C) and water samples were taken for later salinity analysis in the laboratory. The puerulus collectors are in about 5 m water depth, all relatively close inshore except for the collector site near Rat Island in the Houtman Abrolhos group. Lenanton *et al.* (1996) used the temperature data from the puerulus collector sites to suggest the regions and periods off Western Australia where tailor are likely to spawn.

From 1986, self-recording temperature loggers were installed at a number of the collector sites to provide continuous temperature records and supplement the monthly sampling (Brown and Rossbach 1990, Pearce *et al.* 1999). Near-surface and bottom loggers were also deployed on the open shelf off Green Head. For reasons documented in Pearce *et al.* (1999), the temperature logger results have so far only been analysed for the 5-year period 1990 to 1994. Equipment and logistic problems have resulted in some quite substantial gaps in the records, nevertheless this dataset represents the most comprehensive coverage of coastal water temperatures yet undertaken in Western Australia.

For each site, the seasonal temperature and salinity cycles have been derived from the long-term monthly samples, while overall averages have been computed from the briefer temperature logger data.

Winds

The only wind dataset for the open ocean going back sufficiently in time and with geographical coverage extending to the south coast of Western Australia is COADS described above. Monthly mean wind components for 1-degree latitude/longitude squares globally are available for the period 1945 to 1989, and in 2-degree squares from 1854 to 1989, although there are many and large gaps in the earlier years. We have extracted the area 10° to 50°S and 90° to 130°E from the 1-degree dataset to show annual mean winds and seasonal cycles for selected areas off the Western Australian coast.

Coastal wind data are also available from a number of weather stations along the coast operated by the Bureau of Meteorology over varying periods, from some port authorities (*e.g.* Fremantle Port Authority) and from the Seaframe weather/tide stations at Broome, Hillarys and Esperance run by the National Tidal Facility since earlier this decade. For comparison with COADS, monthly mean wind components have been derived from hourly winds measured at the Fremantle Port Authority (FPA) building between 1971 and 1982.

Thermal satellite data

The only feasible way of monitoring the large expanse of surface waters off Western Australia on a regular basis is by satellite remote sensing (Pearce and Pattiaratchi 1997). Thermal satellite imagery from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA series of satellites reveals surface temperature gradients which are generally associated with surface circulation patterns, thus enabling an estimate to be made of the direction of surface currents. In addition, SSTs derived from the satellite sensor provide (within the limits of accuracy) information on ocean thermal conditions in areas where no direct temperature measurements are available.

NOAA/AVHRR imagery has been received in Perth since late 1981 (Pearce 1989) -- this unique dataset is the longest such archive in the Southern Hemisphere. Initially, the low-cost manually-operated system was run as a joint project between CSIRO and the Western Australian Institute of Technology (now Curtin University). In late 1987, the Western Australian Satellite Technology and Applications Consortium (WASTAC) was established to operate a new fully automatic reception and archiving facility, the consortium partners being the WA Department of Land Administration (DOLA -- Remote Sensing Services), the Bureau of Meteorology, Curtin University and CSIRO (through the CSIRO Office of Space Science and Applications, COSSA). Up to 10 NOAA satellite passes a day are now being routinely received. WASTAC has also taken over management of the original Curtin/CSIRO data archive.

The image-processing package used in this project is mNOAA, developed by Curtin University and CSIRO in the late 1980s specifically for processing and displaying NOAA/AVHRR data (Pearce *et al.* 1994). Despite some limitations in mNOAA, we have continued using it both because it adequately meets the project requirements and because of the need for a consistent data format over the 15-year time-series. However, cloud screening is still a problem and has hampered some of the analysis.

When this project commenced in mid-1994, the least cloudy satellite pass for each week was selected from a "Quicklook" facility and ordered from WASTAC and fully processed under mNOAA, involving:

(1) Extracting the data in mNOAA format for each of 7 standard coastal areas at a variety of spatial resolutions (the first 7 entries in Table 1.4).

Table 1.4: Specifications of the standard mNOAA areas. For the earlier period (1983 to early 1994), only areas 1 to 7 were processed; since May 1994, all ten areas have been covered.

Area	Latitude/longitude boundaries	Nominal spatial resolution (km)
1 (whole west coast)	17° to 37°S/106° to 129°E	4.5
2 (south coast)	30° to 40°S/113° to 124°E	2.2
3 (lower west coast)	25° to 35°S/106° to 117°E	2.2
4 (upper west coast)	20° to 30°S/106° to 117°E	2.2
5 (Northwest Shelf)	14° to 24°S/113° to 124°E	2.2
6 (Shark Bay)	23° to 28°S/109.5° to 115.5°E	1.1
7 (Southwest region)	30.5° to 35.5°S/111° to 116.5°E	1.1
8 (Exmouth/Ningaloo)	28° to 33°S/111° to 116.5°E	1.1
9 (Abrolhos)	26.5° to 31.5°S/111° to 116.5°E	1.1
10 (Albany)	33.5° to 38.5°S/115° to 121°E	1.1

(2) Computing of SST using the McMillin and Crosby (1984) SST algorithm, selected by Pearce *et al.* (1989) by comparing surface truth measurements off Perth with NOAA-7 and NOAA-9 satellite-derived temperatures in 1983/84.

(3) Navigating and re-mapping of each image to a standard Transverse Mercator map projection.

(4) Displaying and colour-enhancing on the computer screen. The Area 1 images were all enhanced to a standard colour/temperature scale for direct inter-comparison, but the higher-resolution images were individually enhanced to best show the Leeuwin Current and its associated eddies and meanders.

(5) Recording of each image on 35 mm colour slide and postcard-sized colour print, these being stored in a library of slide and print albums. A duplicate set of slides and prints has been stored in the library of Fisheries WA for use by the fisheries staff.

(6) Archiving of the processed datasets onto magnetic tape and the screen pictures to floppy disc.

During the course of the project, a number of improvements have been made to the procedure to streamline the processing of the imagery and provide better-quality data:

(1) After mid-1994, image data from WASTAC have been acquired via the Remote Sensing Services Section of DOLA in a pre-processed format (*i.e.* geometricall re-mapped and temperature-calibrated). As this has saved much local processing time, all relatively cloud-free images of the existing standard areas as well as three new areas at full spatial (1.1 km) resolution are now being archived from mid-afternoon passes of the most recent satellite (currently NOAA-14) each day. This will enable a much closer examination of some of the shorter-term changes in the SST patterns and also provide higher-frequency time-series data.

(2) The navigation routines originally used the satellite orbital information together with a visual coastline fit to geolocate the images. On some occasions, the resulting fit was a number of pixels in error. A correlation technique for re-navigating the coastline position modified from a program developed by the remote sensing group at the CSIRO Marine Laboratories in Hobart has therefore been implemented for the Area 1 images, reducing the positional errors to (in most cases) less than 2 pixels. At present, only a few selected monthly Area 1 images have been re-mapped in this way.

(3) In the earlier SST validation studies by Pearce *et al.*(1989), the bias and root-mean-square (RMS) difference between the *in situ* and satellite-derived temperatures (using the McMillin and Crosby (1984) algorithm) were about 0.2° and 0.6°C respectively. Subsequent spot-checks spanning a longer time-series and covering a much larger latitude range, however, found occasional differences of more than 2°C from *in situ* measurements. To provide consistency over the 15-year period of the project, during which the operational satellites were NOAA-7 to NOAA-14, the McMillin and Crosby algorithm has been retained in our study. However, the more recent Non-Linear SST (NLSST) algorithm has also been implemented since mid-1995 in tandem with the McMillin and Crosby method. The NLSST should be more accurate because it includes the effect of satellite zenith angle (the angle at which the satellite "sees" the individual pixels across the swath). As the original brightness temperatures in the AVHRR bands 4 and 5 are included in the archived datasets, new SST algorithms can be implemented into the future. An ongoing research project is underway to acquire appropriate *in situ* surface measurements and hence assess the accuracy of the satellite-derived temperatures in local waters.

(4) The issue of cloud contamination has not yet been resolved because of the complexity of the problem. The objective is to remove all possible cloud-contaminated pixels without losing too many cloud-free pixels. A study by Bezaud (1993) using a texture-analysis technique was able to detect clouds on a single mNOAA image but also flagged some apparently clear pixels as cloudy and was very computer-intensive. The simplest and probably most widely-used methods involve "threshold" limits as well as variability in a few of the AVHRR spectral bands; we tested the Saunders and Kriebel (1988) method with some modifications, but the threshold values will clearly require ongoing "fine-tuning" to optimise the technique for our local tropical and subtropical waters. Because the original

visible and near-infrared spectral bands have been retained in the archived datasets, however, future cloud-clearing techniques can be applied as they become available. Research into cloud-screening is continuing, and will be aided by the development of the Common AVHRR Processing System (CAPS -- Prata 1996) in which international "best-practice" methods will be implemented for all aspects of AVHRR data processing including cloud-screening.

A time-series of quasi-weekly sea-surface temperature (SST) images off Western Australia covering the period 1983 to 1997 has been compiled for the present project, extending the initial work undertaken in earlier projects (Pearce and Phillips 1991, Pearce *et al.* 1994), although there are many gaps in the weekly time-series as a result of cloud. Table 1.5 summarises the number of orbits processed in each year over the 15-year period. With the advent of daily imagery from DOLA and WASTAC from mid-1994, the number of images greatly increased. The final "products" are processed digital datasets (containing the raw counts in AVHRR bands 1 and 2, the derived brightness temperatures from bands 4 and 5 and the McMillin and Crosby SST) archived onto magnetic tape and now to CD-ROM, as well as sets of 35mm colour slides and postcard-sized prints. From 1994, the NLSST is included in the datafiles.

Table 1.5: Number of orbits processed by year between June 1983 and June 1997: a total of 1320 orbits over the 15 year period.

1983	21 (orbits)	1984	33
1985	34	1986	26
1987	24	1988	43
1989	45	1990	49
1991	48	1992	60
1993	67	1994	139
1995	295	1996	289
1997	147		

Results and Discussion

This section presents some general analyses of the environmental variables and their significance for recruitment to the various fisheries. More detailed discussions related to specific fisheries are dealt with in Sections 2 to 8.

Coastal sea levels and the SOI

El Nino events

The phenomenon known as *El Nino* has periodically devastated the fishing industry off Peru, being reported as far back as 1525 (Quinn *et al.* 1987). Normally, the cool Humboldt Current flows northwards along the coast of northern Chile and Peru. Aided by wind-driven "upwelling"of cool, nutrient-rich water from below the surface, the continental shelf region off Peru is highly productive and hosts some of the richest fisheries in the world. Every few years, however, a warm, *south*flowing current known as *El Nino* (meaning *The Child* because it generally appears around Christmas time) displaces the cool Humboldt Current along the Peru coast. The upwelling is suppressed, nutrient concentrations decrease, the productivity correspondingly ceases and the lucrative fisheries crash.

More recently, meteorologists have shown that *El Nino* is associated with a much larger-scale atmospheric phenomenon known as the *Southern Oscillation*, involving a "see-sawing" of atmospheric pressure between the southern Pacific and Indian Oceans (Pearce *et al.* 1997). It is now recognised that the onset of an *El Nino* off Peru is simply a local symptom of the more global-scale weather change associated with the Southern Oscillation -- the two phenomena are closely linked and are therefore together known as *ENSO* (**E**l **N**ino/**S**outhern **O**scillation) events.

Normally, the atmospheric pressure over the South Pacific Ocean is relatively high while that off northern Australia is low. This pressure difference, which is quantified in the Southern Oscillation Index (SOI), drives the Pacific southeast trade winds, which in turn force the warm South Equatorial Current to flow westwards towards Australia and create a pool of comparatively warm low-density water northeast of the continent. From here, aided by the wind, it flows through the Indonesian Archipelago into the tropical Indian Ocean, where it creates the conditions for the Leeuwin Current to flow southwards down the Western Australian coast.

On occasion, however, the atmospheric pressure difference between the two oceans weakens or even reverses as the pressure in the Pacific Ocean decreases and that in the Indian Ocean increases. During these ENSO years, the Pacific Southeast Trade winds weaken (or even reverse), the South Equatorial Current weakens (or may reverse) and the warm pool of water off eastern Australia shifts back towards South America to form the *El Nino* Current; the coastal water warms, the upwelling is suppressed and the Peruvian fisheries collapse. At the same time, less warm water now flows past Indonesia into the Indian Ocean, weakening the Leeuwin Current. As the pressure difference returns to normal, the trade winds re-establish and the circulation reverts to the usual pattern. In contrast with the *El Nino* situation where the SOI is persistently negative, the positive SOI phase has now received the name of *La Nina* (*the girl*; Philander 1989).

Monthly smoothed values of the SOI plotted in Figure 1.3 show the periods of negative SOI (summarised in Table 1.6) since 1900. These largely agree with the events listed in Quinn *et al.* (1987) who classified historical weak, moderate, strong or very strong *El Nino* events over the past few centuries based on climate data in northern Peru (floods, storms, winds, destructive events and biological phenomena). There are, however, some negative SOI periods without corresponding *El Ninos* and some events in Quinn's listing which are not matched by markedly low SOIs. Nevertheless, there is a clear link between negative SOIs and classic *El Nino* events off the Peru coast.

ENSO events are rarely the same in structure, duration or interval. The smoothed SOI generally starts dropping to negative values between March and October although the onset of an ENSO event can occur almost any time of year (Figure 1.4b); the demise of an event, on the other hand, is most likely to occur in April. Events tend to occur every 3 to 7 years and generally last for 1 to 2 years (Figure 1.4a); the longer-lasting events such as 1911-1915 and the recent 1990-95 episodes, however, can persist for over 4 years. The 1990-95 event was the longest ENSO this century although examination of Figure 1.3 suggests that this may almost be viewed as three sequential events, with the

SOI almost returning to normal in mid-1992 and early 1994 (this could also apply to the 1911-1913, 1957-1959 and 1976-78 events).

The strongest ENSO of recent times was the 1982-83 episode which was associated with the severe droughts in eastern Australia and indirectly led to the disastrous "Ash Wednesday" bushfires in Adelaide and Melbourne. The latest ENSO event commenced in early 1997 (Pearce *et al.* 1997) with the SOI dropping rapidly until early 1998 and then recovering equally sharply; by May the SOI was again positive (Table 1.6) and a strong *La Nina* situation has in fact developed (Figure 1.3). The SOI has continued strongly positive into 1999 and coastal sea levels off Western Australia are correspondingly high (Bureau of Meteorology monthly DTDS February 1999). Table 1.6 suggests that ENSO events have been more frequent since 1950 than during the first half of this century, with 168 months of negative SOI prior to 1950 and 260 such months in the 47 years since 1950.

ENSO events are manifested off the Australian north-east coast by cooler water, reduced rainfall and meridional wind anomalies (Lough 1994, Delcroix and Lenormand 1997), although both studies point out the lack of a consistent pattern throughout all observed events. Relationships with oceanographic variables off Western Australia are examined below. Recent modelling efforts for predicting ENSO events have been reviewed by Chen (1997).

Table 1.6: Summary of ENSO events between 1900 and 1997 derived from 5-month smoothed SOI values in Figure 1.3, with Quinn *et al.*'s (1987) El Nino classification. ENSO events have been defined here as longer than 8 months and having a minimum SOI of less than -5. The magnitude of the previous positive (La Nina) phase is also indicated together with the month. Quinn's classification is VS = very strong; S = strong; M = moderate; W = near-moderate.

Start	End	Duration Months	El Nino Peak SOI (Month)	Previous La Nina Peak SOI (Month)	Quinn *et al.* Classification
Jul.1904	Apr.1906	22	-29.6 (May.1905)	16.0 (Feb.1904)	1905 W/M
Apr.1911	May.1915	50	-13.8 (Mar.1912)	14.6 (Sep.1910)	1911-12 S; 1914 M
Jul.1918	Apr.1920	22	-10.6 (Feb.1919)	25.4 (Jul.1917)	1918-19 W/M
Jun.1923	Mar.1924	10	-12.0 (Sep.1923)	7.2 (Nov.1922)	1923 M
Jun.1925	Aug.1926	15	-10.4 (Dec.1925)	9.4 (Feb.1925)	1925-26 VS
Jul.1939	Apr.1942	34	-18.6 (Oct.1940)	13.2 (Aug.1938)	1939 M; 1940-41 S
Feb.1946	Apr.1947	15	-10.0 (Aug.1946)	6.6 (Aug.1945)	
Mar.1951	Apr.1952	14	-10.0 (Sep.1951)	16.0 (Aug.1950)	1951 W/M
Oct.1952	Feb.1954	17	-11.8 (Jul.1953)	3.0 (Jul.1952)	1953 M+
Mar.1957	May.1958	15	-8.4 (Nov.1957)	15.6 (Sep.1955)	1957-58 S
Oct.1958	Aug.1959	11	-7.2 (Dec.1958)		
Jun.1963	Feb.1964	9	-9.4 (Nov.1963)	5.4 (Mar.1963)	
Jan.1965	Jul.1966	19	-14.(Sep.1965)	10.6 (Aug.1964)	1965 M+
Sep.1968	Apr.1970	20	-7.4 (Mar.1969)	5.6 (Jul.1968)	
Mar.1972	Apr.1973	14	-14.8 (Jul.1972)	14.0 (Feb.1971)	1972-73 S
Jun.1976	Apr.1978	23	-13.8 (Dec.1977)	18.8 (Sep.1975)	1976 M+
Oct.1979	Apr.1981	19	-5.8 (May.1980)	4.0 (Jul.1979)	
Apr.1982	Jun.1983	15	-29.2 (Jan.1983)	7.8 (Jul.1981)	1982-83 VS
Sep.1986	Feb.1988	18	-18.6 (May.1987)		1987 M
Aug.1990	Jul.1995	60	-18.6 (Feb.1992)		
Mar.1997	May 1998	15	-21.2 (Feb.1998)	7.2 (May.1996)	

Coastal sea level

It is difficult to directly measure the strength of the Leeuwin Current on a regular basis. Monthly and annual mean sea levels measured at Fremantle have been used as a simple index which in general terms reflects the "strength" of the alongshore flow (Pearce and Phillips 1988, Pattiaratchi and Buchan 1991). A stronger southward flow will result in a greater sea level slope across the current and therefore a higher sea level at the coast, with winds and surface water temperatures also contributing to a lesser extent to the sea level changes. Conversely, a relatively low sea level at the coast is an indication of a generally weaker southward current. It should be emphasised that these are fairly gross-level changes representing a large area and time-scales of weeks, and do not necessarily mean that there will be very strong currents encountered everywhere and over the whole period.

As shown earlier, annual mean sea level at Fremantle has effectively risen from 61 cm in 1900 to 75 cm in December 1997, representing an increase of about 14 cm over the past century. It is not clear whether this reflects a true rise (possibly associated with global warming?) because, as pointed out by Wallace (pers.comm.), there has in fact been a slight *drop* in mean sea level over the past couple of decades -- possibly a result of the increased frequency and intensity of ENSO events. This can be seen in the annual time-series (Figure 1.5a) despite the ENSO-scale variations which can obscure the long-term trend; there is a significant correlation (0.34, $p<0.01$) between the annual SOI and annual sea level at Fremantle over the 97-year period (Figure 1.5b).

It is clear from Figure 1.3 that there is also a close link between (smoothed) Fremantle monthly sea level anomalies and the SOI. While there are ENSO events with no response in sea level (*e.g.* 1905 when the SOI was very strongly negative, 1946, 1953 and 1965) and occasions when sea level fell in non-ENSO periods (*e.g.* 1908 and 1931), generally coastal sea levels reflected the ENSO periods quite well. The decadal correlation coefficients between the smoothed monthly sea levels at Fremantle and the corresponding SOIs are:

1900-09	0.12	1910-19	0.72	1920-29	0.57
1930-39	0.06	1940-49	0.60	1950-59	0.72
1960-69	0.35	1970-79	0.82	1980-89	0.73
1990-99	0.73				

These are all significant at the 99% level except for the decade 1900-1910 and the 1930s when there were no distinctive ENSO events. The overall correlation coefficient for the 96-year period is 0.58. Meyers (1996) has shown links between ENSO events and the strength/transport of the Indonesian Throughflow, bringing equatorial Pacific Ocean waters into the tropical Indian Ocean and setting up the meridional pressure gradient which drives the Leeuwin Current (Godfrey and Ridgway 1985). During ENSO periods, the throughflow is weaker, presumably setting up a weaker alongshore pressure gradient and thus weakening the Leeuwin Current.

Annual mean sea levels at the other coastal ports between Port Hedland and Esperance over the 30-year period 1966 to 1996 are highly correlated with that at Fremantle as well as with the SOI (Figure 1.6, Table 1.7), with sea level falling in ENSO years. Despite datagaps, the monthly sea level anomalies at these ports are also highly correlated with Fremantle and the monthly SOI (Figures 1.7

and 1.8, Table 1.8), indicating that Fremantle sea levels may be used with confidence as representative for the whole western Australian coast. Pariwono *et al.* (1986) showed graphically the high regional coherence along the coast as well as the close (inverted) relationship with annual sea levels along the Californian coast implying strong inter-ocean linkages (Bye and Gordon 1982).

It is not clear why the correlation coefficients at Dampier and Port Hedland are so different as these two ports are relatively close together on an open continental shelf, and the correlation between Port Hedland and Fremantle is much higher than that between Carnarvon and Fremantle. Figures 1.6 and 1.7 suggest that the Dampier data in the mid to late 1970s may be suspect; Pariwono *et al.* (1986) pointed out some problems with Australian tidal data.

Annual sea level cycles along the coast reveal an interesting phase lag between the North West Shelf and the west/south coasts (Figure 1.9). Along the north coast, peak sea level occurs in April, then in May at Carnarvon, May/June at Geraldton, then in June from Fremantle southwards and eastwards to Esperance. Accepting that this variation represents the seasonal waxing and waning of the Leeuwin Current, it reflects the progression of the strengthening pulse of the Leeuwin Current from the North West Shelf to the west coast (Pariwono *et al.* 1986) and suggests there is effectively no lag between the southwestern and south coasts.

Table 1.7: Correlation matrix of annual sea levels between Broome and Esperance over the 31-year period, with the SOI. Correlations significant at the 99% level are in italics, and the samples sizes are shown.

	BRO	HED	DAM	CAR	GER	FRE	BUN	ALB	ESP	SOI
BRO	1.00	*0.50*	0.08	0.35	*0.59*	*0.68*	*0.67*	*0.60*	*0.48*	*0.61*
HED	26	1.00	0.39	*0.53*	*0.88*	*0.83*	*0.80*	*0.86*	*0.74*	*0.82*
DAM	26	29	1.00	0.42	*0.48*	0.39	0.30	*0.45*	0.41	*0.48*
CAR	23	26	25	1.00	*0.72*	*0.62*	*0.60*	*0.63*	*0.73*	0.43
GER	27	30	30	26	1.00	*0.94*	*0.92*	*0.96*	*0.89*	*0.84*
FRE	27	30	30	26	31	1.00	*0.97*	*0.94*	*0.86*	*0.81*
BUN	26	29	29	26	30	30	1.00	*0.93*	*0.84*	*0.77*
ALB	27	30	30	26	31	31	30	1.00	*0.87*	*0.85*
ESP	27	30	30	26	31	31	30	31	1.00	*0.72*
SOI	27	30	30	26	31	31	30	31	31	1.00

Table 1.8: Correlation matrix of monthly sea level anomalies between Broome and Esperance over the 31-year period, with the SOI. Correlations significant at the 99% level are in italics, and the samples sizes are shown.

	BRO	HED	DAM	CAR	GER	FRE	BUN	ALB	ESP	SOI
BRO	1.00	*0.53*	*0.16*	*0.26*	*0.45*	*0.48*	*0.45*	*0.39*	*0.23*	*0.40*
HED	253	1.00	*0.62*	*0.67*	*0.78*	*0.72*	*0.69*	*0.70*	*0.57*	*0.67*
DAM	262	307	1.00	*0.51*	*0.48*	*0.38*	*0.33*	*0.38*	*0.30*	*0.34*
CAR	236	265	260	1.00	*0.79*	*0.64*	*0.62*	*0.57*	*0.51*	*0.41*
GER	284	331	344	285	1.00	*0.89*	*0.86*	*0.78*	*0.62*	*0.56*
FRE	284	331	344	285	372	1.00	*0.95*	*0.88*	*0.71*	*0.52*
BUN	275	318	331	285	359	359	1.00	*0.88*	*0.70*	*0.46*
ALB	284	328	344	282	369	369	356	1.00	*0.83*	*0.48*
ESP	280	327	340	281	368	368	355	365	1.00	*0.41*
SOI	284	331	344	285	372	372	359	369	368	1.00

Water temperature and salinity

Reynolds satellite-derived SSTs

Statistical analysis of the monthly Reynolds SSTs between 1982 and 1996 over a large area off Western Australia (20° to 50°S, 100° to 110°E) indicates that surface temperatures are highly correlated with the Southern Oscillation Index, the surface waters being cooler during ENSO periods (Figure 1.10, from Caputi and Pearce, in prep.). The correlation between the SST for the months February/March and the SOI for the year May (of the same year) to April (following year) is 0.93, indicating that the surface temperature in the south-eastern Indian Ocean may be a useful predictor of ENSO events; possible mechanisms for this are currently being explored. Although, as described above, the transport of the Indonesian Throughflow is linked with ENSO events, the lag between the SOI and SST found by Caputi and Pearce (in prep.) suggests that local forcing in the Indian Ocean itself also plays a role in the dynamics of the south-eastern Indian Ocean.

SST transects have been derived from the Reynolds dataset for the latitude band 31° to 32°S (off Perth) and longitude band 117° to 118°E (off Albany) to reveal the gross spatial and temporal variability of the surface thermal structure off Western Australia.

The zonal transect off Perth clearly shows the warm waters of the Leeuwin Current near the coast (Figure 1.11). This increase in surface temperature towards the coast is in contrast with the situation in the southeastern Atlantic and Pacific Oceans where the temperature near the coast can be 4°C cooler than that far offshore because of the cool northward boundary currents and upwelling which occur in those two oceans (Pearce 1991). Surprisingly perhaps, variability (as reflected in the standard deviation) is higher offshore rather than in the strong Leeuwin Current region near the coast; much of this however is related to the larger seasonal cycle offshore (Figures 1.11b and 1.13b), and the standard deviation of the anomalies after removal of the seasonal cycle varies little from offshore to inshore (Figure 1.11a). Nevertheless, this suggests that the intuitive concept of larger variability in energetic Leeuwin Current eddies/meanders near the coast (as seen in the high-resolution satellite imagery discussed later and also suggested by numerical modelling -- Reason and Pearce 1996) may not be realistic, at least on monthly time-scales and 100 km length-scales.

The temperature rise from offshore to the coast is lowest in summer (represented by February -- Figure 1.11b) and highest in autumn/winter (May and August), reflecting the strengthening of the flow of warm tropical waters down the coast during the winter months. The temperature rise starts at about 105°E in winter, suggesting that the "influence" of the Leeuwin Current may extend as far as 1000 km offshore, where large numbers of mid-stage phyllosoma larvae have been caught -- Phillips (1981) found the greatest abundance between 104° and 111°E.

Monthly mean SSTs and anomalies at varying distances from the coast (Figure 1.12a) reveal both seasonal and interannual variability, with years when the summers were especially warm (or cool), and likewise relatively warm or cool winters, leading to years such as 1989 when the annual range was small (about 3°C) and others (for example 1995) with a larger range exceeding 5°C. This pattern appears to be reasonably coherent, with the anomalies generally showing warm or cool periods across the whole transect (Figure 1.12b); 1988 and 1996 were however years when the water warmed near the coast but cooled offshore. The anomalies also reveal multi-year periods of warming (1983 to

1985, 1988/1989 and 1994 to 1996) contrasted with cool periods (1982, 1986/1987 and the extended 1990 to 1993 -- generally corresponding to ENSO events).

These trends are better seen in the annual mean temperatures (Figure 1.13a) where there is a reasonable coherence between the SSTs near the coast and those offshore. Analysis of annual mean SSTs along the transect and Fremantle sea level (Figure 1.14) shows that the correlation progressively decreases from over 0.7 near the coast to about 0.1 at 100°E. The annual temperature range decreases from about 5°C offshore (105°E) to just over 3°C nearer the coast (Figure 1.13b) because advection of warm water down the coast in the Leeuwin Current maintains relatively warm conditions along the continental shelf during the winter months. There is also a lag in the timing of the seasonal cycle with distance offshore: at 105°E the summer peak is in February and the winter minimum in August/September; near the coast, the summer maximum is in March/April and the winter trough in September. These results all suggest a distinction between the offshore region (beyond say 110°E) where larger-scale (air-sea heat flux?) processes may operate and the more coastal waters in which advection by the Leeuwin Current dominates.

Turning to the south coast, it is clear that the inshore-offshore SST gradient is appreciably higher than that off Fremantle, as the temperature continues to decrease with latitude into the Southern Ocean (Figure 1.15). This follows the pattern in AVHRR satellite images which show an increasing temperature contrast between the Leeuwin Current and offshore waters with latitude southwards. The standard deviation of SST peaks at 41°S, about the latitude of the Subtropical Convergence (Deacon 1937), but (as on the west coast), after removal of the seasonal signal, the standard deviation is effectively constant with distance offshore. The monthly SSTs exhibit similar variability to those off Fremantle (Figure 1.16) and the interannual pattern in the anomalies also reflects the ENSO-related signal. Correlation between annual mean SSTs along the south coast (Figure 1.17a) and those off Fremantle is high (0.64, $p<0.01$), as is the correlation with Albany sea level (0.80, $p<0.01$), but the relationship with the SOI (0.42) is not significant, indicating a weaker link with ENSO events than off Fremantle. In contrast with the west coast situation (Figure 1.13b), the amplitude of the seasonal cycle off Albany (Figures 1.16a and 1.17b) is higher near the coast (3.5°C) than offshore (about 2°C) and the change in phase is less pronounced than off Fremantle.

The temperature difference between the warm Leeuwin Current and the cooler water further offshore along both the west and south coasts may be considered as a simple index of the surface thermal structure possibly related to the "strength" of the Current. For the west coast, this index has been defined as the Reynolds SST difference between the coastal block and the block 10 degrees further offshore (*i.e.* $T_{115.5} - T_{105.5}$), while off Albany it is defined as the SST difference over 5 degrees of latitude ($T_{35.5} - T_{40.5}$) because of the larger offshore gradient along the south coast.

Monthly values of the SST gradient index vary between 1 (summer) and 4 (winter) off Fremantle compared with 3 to 8 for the Albany transect (Figure 1.18), so are noticeably higher along the south coast despite being calculated over only 5 degrees latitude compared with 10 degrees longitude off the west coast. There is appreciable seasonal and interannual variability. Along both the west and south coasts, the seasonal index shows an encouraging increase in mid-year when the Leeuwin Current is flowing more strongly (Figures 1.13b and 1.17b); indeed there is a sudden and rapid rise in the south coast index between March and May as the Leeuwin Current strengthens, lagging about a month behind the rise in the west coast index.

The clear seasonal pattern for the SST indices in each region is out of phase with the SST itself (which peaks between February and April -- Figures 1.13b and 1.17b) but reasonably in phase with the coastal sea levels which peak in May-June (Figure 1.9). This suggests there may be a real dynamical significance in the SST gradient index as the raised sea levels in winter are clearly not simply due to higher water temperatures.

Annual values of the SST gradient index are highly correlated with the coastal SST: 0.56 ($p<0.05$) off the west coast (Figure 1.13a) and 0.84 ($p<0.01$) off Albany (Figure 1.17a) as well as between the index and the coastal sea level (0.49, $p<0.05$ off Fremantle, and 0.65, $p<0.01$ off Albany). A third (alongshore) gradient index has also been computed as the SST difference between the coastal block off Exmouth (22°S) and that off Cape Leeuwin (34°S), as this alongshore difference may be expected to reflect varying rates of transport of warm water down the west coast (ignoring air-sea heat fluxes). Somewhat disappointingly, comparing the 3 different indices (Figure 1.19) indicates that they are not well correlated with one another, nor with the SOI, despite the individually good correlations with sea levels.

Comparison of the Reynolds climatological SSTs with COADS for the period 1982 to 1989 when the 2 datasets overlapped indicates that they agree to within 0.5°C over much of the southeastern Indian Ocean (Figure 1.20). In both seasons, there are regions where the surface temperature difference is greater than -0.5° (the Reynolds SSTs being lower than COADS), but this is understandable bearing in mind the differences in measuring techniques and data coverage. We have chosen to use the Reynolds monthly data in preference to COADS because the latter (presently) extends only to 1989, and the Reynolds data is also being updated on a monthly basis into the future.

<u>CSIRO coastal monitoring station results</u>

The CSIRO monitoring station off Rottnest Island provides the only longterm hydrological dataset for the southwestern continental shelf and as such provides invaluable information for comparison with more recent and more global data such as the Reynolds surface temperatures. The Geraldton and Albany stations also provide sufficiently long data to reliably show seasonal variations and vertical structure; the data off Augusta are barely adequate for this, and the Esperance station data are too brief to yield any meaningful results. This is the first published analysis of the coastal station data in any detail (see also Pearce *et al.* in prep.(a)).

Annual depth-averaged temperature cycles derived from the optimal interpolation analysis show the expected pattern at all sites (Figure 1.21a). In the shallow tropical waters near Barrow Island, the mean annual temperature range is almost 10°C. Off Geraldton the range is 3.8°C, and further south it is about 3°C. Note the gradual shift in peak temperature from March/April off Geraldton, April/May off Rottnest and Augusta, to May near Albany, reflecting the phase lag as the strengthening pulse of the Leeuwin Current migrates southwards. The lowest temperatures likewise shift from July-August at Barrow Island to September off Geraldton to October/November between Rottnest and Albany.

The annual salinity cycles (Figure 1.21b) are less well-defined, although there is a complete phase change between the North West Shelf (Barrow Island, where the peak salinity occurs between June and August as a result of the summer precipitation in the tropics) and the southwest, with high salinity water in summer because of coastal evaporation and lowest salinities in winter due to winter precipitation and the low-salinity Leeuwin Current. Nevertheless, all the mean salinities lie in the relatively narrow salinity range between 35 and 36 ppt.

Nutrient cycles on the continental shelf are even less regular: highest nitrates and silicates tend to occur during the winter months (as found by Pearce *et al.* 1985, Johannes *et al.* 1994). There appears to be a double peak at Augusta near Cape Leeuwin, with both nutrients having higher concentrations in March-April and July-Augustand than at the other sites (Figure 1.21c,d); the late summer nutrient peak is unlikely to be a result of upwelling near the Capes reported by Pearce and Pattiaratchi (1999) and Gersbach *et al.* (1999). Nevertheless, these nutrient levels are all much lower than those in the upwelling regions of the world where nitrate and silicate concentrations reach 30 µM and 48 µM respectively (Rochford 1980; Pearce *et al.* in prep.(b)). Further offshore in the Leeuwin Current, nutrient levels are generally even lower (Pearce *et al.* 1992),

The annual progression of the water properties on the continental shelf off Geraldton and Rottnest Island (Figure 1.22) clearly shows the transition between warming coastal water of high salinity (evaporation) between February and April, to cool low salinity waters in the winter months. The higher salinities and more complex pattern off Geraldton in summer compared with Rottnest are likely due to restricted across-shelf mixing from the outer continental shelf through the Abrolhos Islands towards the coast (Pearce 1997) as well as the shallower water in the channel between the Islands and the mainland. The winter patterns are more comparable.

Annual mean temperatures for the three coastal stations with sufficient data to show any interannual variability (Geraldton, Rottnest and Albany) generally agree well together and with the Reynolds data, bearing in mind the spot sampling (in space and time) and the depth-averaging for the *in situ* measurements versus the more regular satellite observations averaged over 100 km squares (Figure 1.23a). The Rottnest samples, which comprise the longest dataset, agree very closely with the Reynolds block off Perth, as the position of the Rottnest station is almost in the middle of the Reynolds block 115°E to the coast. The Reynolds SSTs for the Geraldton block also match the interannual variation shown by the 7 years of *in situ* measurements but are a degree too high -- the reason for this is not clear. The reverse is true at Albany, where the Reynolds data are not cotemporal with the 5 completed years of *in situ* temperatures but appear to be a degree warmer (and, incidentally, do not appear to follow the same interannual pattern as the Geraldton and Rottnest coastal stations) -- this is probably because the Albany station was relatively close inshore while the Reynolds 1-degree block extends 100 km offshore into the warm Leeuwin Current.

Nevertheless, as the Reynolds SSTs off Geraldton, Rottnest and Albany all follow a consistent interannnual pattern and match the Rottnest station data, we conclude that the Reynolds dataset may be reliably used for studying interannual variability on the larger spatial (100 km) and temporal (seasonal to interannual) scales. COADS annual temperatures also match the Reynolds values reasonably well (Figure 1.23b).

The vertical thermal structure at the coastal stations (Figure 1.24) indicates that stratification on the continental shelf off Western Australia is generally small, largely because of the down-warping of the isotherms under the south-flowing Leeuwin Current (in contrast with the uplifting in the upwelling Benguela and Humboldt situations -- Godfrey and Ridgway 1985) and wind-induced vertical mixing. Pearce (1991) showed the difference in thermal structure in the top 20 m of water off the west coast of southern Africa (averages some 4°C in summer) and off Rottnest (about 0.5°C).

At the Rottnest station, where the longest time-series exists, 94% of the vertical temperature differences between the "surface" (1 m reversing thermometer) and near the seabed in 55 m water depth were less than 2°C (Figure 1.24b). Most of the 37 differences greater than 2°C were in January and February, and were often associated with a distinct cooling near the seabed (rather than a warming of the surface layer) and sometimes accompanied by raised nitrate levels (about 1µM compared with typical column values of less than 0.5µM). This is suggestive of a sporadic upwelling process possibly associated with flow up the Rottnest Trench (?) during the strong northwards upwelling-favourable wind conditions in the summer months. On only a few occasions was the vertical stratification associated with surface heating of over 1 °C. Close examination of the raw data suggest that those stations when the surface was apparently a degree *cooler* than the bottom were most likely errors in the dataset.

As found by Pearce (1997), the thermal stratification off Geraldton was also minimal for most of the year (Figure 1.24a), being mainly evident during January and February, and occasionally in mid-winter; only 9% of stations had a surface-bottom temperature differential of more than 1°C. Augusta and Albany, albeit with much less data, showed the same pattern (Figure 1.24c,d), although at Albany there was a much more uniform layering than at the other three stations, with about half the observations showing differentials of 1°C.

Temperature/salinity data from the puerulus collector sites:

Temperatures and salinities measured at the puerulus collector sites by CSIRO and Fisheries WA represent the most comprehensive dataset available for our nearshore waters, covering almost 3 decades. While there are some differences between the results from the monthly spot samples and the continuous temperature loggers because of the length of the time-series and the different sampling frequencies and methods used, both datasets show the gross temperature/salinity properties with time and latitude along the coast.

Annual mean temperatures from the sampling sites show the overall drop in temperature along the west coast between Shark Bay and Cape Mentelle (Figure 1.25, from Pearce *et al.* 1998). The net alongshore temperature gradient is about 0.4° to 0.5°C per degree of latitude, very similar to that derived for the open-ocean waters from oceanographic atlas data. The Green Head value is an outlier because of the deeper water and offshore location where it is more influenced by the warm Leeuwin Current, particularly in winter.

Differences in the annual summer-to-winter temperature range (Figure 1.26) may be interpreted as reflecting variations in cross-shelf mixing of the inshore and open-shelf waters at the different sites along the coast. At most sites, the shallow inshore waters are strongly influenced by coastal heating/cooling and precipitation/evaporation processes and the annual temperature and salinity ranges are of order 6° to 7°C and 1 ppt respectively. However, some sites (such as Shark Bay, Rat Island, Cape Mentelle and Augusta) have relatively small annual ranges (3° to 4°C, about 0.5 ppt), suggesting that these areas are well flushed with water from offshore, which is generally warmer in winter and cooler in summer than the coastal waters. The Shark Bay collector site is in South Passage where strong tidal movements bring in open-ocean water; Rat Island is near the edge of the continental shelf and so close to the warm, low-salinity Leeuwin Current (Pearce 1997), and both Cape Mentelle and Augusta experience the cool Capes Current in summer and the warming influence of the Leeuwin Current which moves closer inshore in winter (Pearce and Pattiaratchi 1999). On the other hand regions like Cliff Head, Garden Island and Warnbro experience much larger annual ranges in both temperature and salinity (7°C, >1.5 ppt) indicating more restricted flushing and longer residence times at those sites. These differences could well contribute to more or less puerulus settlement, feeding and survival in the different coastal areas.

The timing of the summer peak temperature tends to confirm this: the South Passage (Shark Bay) site is warmest between March and May, Rat Island in March, Cape Mentelle in March-April and Augusta from March to May (Figure 1.26) compared with February for the other sites where air-sea heat flux tends to dominate. The winter minimum temperature at those four sites is also higher than elsewhere, indicating a greater influence of the warm Leeuwin Current. The salinity cycles display similar characteristics to the temperature.

Monthly mean temperatures for all the temperature logger sites between 1990 and 1994 are tabulated in Pearce *et al.* (1998), where histograms of both hourly and daily temperature changes are presented to show the magnitudes of temperature variability likely to be experienced at each site.

Winds

The winds are described separately for the north, west and south coasts as the patterns are quite different in those 3 regions. The annual mean wind components and mean seasonal patterns have been derived from COADS for selected blocks along the coast: north of Broome, Port Hedland and Exmouth Gulf on the north coast; Exmouth, Shark Bay, Geraldton, Perth and Cape Leeuwin along the west coast; and Albany, Cape Pasley and Eucla on the south coast. It is worth re-stating that, by convention, winds are generally described by the direction they are coming *from*, e.g. a southwester blows from the southwest to the northeast. By contrast, a southerly current is one flowing *towards* the south. Wind components, however, follow the current convention, *i.e.* are blowing *towards*, and we use the term "eastwards" (for example) to emphasise this.

Along the coast of the Northwest Shelf, the seasonal pattern is especially pronounced for the zonal (east-west) component, with marked westerly winds in summer and easterlies in winter right along the coast; monthly speeds average about 4 m/s or 8 knots in both these main seasons (Figure 1.27). The transition between easterlies and westerlies seems to occur consistently in early April and early September. Meridionally, the wind tends to be southerly (northward) throughout the year, although the strongest southerlies occur in spring and summer in the western (Exmouth) end of the

Shelf and in winter further east; in winter, mean southerly wind components are about 2 m/s all along the coast.

The strong southerlies indicated in Figure 1.27 are reflected in the annual mean winds (Figure 1.28), where the wind speeds in the western sector (Exmouth) are more than double those further east because of the differing seasonal patterns. Annual mean eastward components have been positive (to the east) at or below 1 m/s since the 1950s. Interestingly, interannual variability was much higher before about 1957 than after that year -- the reason for this is unknown, but may reflect limitations in the raw data coverage. Although there is little visual coherence in either the zonal or meridional wind components along the coast at annual scales, correlation coefficients between adjacent sites (which are separated by some 400 km) are in fact significant at either the 5% or 1% levels. There is no correlation with annual values of the SOI.

Turning now to the west coast, the monthly meridional (north-south) component is steadily from the south all along the coast between Exmouth and Cape Leeuwin throughout the year (Figure 1.29), albeit more strongly and consistently in the summer months (5 to 8 m/s) than in winter when westerly storms occur and wind directions are highly variable. There is a complete reversal in the seasonal zonal (east-west, or onshore-offshore) components with latitude, reflecting the seasonal migration of the atmospheric high-pressure belt from south to north between summer and winter. In the northernmost blocks (22.5°S,off Exmouth, and 25.5°S, Shark Bay), the winds tend to be westerlies in summer and easterlies in winter; in the south, on the other hand, the reverse is the case, with the winds off Perth (31.5°S) and the southern Capes (34.5°S) blowing increasingly strongly from the west in winter. The Geraldton/Abrolhos area (28.5°S) is in the transition zone between these two regimes, with relatively weak (2 m/s) easterlies in summer and little zonal component for the rest of the year. These COADS-derived wind patterns are supported by time-series plots from coastal weather stations presented for the Leeuwin Current Interdisciplinary Experiment (LUCIE) period by Forbes and Morrow (1989). This obviously has implications for latitudinal differences in surface wind-driven onshore currents during the time of puerulus settlement in late winter/spring. At least on monthly time-scales, it would appear that the stronger westerlies (assisting larval transport towards the coast) occur along the lower west coast where settlement is in fact poorest, and well south of the mid-west where most settlement occurs (Phillips *et al.* 1991). Individual storm events, of course, could assist the shoreward movement of larval pulses at any latitudes.

Coherence between adjacent sites along the west coast is very high with correlation coefficients of 0.7 to 0.9 for both the zonal and meridional annual mean wind components (Figure 1.30). There is again no correlation with the SOI, nor indeed with coastal sea levels -- correlation coefficients between the annual mean southerly and westerly wind components off Fremantle and annual mean sea level there over the 24-year period 1966 to 1989 at the same site are very low. Analysis of the monthly wind anomalies against Fremantle sea level between 1966 and 1989 suggested some relationship (correlation between sea level and the north/east components is -0.32/0.23, both significant at the 1% level), indicating that at monthly timescales the wind does indeed play a role in sea level variability. As would be expected, stronger southerlies reduce coastal sea level while strong westerlies raise sea level at the coast. Most of the sea level variability at Fremantle at interannual timescales therefore appears to be related to the alongshore flow (the Leeuwin Current), and the wind plays a more direct role at monthly periods.

There are strong seasonal patterns in both the northward (on/offshore) and eastward (alongshore) wind components on the south coast (Figure 1.31). During the summer months, the winds blow from the southeast all along the coast whereas in winter they are predominantly westerlies, following the north-south migration of the high-pressure belt. There is a particularly consistent pattern in the zonal wind components, with the transitions between easterlies and westerlies occurring in April and November. Petrusevics (1995) showed that the presence of westerly winds in this area following the time of spawning of the Australian salmon provides a mechanism for wind-driven shelf currents to transport the salmon larvae eastwards to South Australian waters, and he found a significant relationship between the duration of the westerly winds at Albany and salmon recruitment in the Gulf of St.Vincent. At annual scales (Figure 1.32), the net winds tend to be from the southwest. The correlation between the winds in adjacent regions is high (0.62 to 0.96, $p<0.01$), but there is no correlation between annual mean sea level at Albany and either the alongshore or cross-shelf wind component.

The differences in the winds in the three regions may best be visualised in the seasonal mean wind vectors (Figure 1.33). Along the west coast, the strong southerlies during the summer months are responsible for an offshore transport of the surface waters carrying the early stage rock lobster larvae out into the southeastern Indian Ocean, where they spend the winter. By late winter and early spring, westerly winds are generally more pronounced in the south of the region, so any wind-driven assistance to the returning larvae is more likely south of the Abrolhos Islands. The strong southerlies right along the west coast in summer are also believed to be responsible for the northwards counter-currents on the inner conrtinental shelf near Cape Leeuwin (the Capes Current -- Pearce and Pattiaratchi 1999, Gersbach *et al.* 1999), the Abrolhos Islands (Cresswell *et al.* 1989, Pearce 1997) and in the north (Ningaloo Current -- Taylor and Pearce, in press).

On the south coast, the winds are largely westerly during the winter months, but winds with an easterly component blow in summer. As the strongest flow in the eastward Leeuwin Current tends to be further out on the shelf (Cresswell and Peterson 1993), nearshore currents are likely to be generated by these prevailing winds. Newly-hatched salmon larvae in surface waters may be constrained to the nearshore region by the southeasterlies around the spawning time of March/April, but from May there is likely to be an eastward transport along the coast, carrying the larvae and juveniles towards South Australia. Petrusevics (1995) pointed out the consistency of onset of these westerlies in April and May and their duration over winter, resulting in recruitment of salmon larvae in Barker Inlet in Gulf St.Vincent (see also Section 8 of this report).

The COADS wind data can be compared with monthly mean winds measured at the coast by the Fremantle Port Authority (FPA) building between 1971 and 1981 (Pearce unpublished data). These exhibit generally similar seasonal characteristics to the COADS open ocean winds at 31.5°S (Figures 1.29 and 1.34b), although wind speeds from COADS are about double the FPA speeds. This may be due to stronger winds out at sea than along the coast, differences in the methods of sampling and analysis (*e.g.* spot samples at Fremantle compared with temporally- and spatially- averaged COADS), and land-sea breeze effects.The strong seasonal change in the meridional component is very similar in both although the FPA winds have a reversal to northerly in mid-winter, and the zonal winds at FPA are easterlies in summer and westerly from May to December. At annual scales, the meridional components at FPA (Figure 1.34a) are not closely related to those from COADS at 31.5°S (Figure 1.30), whereas the zonal FPA components are correlated with both components of COADS at the 1% level. The FPA monthly wind vectors (Figure 1.35) illustrate the high degree of seasonal and interannual variability in the wind field at the coast, particularly during the winter months.

Other sites where seasonal wind data have previously been analysed are Cape Cuvier (south of the Ningaloo Reef -- see Taylor and Pearce, in press), the Abrolhos Islands (Pearce 1997) and the Cape Naturaliste/Cape Leeuwin area (Pearce and Pattiaratchi, 1999), and these generally match the COADS seasonal wind patterns quite well. The winds at the two sites in the Capes area show the difference that coastal topography can make to the wind field, Cape Naturaliste and Cape Leeuwin being only about 100 km apart. Although the basic pattern at the two sites was the same (strong and persistent southerlies in summer and equally strong westerlies in winter, in line with the COADS data in Figure 1.29), Cape Leeuwin experienced far more pronounced easterly components in the summer period.

SST satellite imagery

The AVHRR-SST time-series produced in this project represents the longest archive of processed full-resolution SST imagery available in Australia. It will be used into the future for ongoing application to marine research along our coast:

1) examination of mesoscale current patterns along both west and south coasts;
2) estimation of coastal SSTs where no *in situ* data are available;
3) derivation of thermal "indices" relating to seasonal and interannual variability in water properties and/or oceanic processes (*e.g.* the Leeuwin Current).
4) assessment of the accuracy of satellite-derived SSTs for climate and other applications, as part of a national SST calibration/validation project.

SST images

Because the SST images clearly show the mesoscale (order 100 km) variability in the Leeuwin Current system as well as finer-scale features closer inshore, they have been used in basic studies of oceanic processes off Western Australia. While a complete review of the ocean circulation off Western Australia is inappropriate here, a summary of the main features of the ocean currents focussing on the application of satellite thermal imagery provides a useful background to the subsequent discussions of larval recruitment.

The Leeuwin Current takes on its identity as a distinctive boundary current in the vicinity of Northwest Cape (Exmouth), having its source in the waters of the Northwest Shelf and eastern Indian Ocean. Because the continental shelf is narrow off the Ningaloo Reef, the Leeuwin Current (which tends to flow along the edge of the continental shelf) is relatively close inshore.

Nearer the coast, however, satellite imagery combined with some visual observations along the Ningaloo Reef system have shown the presence of a seasonal northward counter-current during the summer months (Taylor and Pearce, in press). The images frequently show the warm Leeuwin Current along (or offshore of) the shelf break, with a band of cooler water streaming northwards along the Ningaloo Reef and continuing northeastwards past the Muiron Islands. This current, which has been named the "Ningaloo Current", appears to be largely driven by the strong southerly winds prevailing in the area between September and April. Taylor and Pearce (in press) suggest that this recirculation may contribute to the local retention of productivity from the annual coral mass spawning in March/April each year, rather than the spawn being lost to the south in the Leeuwin Current.

The intrusion of open-shelf water into Shark Bay is evident in most satellite images, apparently occurring about equally through the northern (Geographe Channel) and southern (Naturaliste Channel) entrances. When the Leeuwin Current is in its normal position near the shelf break, this water would be from the inner-shelf region and so cooler than the Leeuwin Current. On occasion, however, the Leeuwin Current floods across the shelf towards the coast, and the tropical water then enters the Bay directly. As it mixes with the Bay water and gains/loses heat from/to the atmosphere, it loses its thermal "signature" and so cannot be further tracked from the satellite imagery.

Links between sea level and scallop recruitment have led to the hypothesis that a strong Leeuwin Current may set up circulation patterns in Shark Bay that sweep the scallop spat away from suitable settling ground and so result in poor recruitment (Joll and Caputi 1995a; see also Section 3); in ENSO years with a weaker Leeuwin Current, on the other hand, settlement and recruitment are much higher. A preliminary examination of the satellite imagery has not yet indicated any consistent pattern to verify this, partly because of the high current variability in that area and also the mixing problem mentioned above.

Current patterns in the vicinity of the Houtman Abrolhos Islands were examined by Pearce (1997) using AVHRR SST imagery over the period 1990 to 1995, and classified into 5 basic patterns (Figure 1.36) which are typical of the mesoscale current structures along the west coast between Shark Bay and Cape Leeuwin:

* Pattern A, in which the Leeuwin Current flows southwards along the edge of the continental shelf past the Islands, effectively bathing them in the warm tropical water. Interaction with the islands results in Leeuwin Current water penetrating through the island chain towards the coast.

* In pattern B, the Leeuwin Current deflects offshore some distance north of the Abrolhos Islands in a large loop, returning to the coast further south. These meanders often extend over 300 km from the coast (see below), and the associated offshore/onshore currents can reach speeds exceeding 1 m/s or 2 knots according to satellite-tracked drifting buoys (Pearce and Phillips 1994).

* If one of these meanders is situated south of the Abrolhos Islands, the offshore flow along the northern segment of the meander may commence immediately offshore of the islands (pattern C).

* In the opposite case where a meander is north of the islands, the shoreward return flow may take place directly towards the island group (pattern D).

* As the meander develops, it often evolves into a tear-drop shape (pattern E) where the shorewards flow along the southern limb starts veering northwards before suddenly curving back to the south along the shelf break. The sharp cyclonic (clockwise) curvature may be associated with some localised upwelling of cooler subsurface water (Pearce and Griffiths 1991) and could perhaps contribute a pulse

of higher-nutrient water onto the outer continental shelf and the islands. Eventually, the narrowing neck of the meander may pinch off completely to form a free-standing anti-clockwise warm eddy (see Figure 13 of Pearce and Griffiths 1991).

Analysis of cloud-free images over the 6-year period indicated that pattern A tends to occur about 64% of the time, reasonably distributed through the year; pattern B followed with 17%, and the other 3 patterns were each observed less than 10% of the time. Pearce (1997) suggested that there may be a tendency for the Leeuwin Current to be further offshore in summer (when the opposing windstress is strongest) than in winter but could not quantify this from the available imagery.

More detailed analysis of a few meander features by Pearce and Griffiths (1991) showed similarities between the structure and evolution of these meanders and features in laboratory experiments with coastal currents driven by steady thermal forcing. In a comparison of currents and water properties from the Leeuwin Current Interdisciplinary Experiment (LUCIE) in July 1987 and an eddy-resolving global ocean circulation model, Reason and Pearce (1996) measured the offshore extent of the mesoscale meanders in the winters between 1987 and 1994. While 22% extended less than 200 km offshore, and 60% were within 300 km of the coast, over 10% could still be identified more than 450 km offshore. The modelled currents realistically reproduced many of the mesoscale features revealed in the satellite imagery (although the model meanders tended to be larger than those in nature -- Reason *et al.* 1997), and the computed current speeds matched the direct measurements quite well.

Although the alongshore speed of the Leeuwin Current is typically 0.5 to 1 m/s (1 to 2 knots), the offshore excursions in the large meanders result in a slower net southwards movement, with a consequently longer transport time for migration of tropical larvae down the coast (Hutchins and Pearce 1994). Using satellite images, these authors demonstrated that recruitment of tropical fish larvae at Rottnest Island was probably due to entrainment in warm intrusions of the Leeuwin Current onto the continental shelf. Similar penetration of tongues of warm water from the Leeuwin Current towards the coast was noted by Pearce and Griffiths (1991) from satellite imagery in May 1985 and by Pearce (1992) in July 1991. Mills *et al.* (1996) used AVHRR imagery to show that mesoscale features of the Leeuwin Current can have an important influence on the adjacent shelf waters, and that the density structure of the water and the wind both play a major role in cross-shelf transport processes.

As the Leeuwin Current approaches the Cape Naturaliste/Cape Leeuwin area, it tends to ride up onto the continental shelf and flood across towards the coast, before rounding Cape Leeuwin and heading eastwards towards the Great Australian Bight (Legeckis and Cresswell 1981). Satellite imagery shows, however, that during the summer months the Current weakens in the face of increasing southerly wind stress, which in fact drives an inshore countercurrent from the Capes northwards up the inner continental shelf and past Rottnest Island (Pearce *et al.* 1996; Pearce and Pattiaratchi, 1999; Gersbach *et al.* 1999). Analysis of satellite SST transects across the shelf and Leeuwin Current off Cape Mentelle (34°S) has confirmed that the Leeuwin Current tends to drift offshore in the summer months, being apparently displaced by the Capes Current. Deriving averages from Figure 8 of Pearce and Pattiaratchi (1999), the mean distance offshore of the peak SST (representing the "core" of the Leeuwin Current) is about 60 km in January/February and only about 37 km in August/September. Following the seasonal variation in the alongshore wind field between the Capes, the Capes Current is most evident between the months of October and March/April and may also be associated with some localised upwelling (Gersbach *et al.* 1999).

Phillips *et al.* (1991) attributed variations in puerulus settlement at the Cape Mentelle collector site (Section 2) to the presence or absence of the Leeuwin Current on the continental shelf: settlement was higher when the Leeuwin Current was close inshore, and weaker when the (as-yet unnamed) Capes Current was flowing. Examination of the satellite imagery over a longer period, however, has indicated that the (rare) times of high puerulus settlement at Cape Mentelle do not always co-incide with the Leeuwin Current flowing close inshore along that part of the coast. The Capes Current may also play a role in the northwards migration and dispersal of some finfish species during the summer months, either in the egg/larval phase (*e.g.* tailor *Pomatomus saltatrix* -- Lenanton *et al.* 1996) or as adult fish (Australian salmon *Arripis truttaceus* -- Lenanton *et al.* 1991).

At the time of the potentially disastrous mass mortality of pilchards in the autumn of 1995, satellite imagery indicated that the Capes Current had ceased by the time the "kill" moved northwards past Cape Leeuwin, with the Leeuwin Current flowing southwards close inshore between the Capes (Fletcher *et al.* 1997). Clearly, there was no advective mechanism for the northward migration of the event, which was subsequently found to be asphyxiation attributed to a virus.

On rounding Cape Leeuwin and flowing eastwards, the Leeuwin Current continues to form meanders and eddies along its offshore flank, with consequent disruption of the alongshore stream (Legeckis and Cresswell 1981, Griffiths and Pearce 1985b). The offshore eddies generally take the form of "eddy pairs" (Griffiths and Pearce 1985b) with both clockwise and anticlockwise elements and diameters between 100 and 140 km. Using a combination of thermal satellite images and direct surface current measurements from a research vessel, Cresswell and Peterson (1993) found that current speeds in the eddies were up to 1 m/s (2 knots), extended 200 km offshore and had a lifetime of 3 to 4 months. While many eddies are later re-absorbed into the Leeuwin Current, some separate completely from the Current and drift away into the Southern Ocean (Griffiths and Pearce 1985a).

The fate of the Leeuwin Current south of Australia is presently unclear. Satellite images frequently show a band of warm (Leeuwin Current?) water extending across the Great Australian Bight and even continuing down the west coast of Tasmania (Nilsson *et al.* 1989). Examination of directly-measured currents and *in situ* water properties, however, suggests that the Leeuwin Current may in fact dissipate in its passage eastwards to be replaced by a new water body and current system (Rochford 1986). Cresswell and Peterson (1993), for example, felt that the Current "was arrested" at 34°S near Cape Leeuwin in March 1987, and they were able to trace the subsequent eastward advance of the leading edge of the Current towards the Bight at about 20 km/day. Analysis of oceanographic data from a research vessel in July 1994 indicated that the eastward limit of the Leeuwin Current at that time was about 124°E near Israelite Bay (Petrusevics 1995).

Estimation of SSTs in Shark Bay

Although the monthly 100 km Reynolds SST dataset is in many ways better than the mNOAA product for larger-scale open-ocean SSTs, the 1 km resolution local imagery is required for any higher-frequency (*e.g.*daily) temperatures or nearshore analysis. A prime example is Shark Bay, because of the potential importance of temperature for scallop recruitment and growth and the lack of long-term *in situ* temperature data in that area. Full-resolution SSTs have been extracted from all processed cloud-free mNOAA images between mid-1983 and the end of 1997. Prior to 1994, the number of images processed in each month varied between zero and 6, but from mid-1994 between 10 and 30 SSTs were available per month.

The time-series (with a number of gaps in the 1980s because of cloud) shows both the seasonal and interannual variabiliy in the deeper waters of Shark Bay, with monthly mean temperatures varying between about 18° and 26°C (Figure 1.37). As described earlier, the monthly SSTs have been derived for the whole period using the McMillin and Crosby algorithm, supplemented by the NLSST from 1995; it is clear that (at least for the monthly means) the McMillin and Crosby method gives similar surface temperatures to the NLSST and hence can be considered sufficiently accurate for estimating SSTs at monthly and longer timescales.

Annual mean temperatures in Shark Bay derived from the mNOAA data over the 15-year period (Figure 1.38a) are highly correlated (0.86, $p<0.01$) with the Reynolds temperatures for the block 25° to 26°S, 113° to 114°E covering the main part of Shark Bay, although there is an offset by about 1°C -- not surprising bearing in mind the differences in scale and method of analysis. The annual SSTs are also significantly correlated with the annual mean sea level at Carnarvon (0.76, $p<0.01$) and Fremantle (0.79, $p<0.01$); correlation with the SOI is poorer (0.54, $p<0.05$). It is interesting that agreement of temperature with sea level is better for the *La Nina* periods (1988/89 and 1996) than for the ENSO years of 1986/87 and 1990-94, suggesting that the presumed strong Leeuwin Current and associated high sea levels in non-ENSO years may well force more offshore water into the Bay than in the weaker current/low sea level ENSO years. This would support the hypothesis that a stronger Leeuwin Current results in more active circulation patterns in Shark Bay sweeping scallop larvae away from suitable habitat for settlement and hence leading to poorer recruitment.

The mean seasonal pattern derived from the full-resolution mNOAA data (Figure 1.38b) shows a winter minimum of 21°C between July and August and a peak of about 25°C in February-March, not very different from the seasonal Reynolds SST pattern for the Bay, although the latter lags the mNOAA cycle by about a month and may again be due to the different spatial scales. In the shallower eastern parts of the Bay, Pearce and Burton (1994, reproduced in Pearce *et al.* 1994) analysed zonal mNOAA SST transects to show that the annual SST amplitude is over 8°C in the shallow water where there is probably less active exchange with the deeper western waters.

Derivation of SST indices

To enable correlations to be made between physical oceanic variables (temperature, currents, etc) and recruitment data, quantitative SST indices have been derived from the satellite imagery to represent thermal variability of the oceanic surface waters. After some experimentation, four indices have been tested over the west coast region 25° to 34°S and 110° to 116°E, as this is the area where the Leeuwin Current is most likely to affect the larval migration of lobster larvae. The indices are defined as:

1) CLIM1, the median of the SST anomaly over the whole area; this is effectively a surface temperature difference from the climatological average for that month.

2) CLIM2, the difference between the 10th and 90th percentiles of the SST anomaly, representing the range of SST variability over the area and ignoring outliers.

3) SSTgrad, the mean magnitude of the gradient of the SST anomaly over the whole area, which should be related to the horizontal density structure and therefore to surface currents.

4) ALONG, the SST standard deviation along an inclined transect approximately parallell to the coast between Shark Bay and Geographe Bay. The transect was selected to match one of the TOPEX altimeter trajectories.

The first three indices are based on SST anomalies from the Shea *et al.* (1990) dataset, being calculated as the difference between the pixel SST in the mNOAA image and the monthly climatological SST from the Shea dataset; the least cloudy "Area 1" remapped image (Table 1.4) in each month over the period 1983 to 1996 was used. Cloudy pixels were flagged by applying a simple threshold test to the SST anomaly value: any pixel more than 2°C colder than the climatological SST was considered to be cloudy. The alongshore transect, derived from *all* "Area 3" images (Table 1.4) over the period 1983 to 1997, intersects many of the offshore meanders and eddies associated with the Leeuwin Current, so the SST variability (represented by the standard deviation) may reflect the thermal topography and hence the mesoscale structure of the Leeuwin Current.

With such a large dataset spanning 15 years, computer programs have been developed to automatically extract these thermal indices from the mNOAA images. However, this aspect of the project has been hindered by the lack of effective automatic cloud-screening techniques, and the derived indices are also to some extent dependent on the actual cloud-free area remaining in the mNOAA image. The present results should therefore be viewed as a preliminary attempt to use the satellite imagery in a quantitative manner.

Nevertheless, there are some encouraging results, particularly at the seasonal scale. Plotting the individual months as a time-series (not shown) indicates a high degree of scatter but a seasonal cycle is evident. For the mean seasonal pattern (Figure 1.39b), all four indices show a rise in winter when the Leeuwin Current is flowing more strongly; CLIM1 peaks a little early in April, but CLIM2 and ALONG are both highest between May and July, similar to the coastal sea level (Figure 1.9) which is presently being used as an index of the Leeuwin Current. SSTgrad has the most impressive seasonal variation with a sharply-defined rise between May and July.

Interannually (Figure 1.39a), the mean CLIM1, CLIM2 and SSTgrad show troughs in 1986 and 1992; the peaks are not as consistent but all 3 indices are rising at the end of the period shown in line with the recovery from the ENSO of the early 1990s. ALONG does not match as well. The two CLIM indices are significantly correlated with each other (0.77, $p<0.01$) and with the Reynolds SST index for the west coast defined earlier (0.51 and 0.60 respectively, $p<0.01$), and CLIM2 is also linked with Fremantle sea level (0.72, $p<0.01$). Neither SSTgrad nor ALONG are correlated with any other variable. The associations of CLIM1 and CLIM2 with the Reynolds SST Index may be expected because they are all effectively surface temperatures (albeit at grossly different length-scales), but the correlation between CLIM2 and annual sea level at Fremantle is interesting because it implies a relationship between temperature variability and the Leeuwin Current which may be real.

Two other indices which have not yet been tested because of the cloud-screening problem but may prove useful are the distances offshore of the Leeuwin Current "core" and its offshore boundary derived from the peak SST and the position of the maximum offshore SST gradient. This index would monitor changes in the inshore-offshore position of the thermal fronts associated with the Leeuwin Current and its meanders, which may influence hydrographic changes on the continental shelf and associated coastal waters. With improvements in cloud-screening techniques, all these indices may be refined to a useful level -- work is continuing.

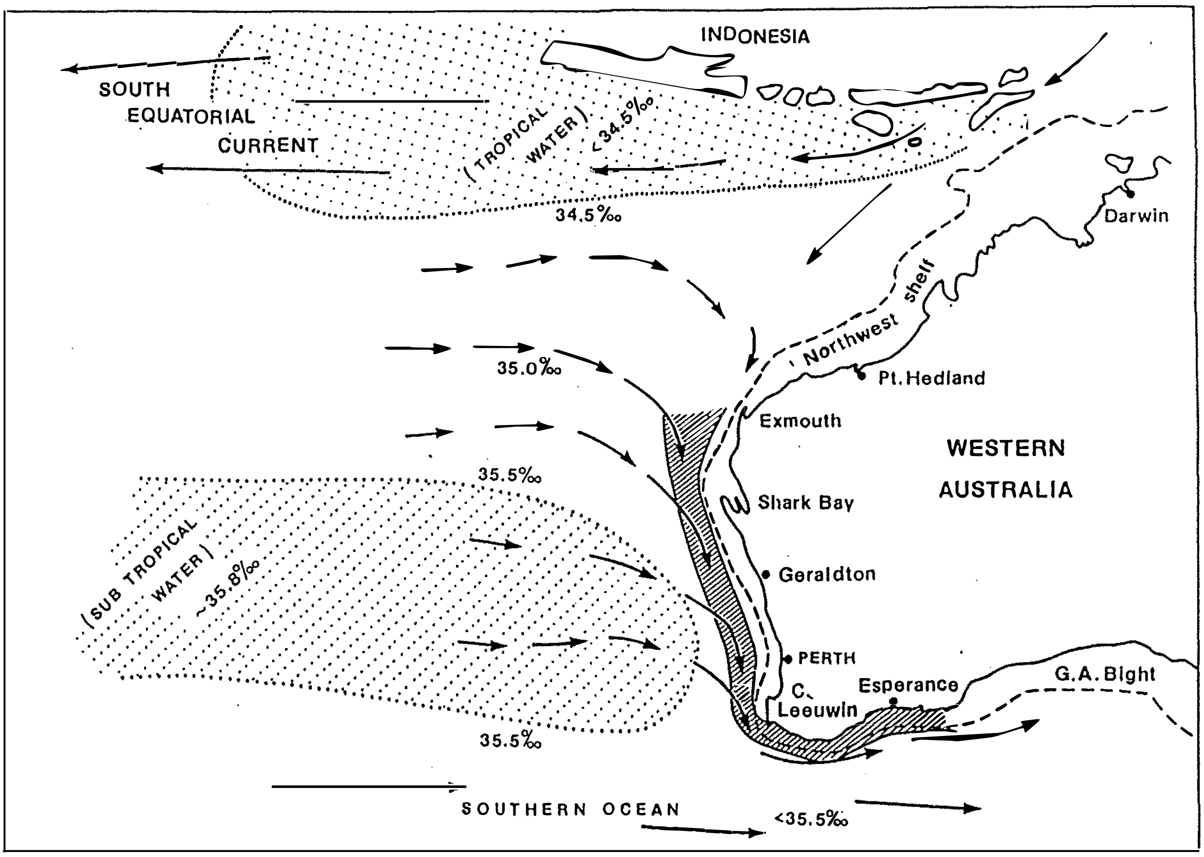


Figure 1.1: Map of the southeastern Indian Ocean showing the main oceanic features off Western Australia: a diagrammatic Leeuwin Current (shaded), the geostrophic inflow from the west, and the salinity of the main surface water masses (stippled), after Pearce and Cresswell (1985).

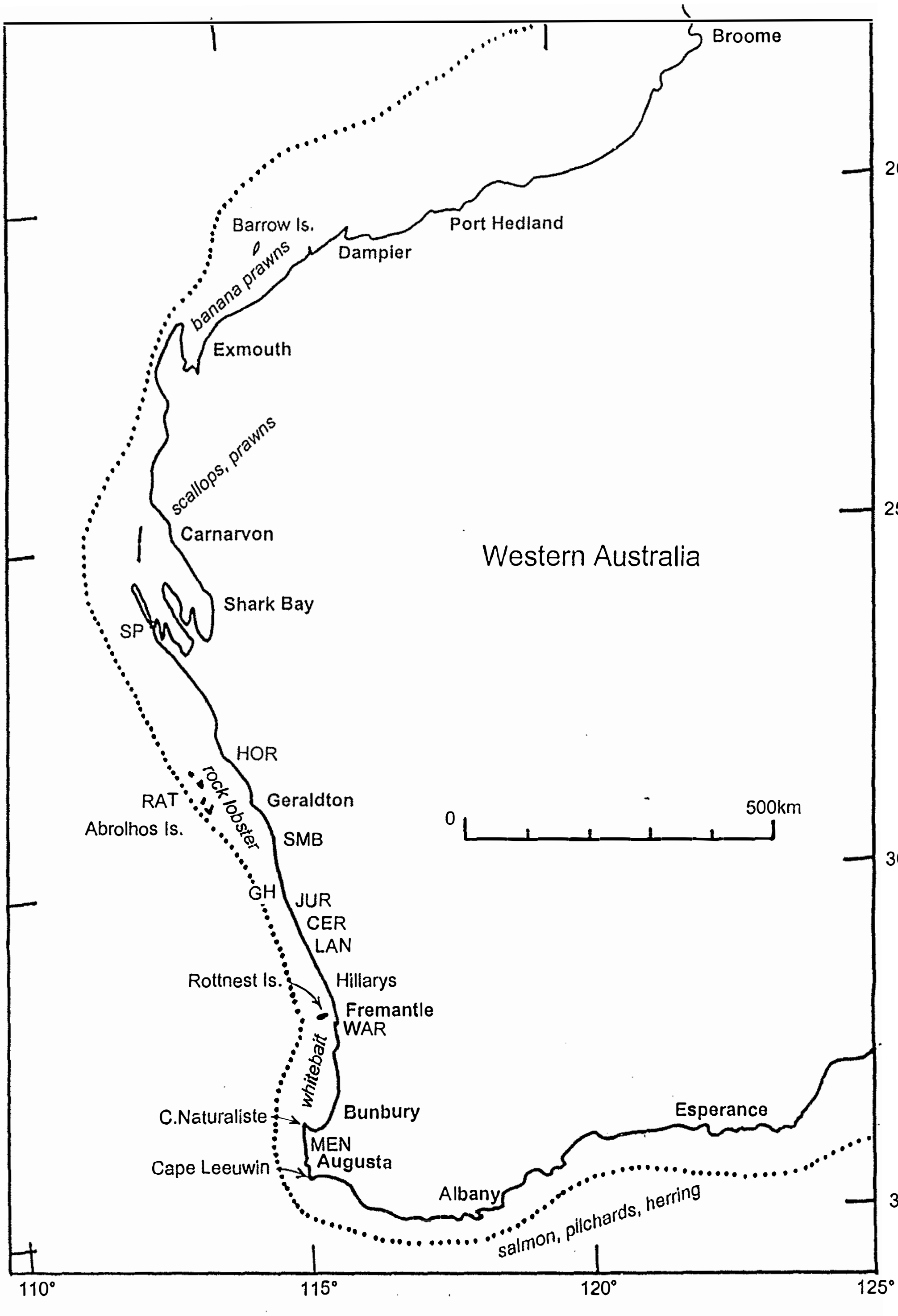
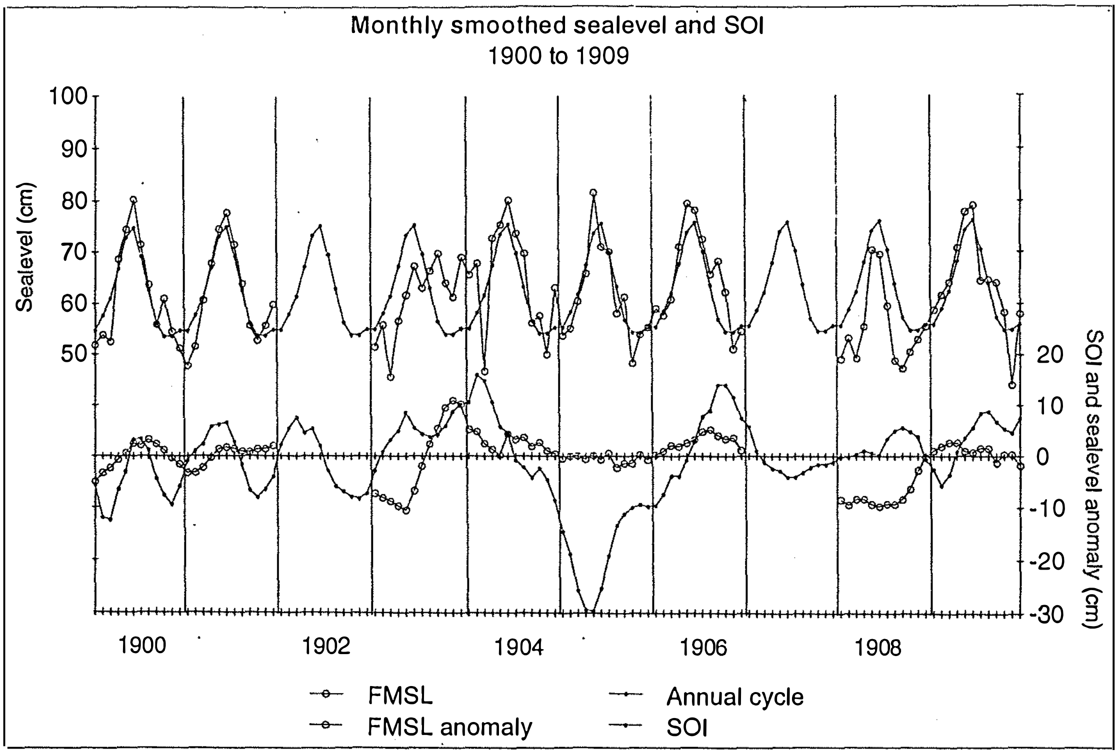


Figure 1.2: Map showing the locations of the major fisheries discussed in this report and the sites where environmental data have been collected. The puerulus collector sites are abbreviated as SP South Passage, HOR Horrocks Beach, RAT Rat Island (Houtman Abrolhos Islands), SMB Seven-Mile Beach (Dongara), GH Green Head (offshore temperature logger site), JUR Jurien Bay, CER Cervantes, LAN Lancelin, WAR Warnbro Sound, MEN Cape Mentelle.



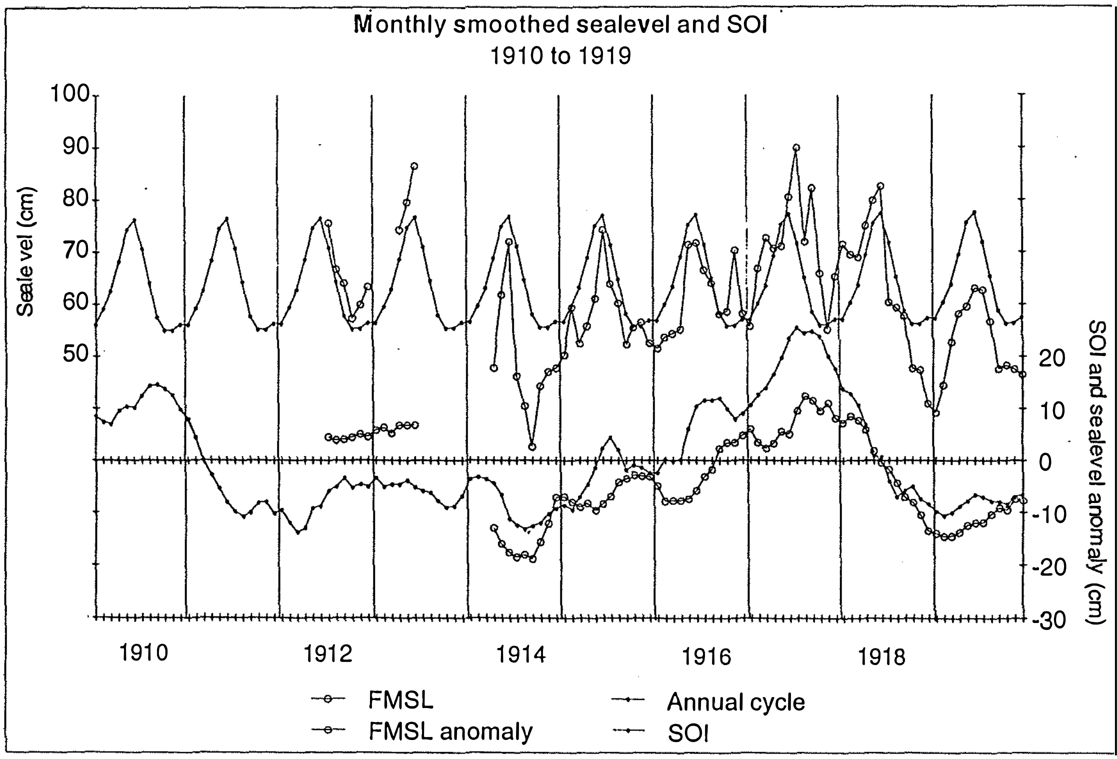
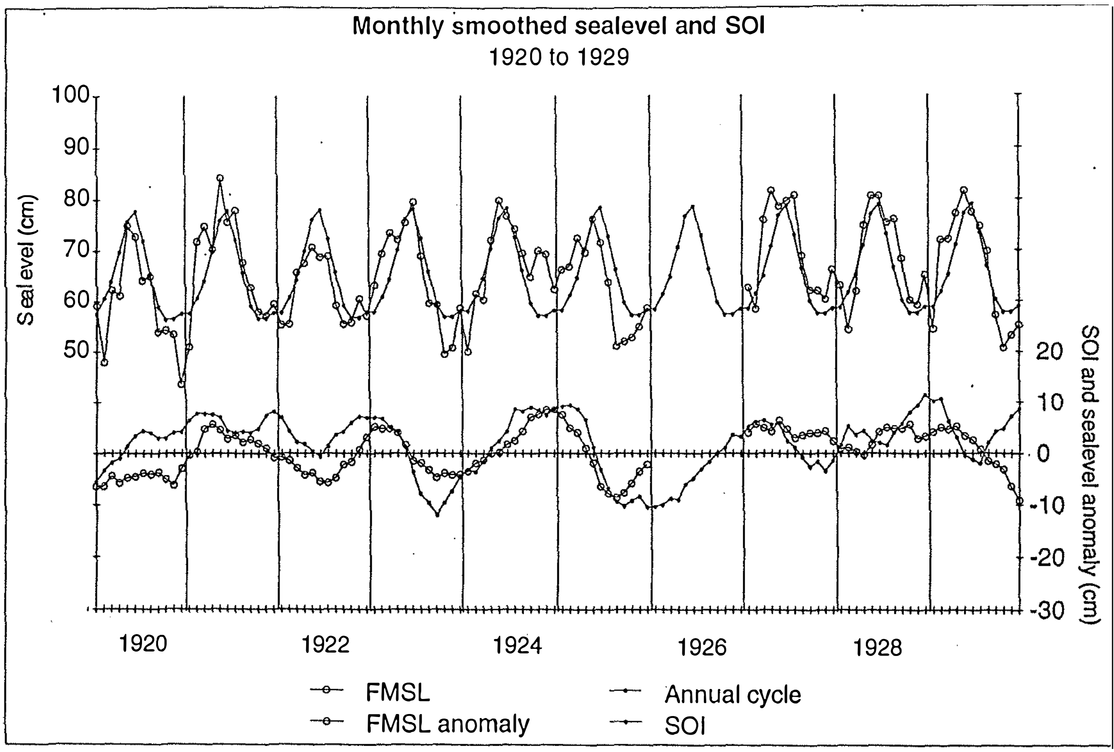
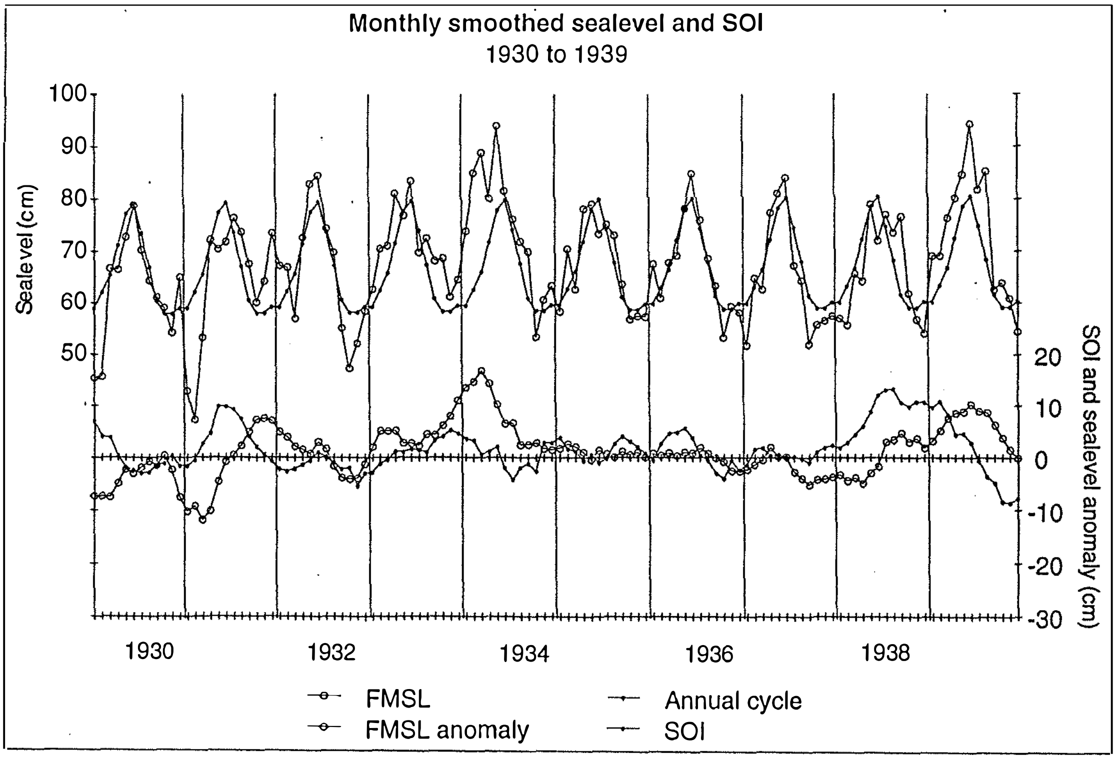
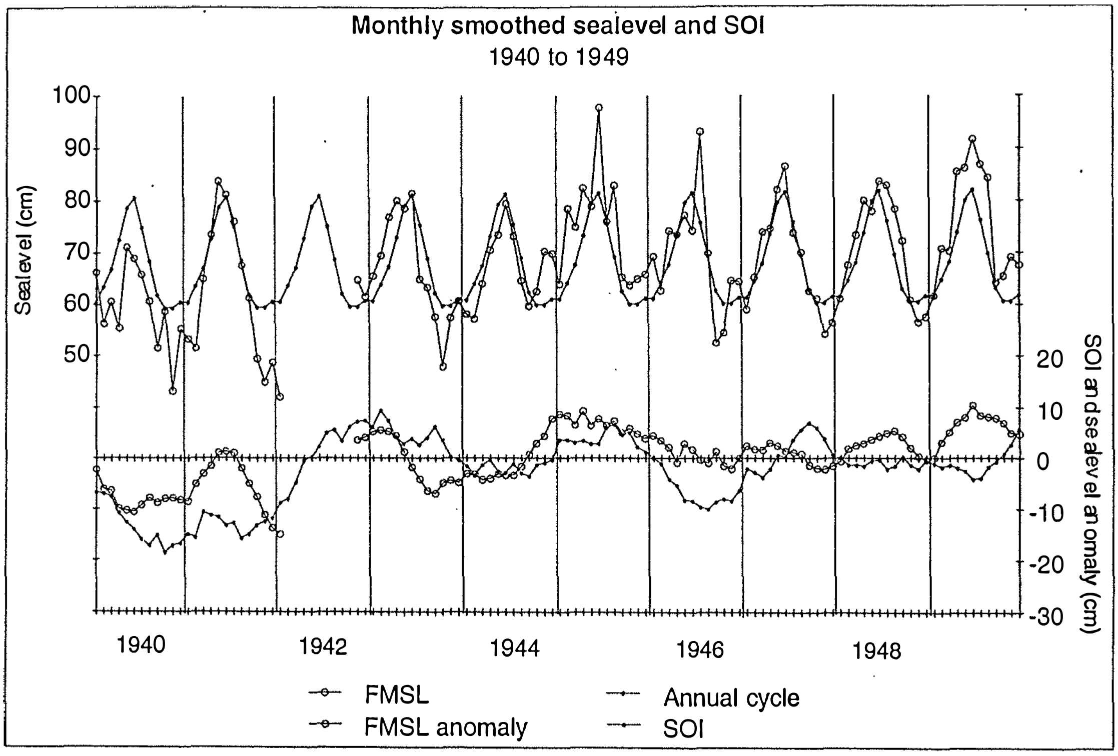
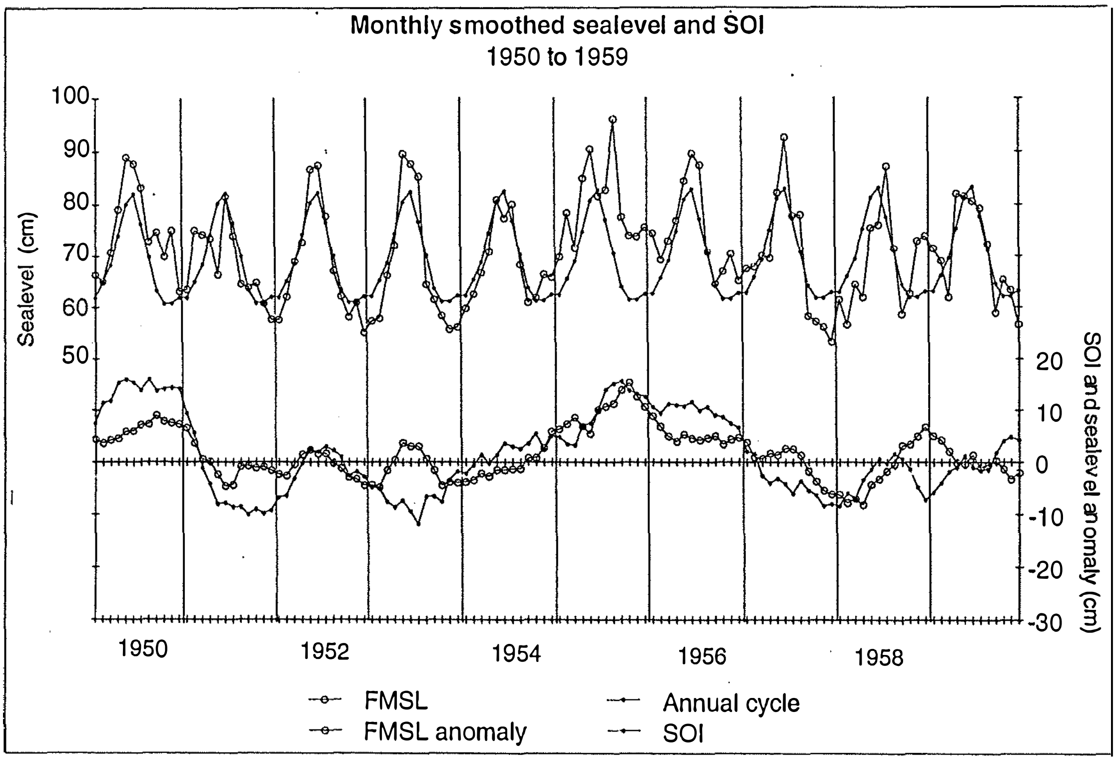


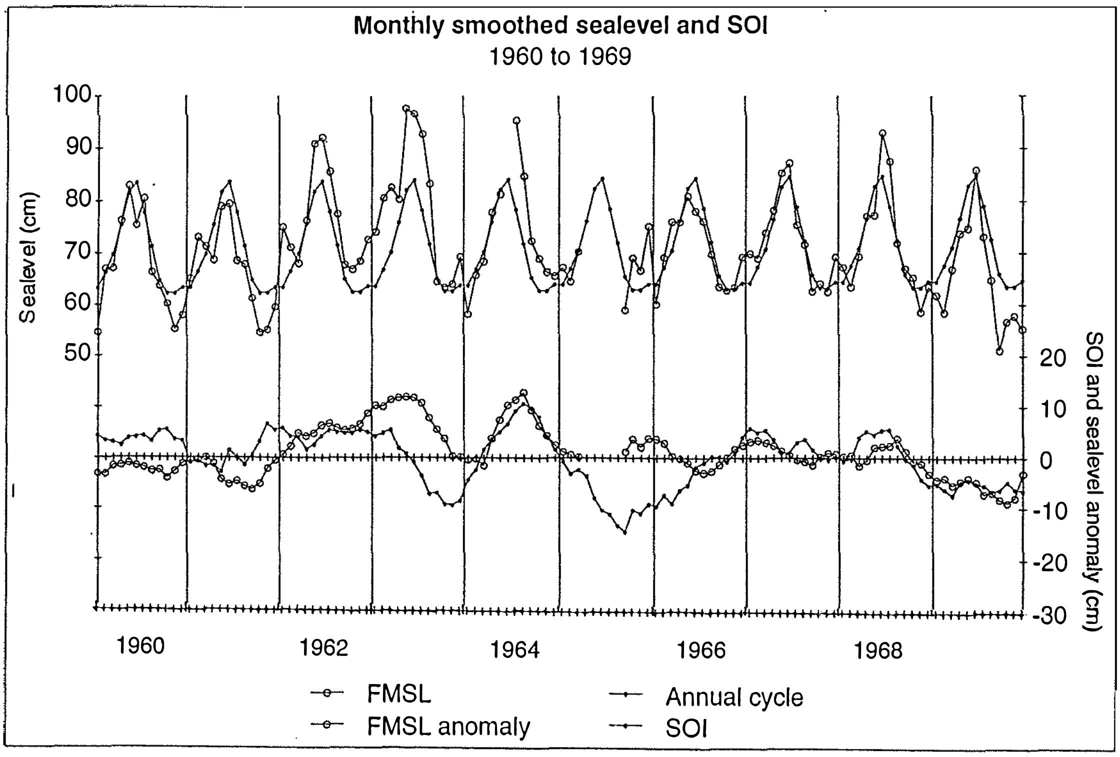
Figure 1.3: Upper panel of each decadal plot: Monthly mean values of Fremantle sea level (open circles) compared with the long-term mean annual cycle including the long-term increasing trend (dots). Lower panel: 5-month smoothed sea level anomaly (difference between the individual monthly sea level and the mean cycle -- open circles) and the 5-month smoothed Southern Oscillation Index (SOI - dots). ENSO episodes are indicated by negative SOI values. There were sealevel data gaps in 1902, 1907, 1910-13, 1926 and 1942.

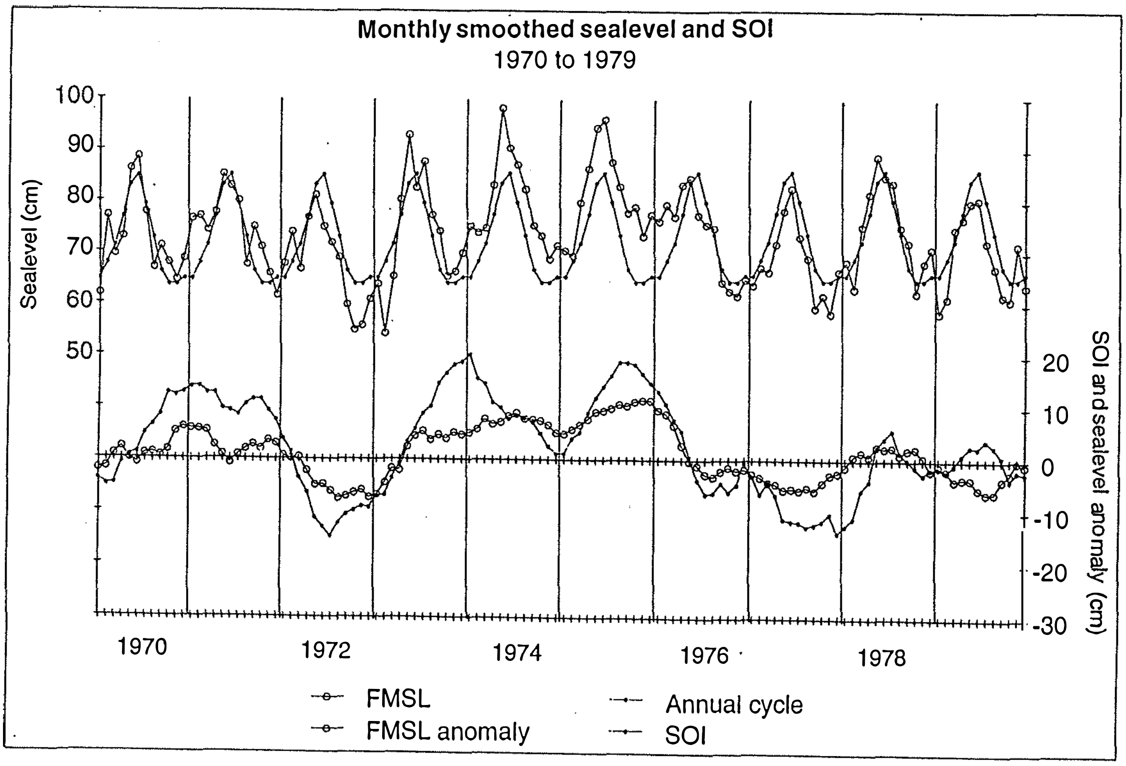

Monthly smoothed sealevel and SOI
1920 to 1929
Sealevel (cm)
SOI and sealevel anomaly (cm)
100
90
80
70
60
50
20
10
0
-10
-20
-30
1920
1922
1924
1926
1928
FMSL
FMSL anomaly
Annual cycle
SOI

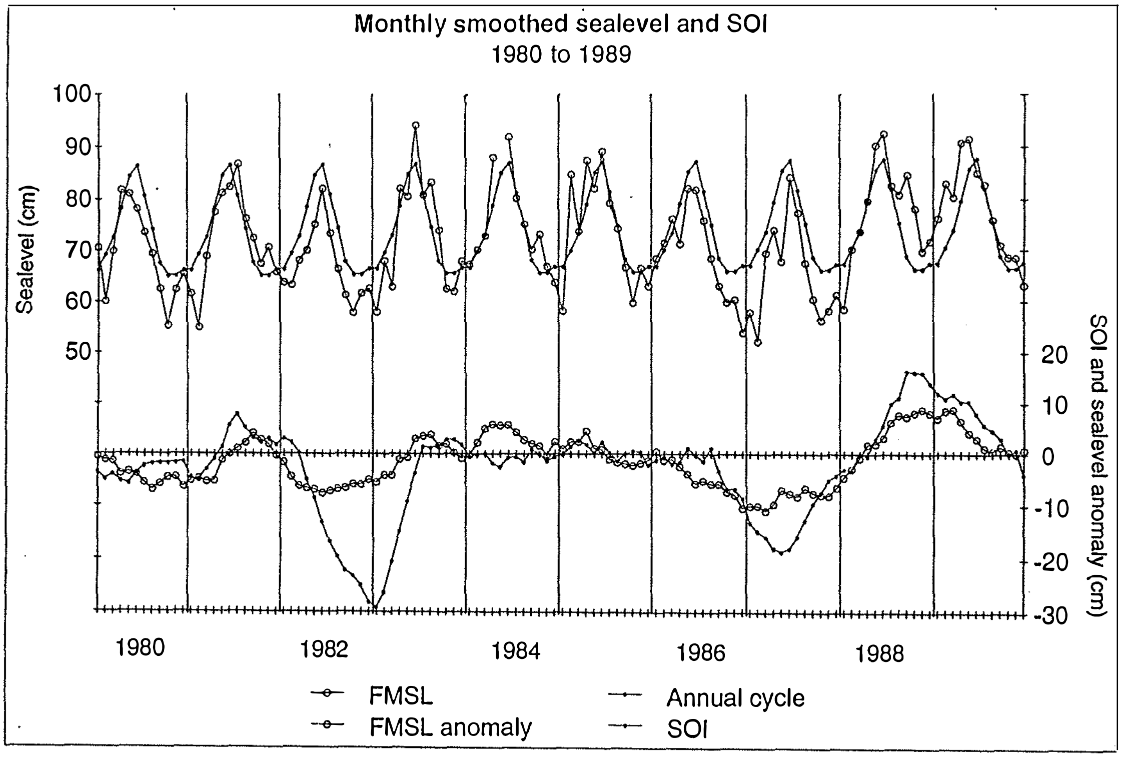

Monthly smoothed sealevel and SOI
1930 to 1939
Sealevel (cm)
SOI and sealevel anomaly (cm)
100
90
80
70
60
50
20
10
0
-10
-20
-30
1930
1932
1934
1936
1938
FMSL
FMSL anomaly
Annual cycle
SOI

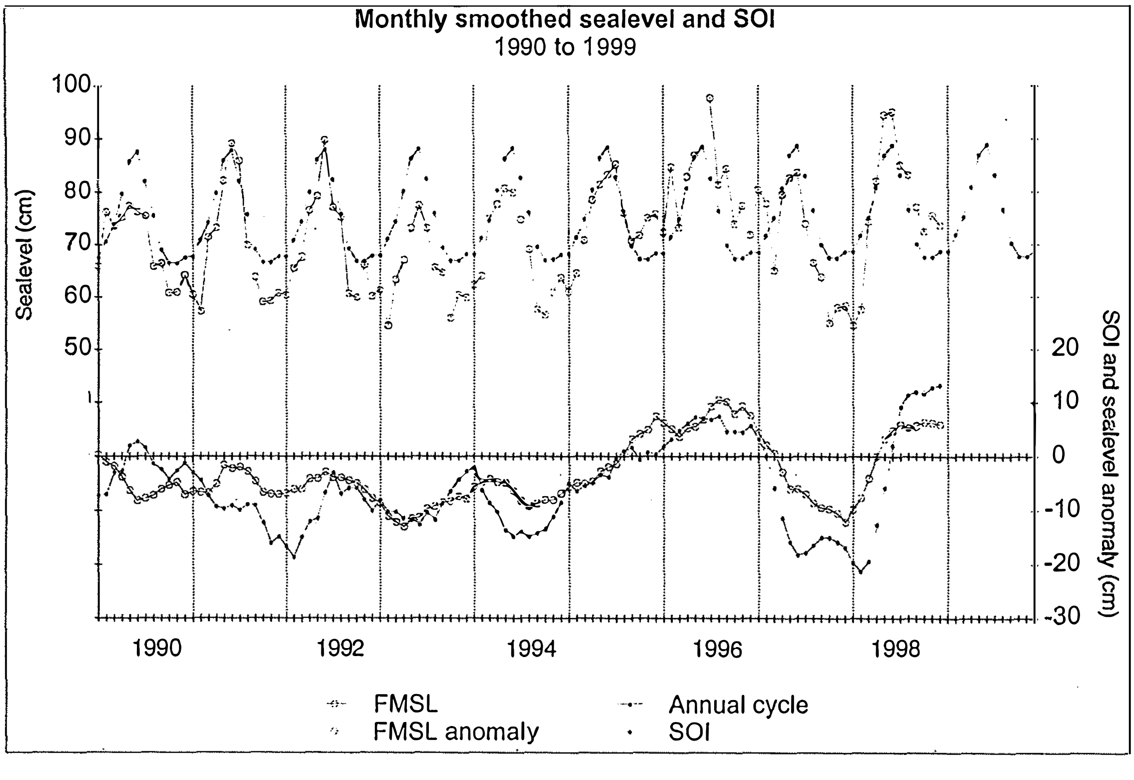

Monthly smoothed sealevel and SOI
1940 to 1949
Sealevel (cm)
100
90
80
70
60
50
SOI and sealevel anomaly (cm)
20
10
0
-10
-20
-30
1940
1942
1944
1946
1948
FMSL
FMSL anomaly
Annual cycle
SOI

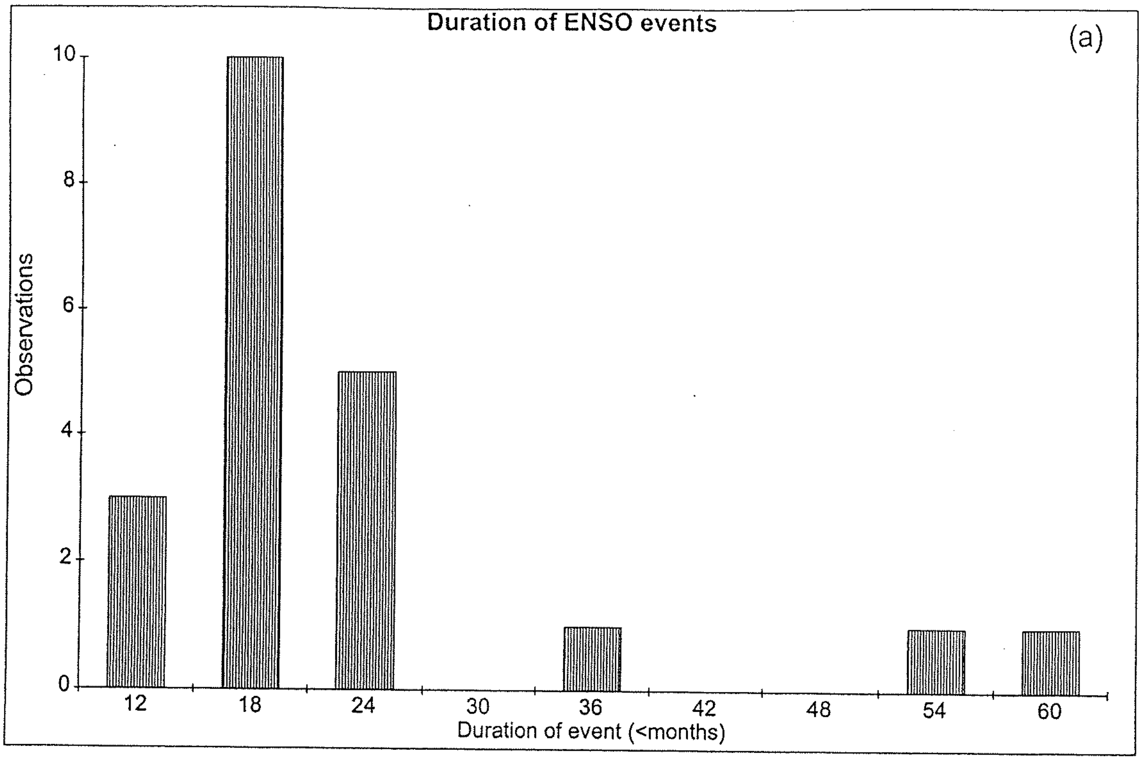

Monthly smoothed sealevel and SOI
1950 to 1959
Sealevel (cm)
100
90
80
70
60
50
SOI and sealevel anomaly (cm)
20
10
0
-10
-20
-30
1950
1952
1954
1956
1958
FMSL
FMSL anomaly
Annual cycle
SOI


Monthly smoothed sealevel and SOI
1960 to 1969
Sealevel (cm)
100
90
80
70
60
50
SOI and sealevel anomaly (cm)
20
10
0
-10
-20
-30
1960
1962
1964
1966
1968
FMSL
FMSL anomaly
Annual cycle
SOI


Monthly smoothed sealevel and SOI
1970 to 1979
Sealevel (cm)
100
90
80
70
60
50
SOI and sealevel anomaly (cm)
20
10
0
-10
-20
-30
1970
1972
1974
1976
1978
FMSL
FMSL anomaly
Annual cycle
SOI


Monthly smoothed sealevel and SOI
1980 to 1989
Sealevel (cm)
100
90
80
70
60
50
SOI and sealevel anomaly (cm)
20
10
0
-10
-20
-30
1980
1982
1984
1986
1988
FMSL
FMSL anomaly
Annual cycle
SOI


Monthly smoothed sealevel and SOI
1990 to 1999
Sealevel (cm)
100
90
80
70
60
50
SOI and sealevel anomaly (cm)
20
10
0
-10
-20
-30
1990
1992
1994
1996
1998
FMSL
FMSL anomaly
Annual cycle
SOI



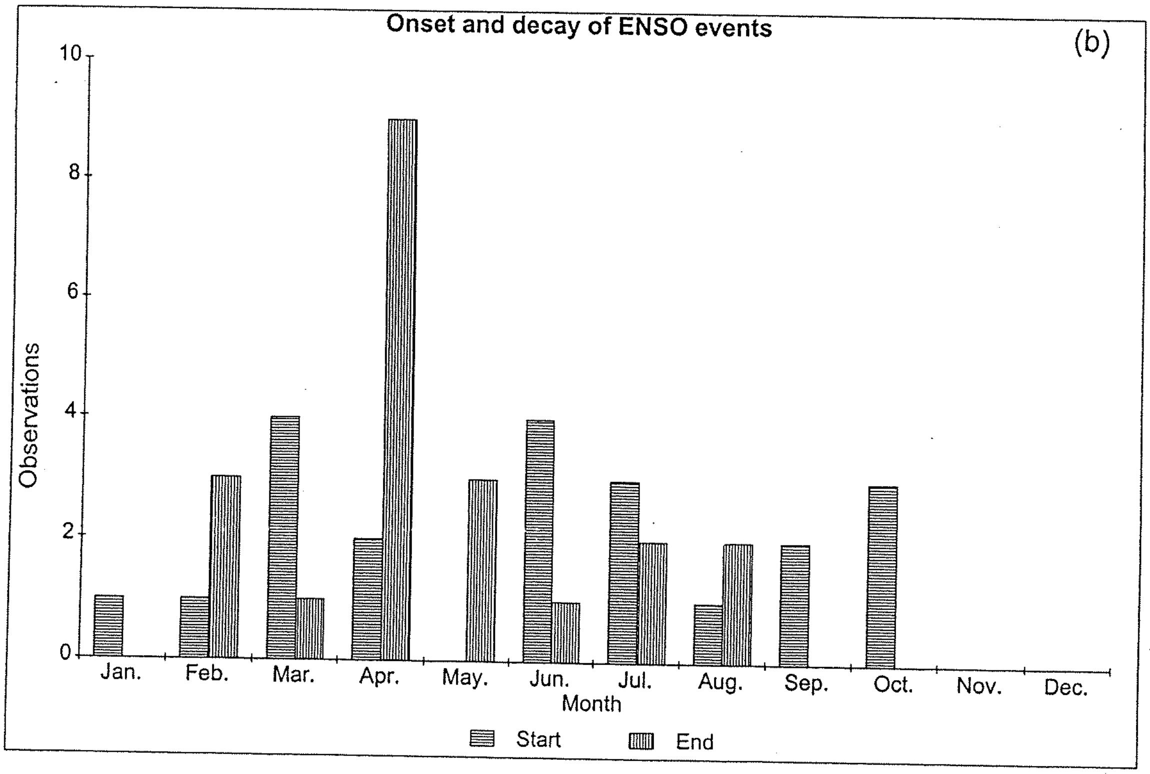
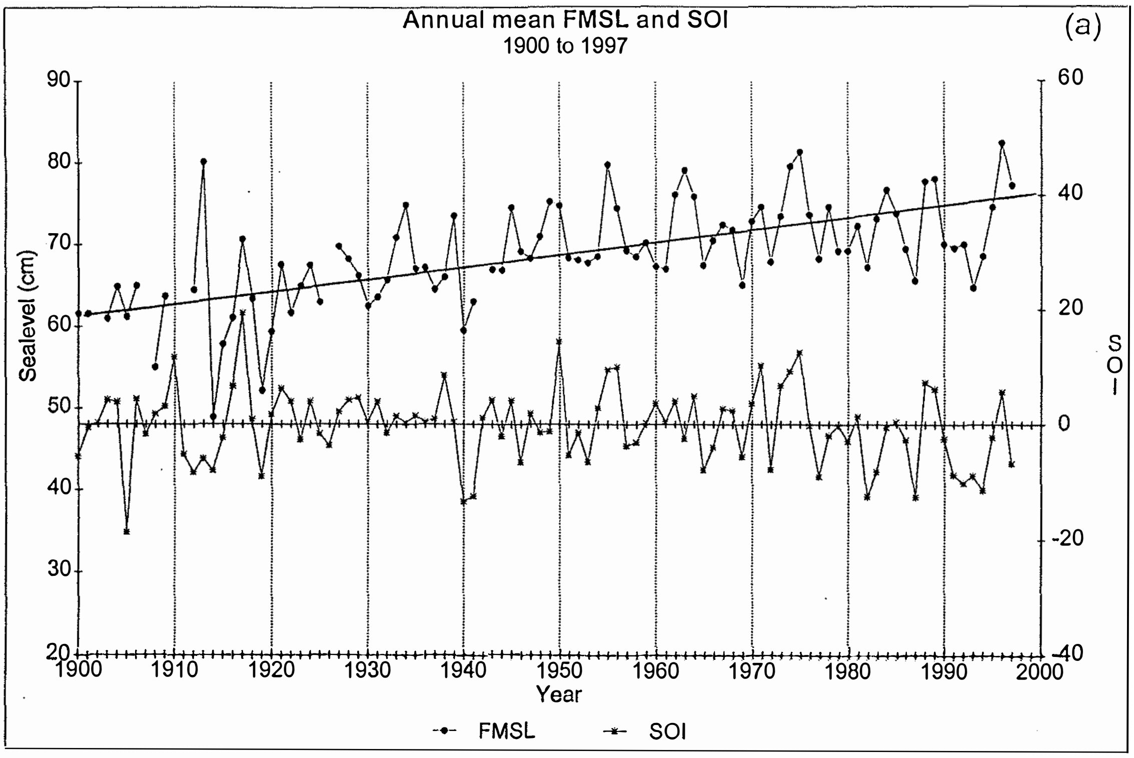


Figure 1.4: (a) Bar chart of the duration of the ENSO events between 1900 and the present. The bar at 18 months, for example, represents events with durations of 13 to 18 months, from Table 1.6. (b) Bar-chart of the frequency of the months in which an ENSO commenced (horizontal shading) and ended (vertical shading).



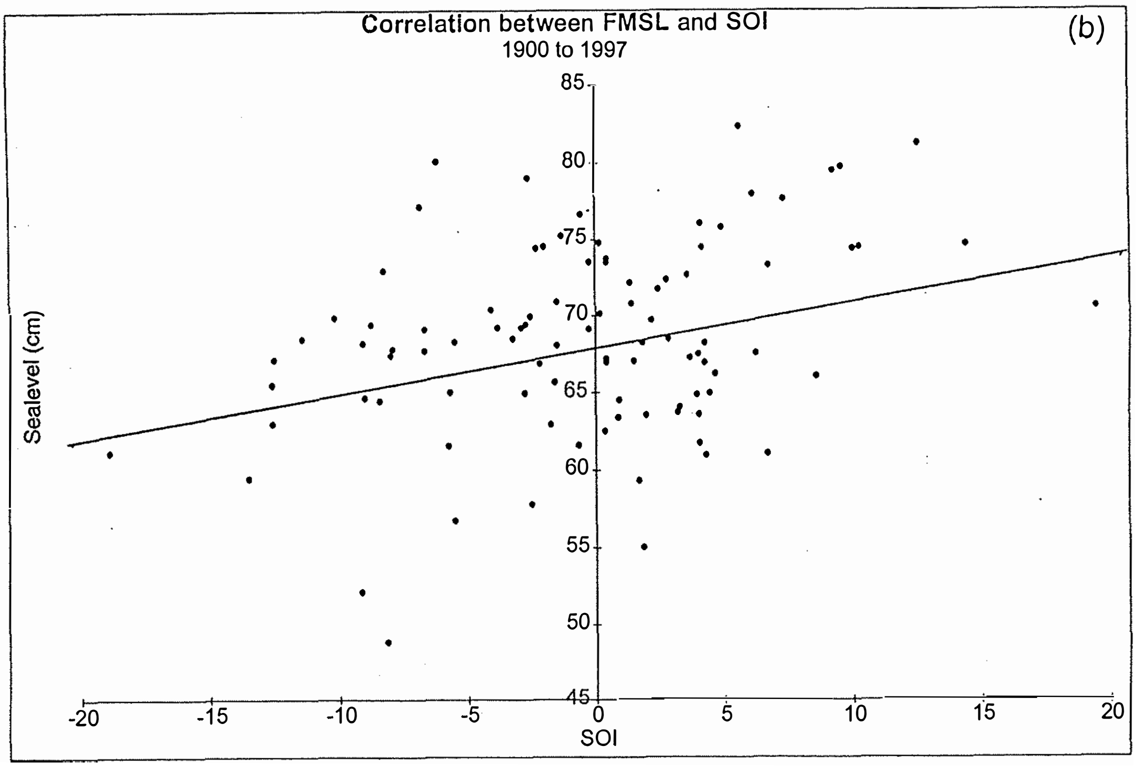
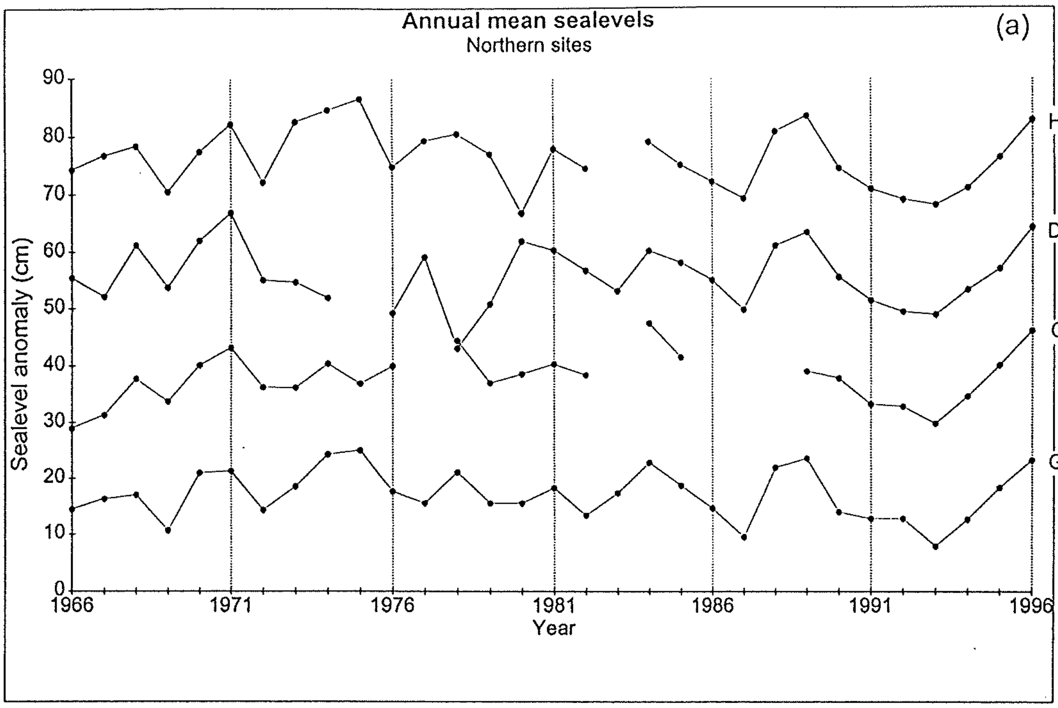


Figure 1.5: (a) Annual mean sea level at Fremantle (upper line with circles) and annual SOI (lower line with asterisks) between 1900 and 1997. The trend line in sea level discussed in the text has been inserted. (b) Scatter-plot of annual mean sea level at Fremantle and annual SOI, with the regression line indicated.



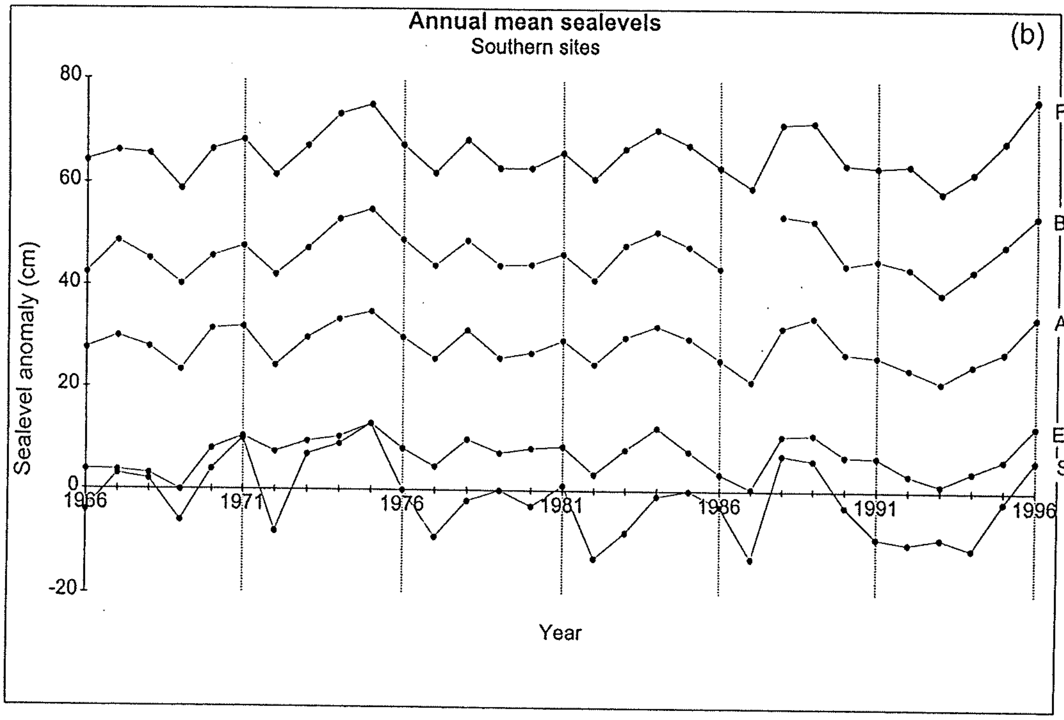
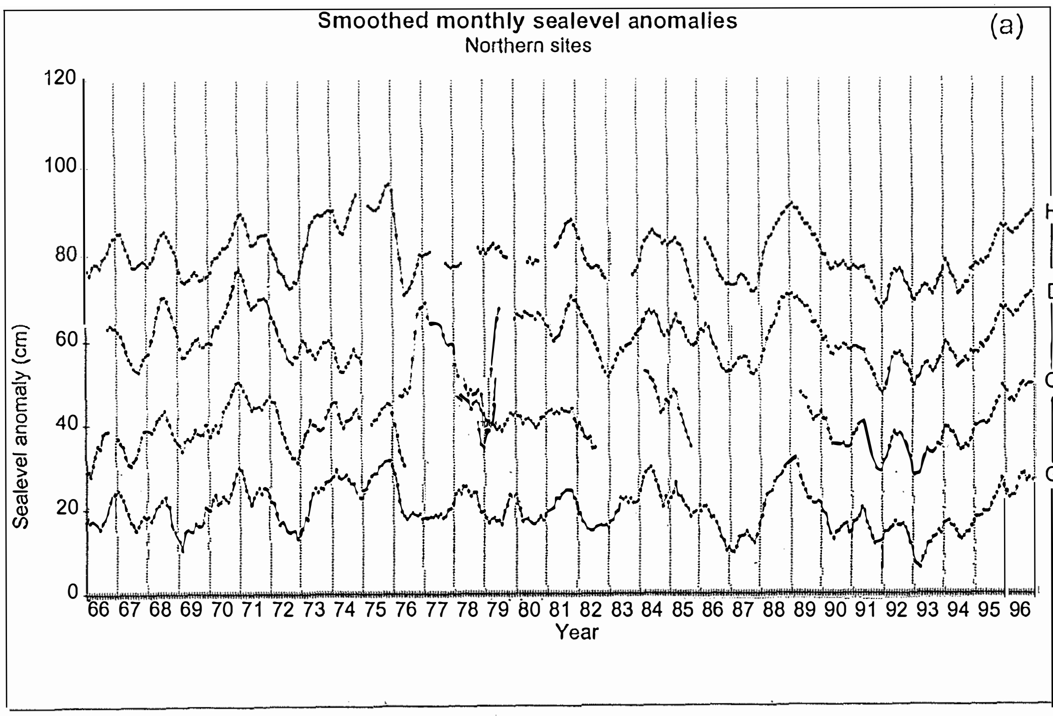


Figure 1.6: Annual mean sea levels for the period 1966 to 1996 at 8 ports along the Western Australian coast between Port Hedland and Esperance, offset to avoid clutter. The sites are (a, top to bottom) Port Hedland HED, Dampier DAM, Carnarvon CAR, Geraldton GER, and (b) Fremantle FRE, Bunbury BUN, Albany ALB and Esperance ESP, with the SOI the lowest graph.



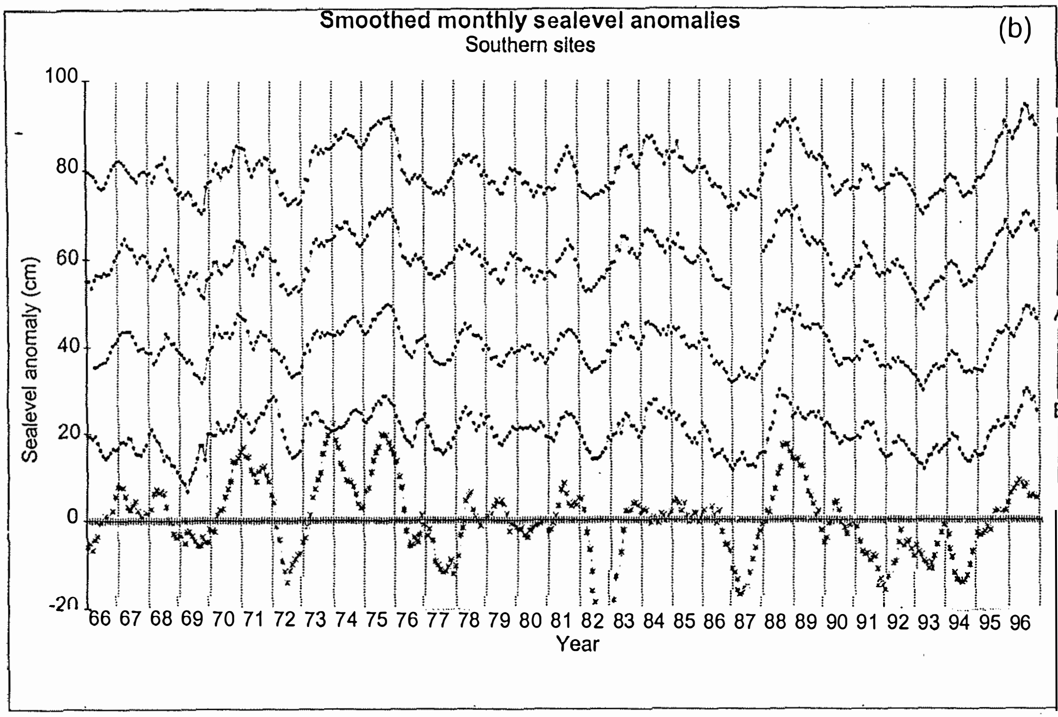


Figure 1.7: 5-month smoothed monthly mean sea level anomalies for the period 1966 to 1996 at 8 ports between Port Hedland and Esperance, as well as the SOI. The anomalies have been computed by subtracting the annual cycles at each port, and the curves have been offset to avoid clutter. The sites are as in Figure 1.6.

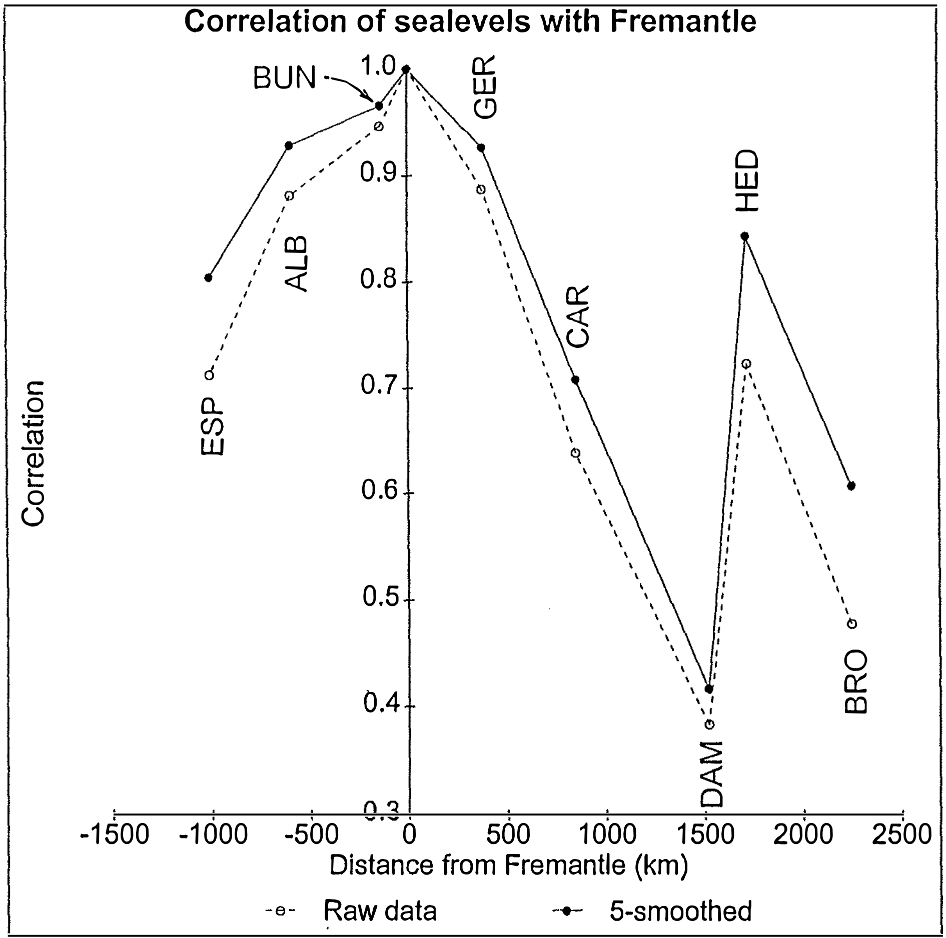
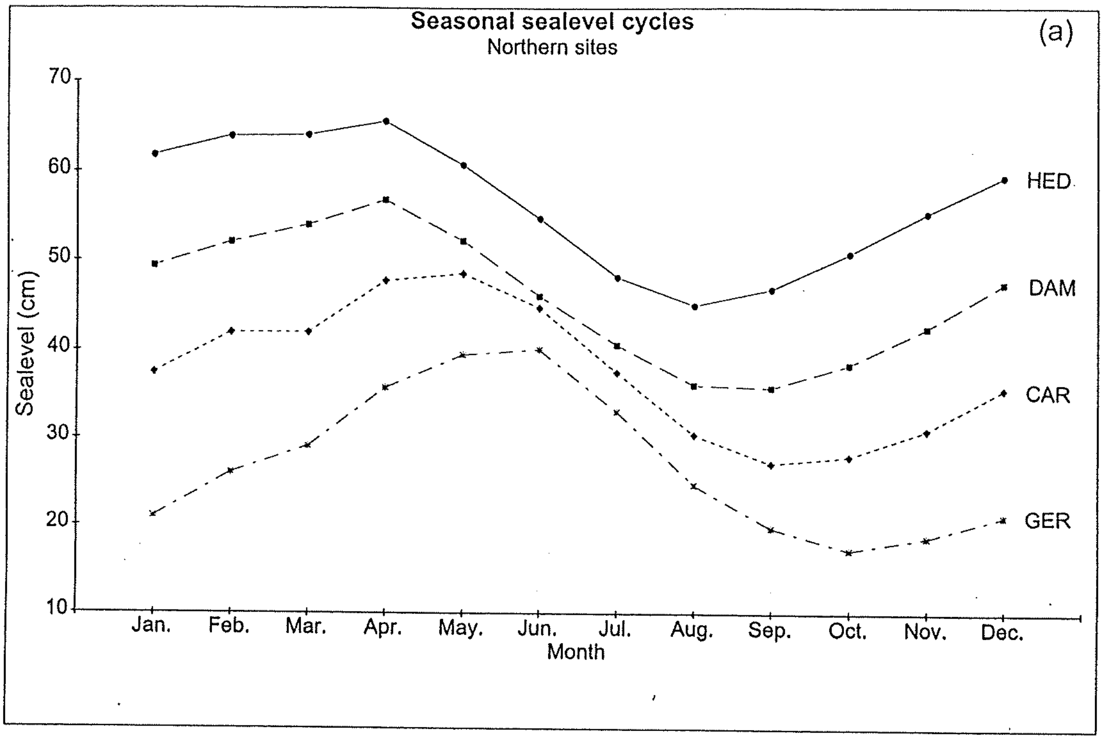


Figure 1.8: Correlation coefficient of monthly sea level anomalies (with the 5-month smoothed data in dashed lines) relative to sea level at Fremantle, as a function of distance from Fremantle (from Table 1.8). The sites are as in Figure 1.6, with the addition of Broome BRO.



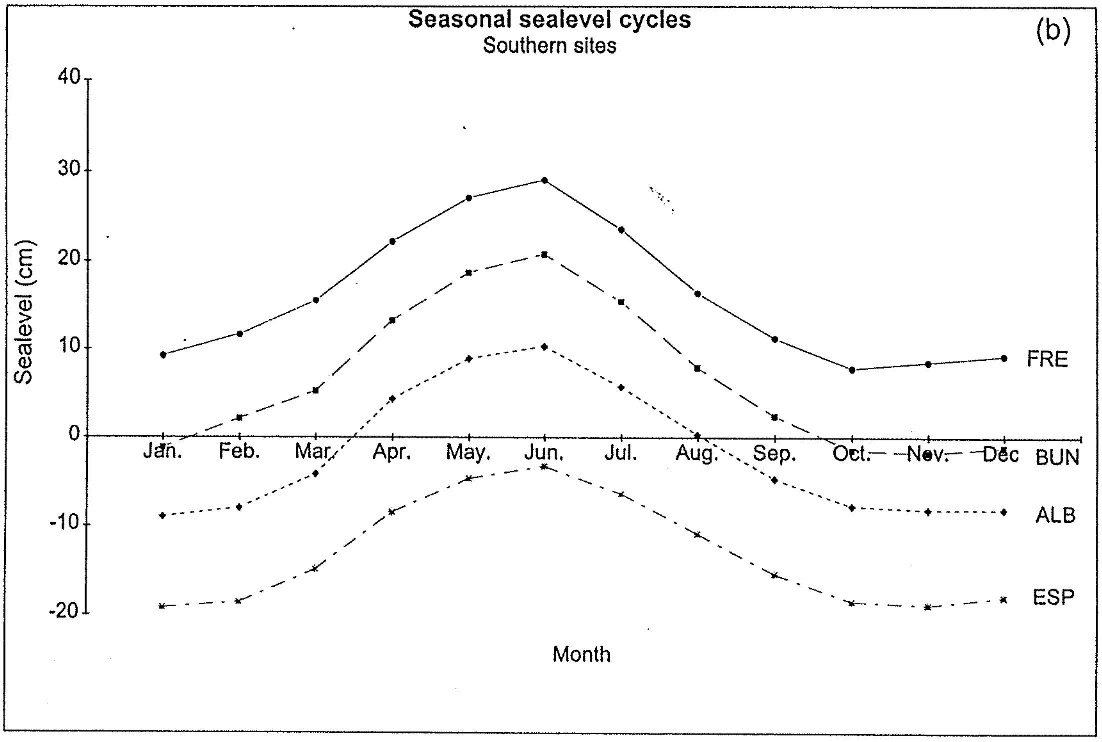


Figure 1.9: Annual sea level cycles along the west coast, offset to avoid clutter. The sites are as in Figure 1.6.

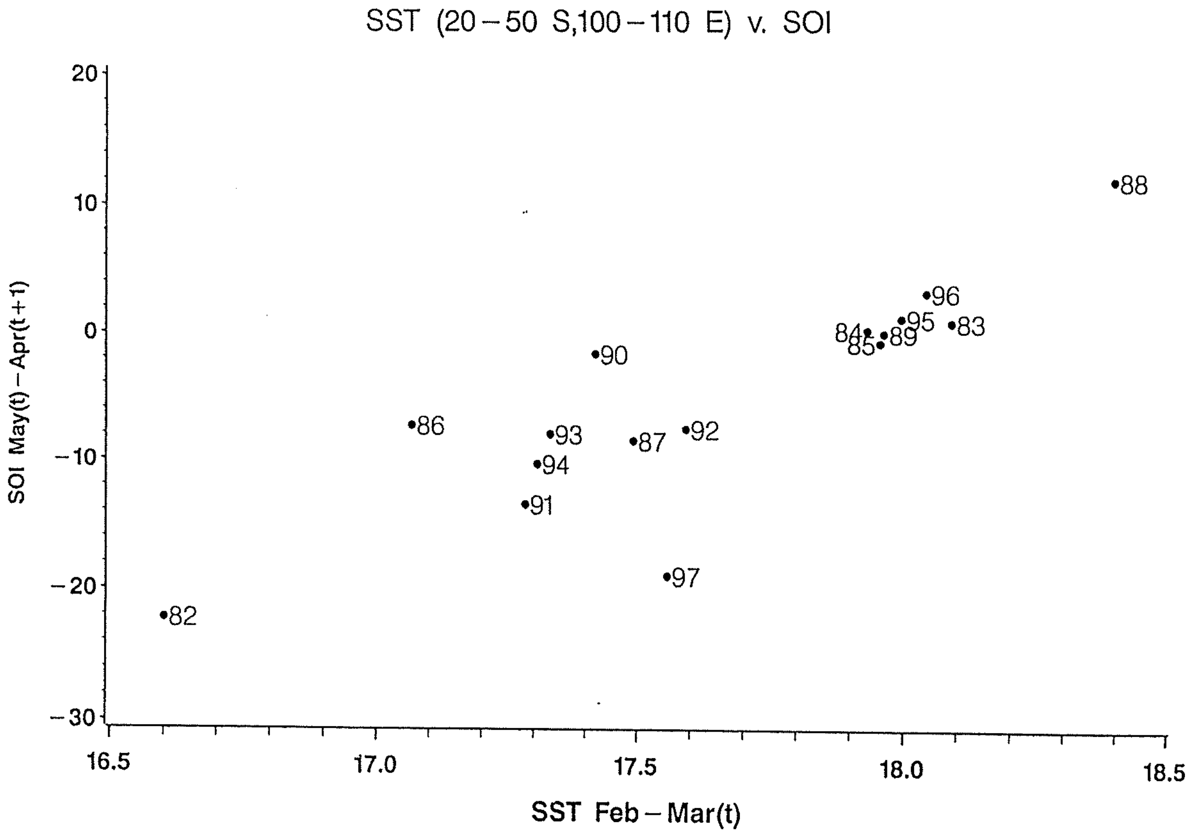
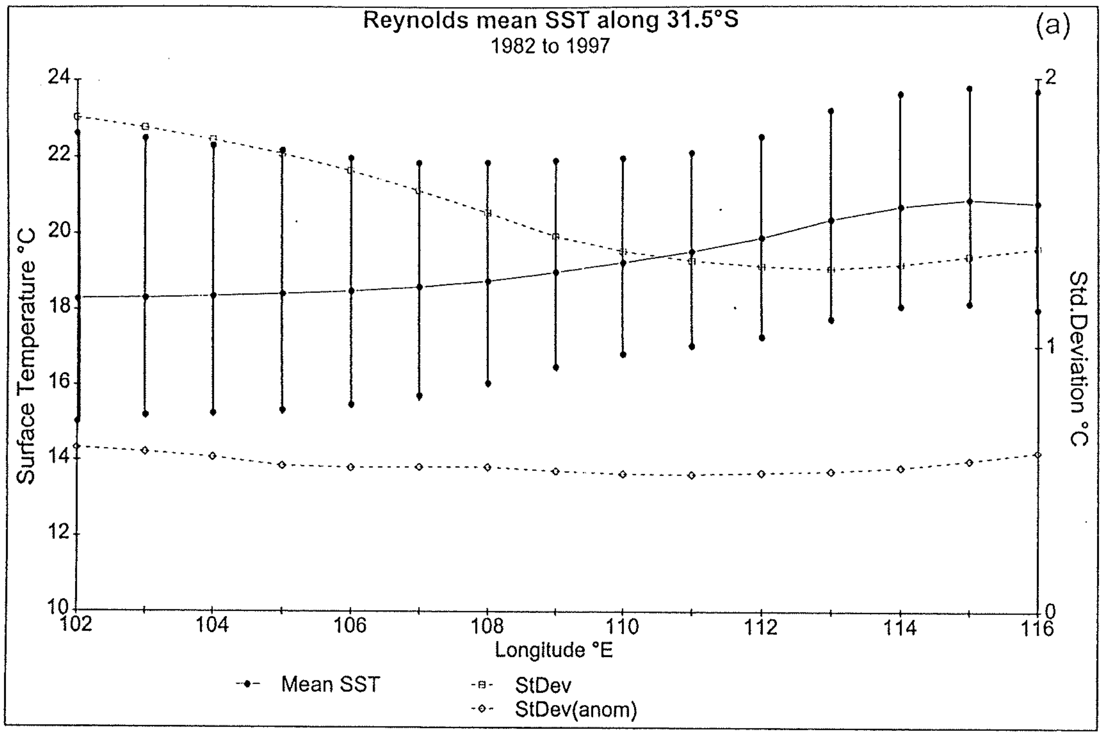


Figure 1.10: Scatter-plot of the Southern Oscillation Index SOI for May of one year (t) to April of the next (t+1), against the Reynolds sea-surface temperature SST for February/March of the first year (t), over the geographic block 20° to 50°S, 100° to 110°E,. The numbers indicate the years (*e.g.* 87 represents 1987). The correlation coefficient is 0.93, which is significant at the 1% level. After Caputi and Pearce (in prep.).



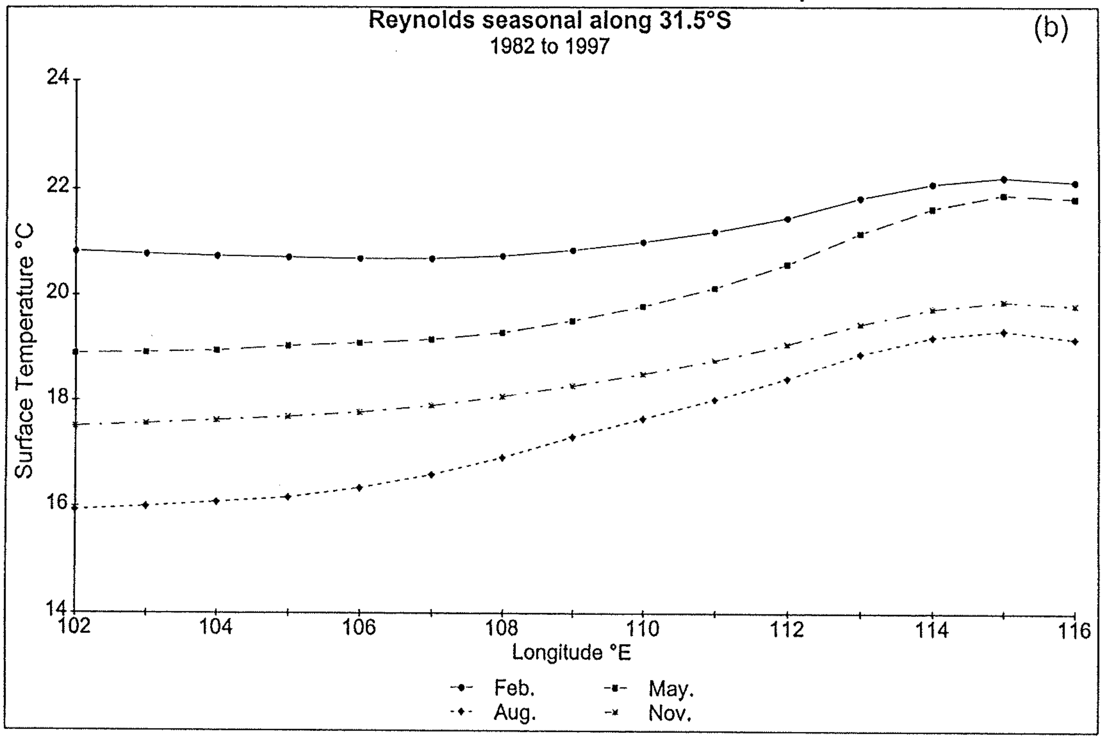
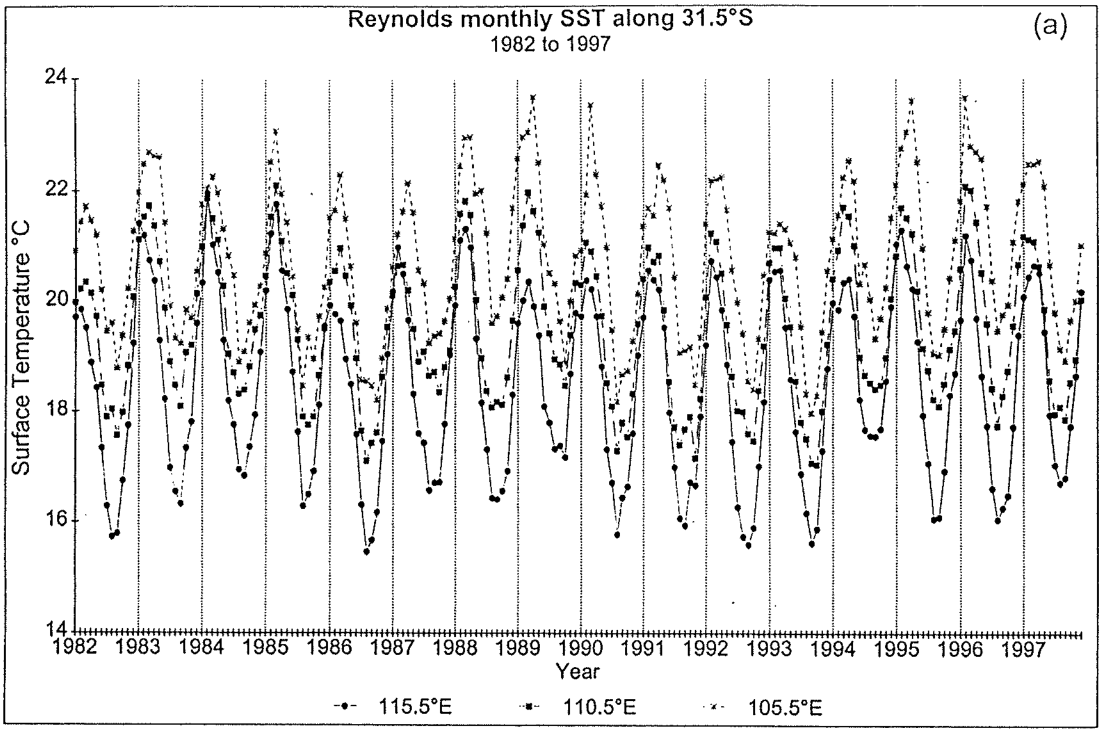


Figure 1.11: (a) Overall mean SST transect along latitude band 31° to 32°S (off Perth) between 102°E and the Western Australian coast from the Reynolds SST dataset 1982 to 1997. The mean is the solid line with filled circles, the vertical bars representing the overall monthly minimum and maximum over the 16-year period. The open squares are the standard deviations (right axis), and the open diamonds are the standard deviations of the anomalies, after the mean seasonal cycle has been removed. (b) Seasonal SST transects along the same latitude band in February (filled circles, representing summer), May (squares, autumn), August (diamonds, winter) and November (asterisks, spring).



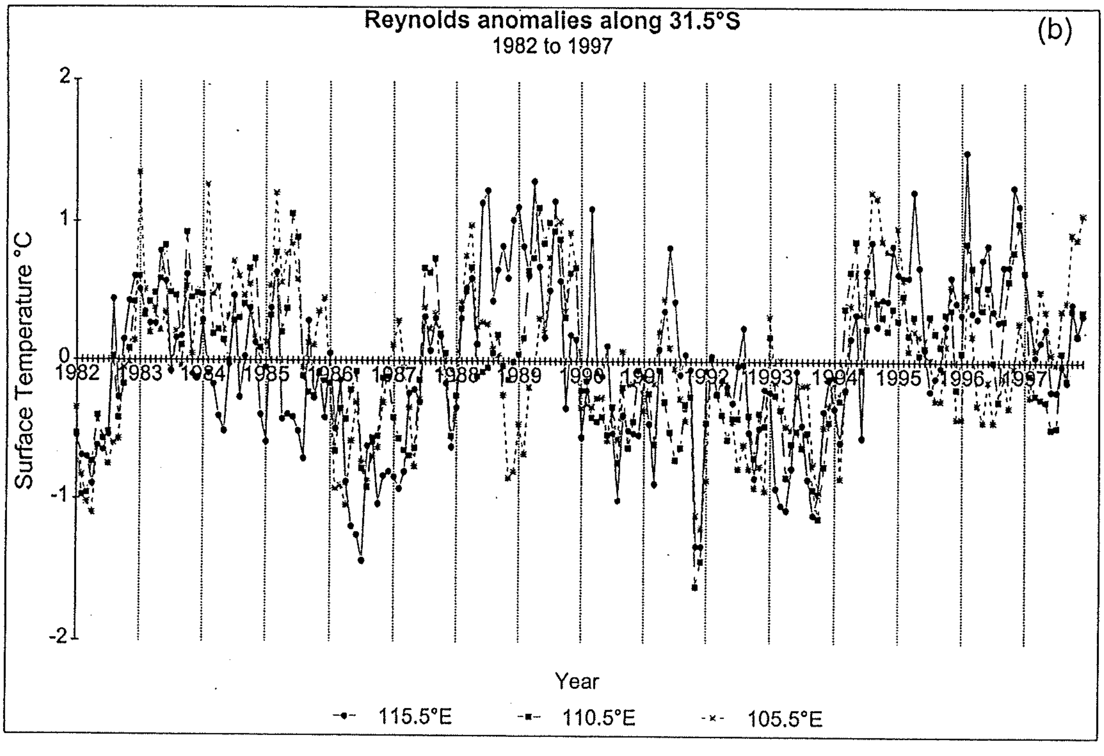
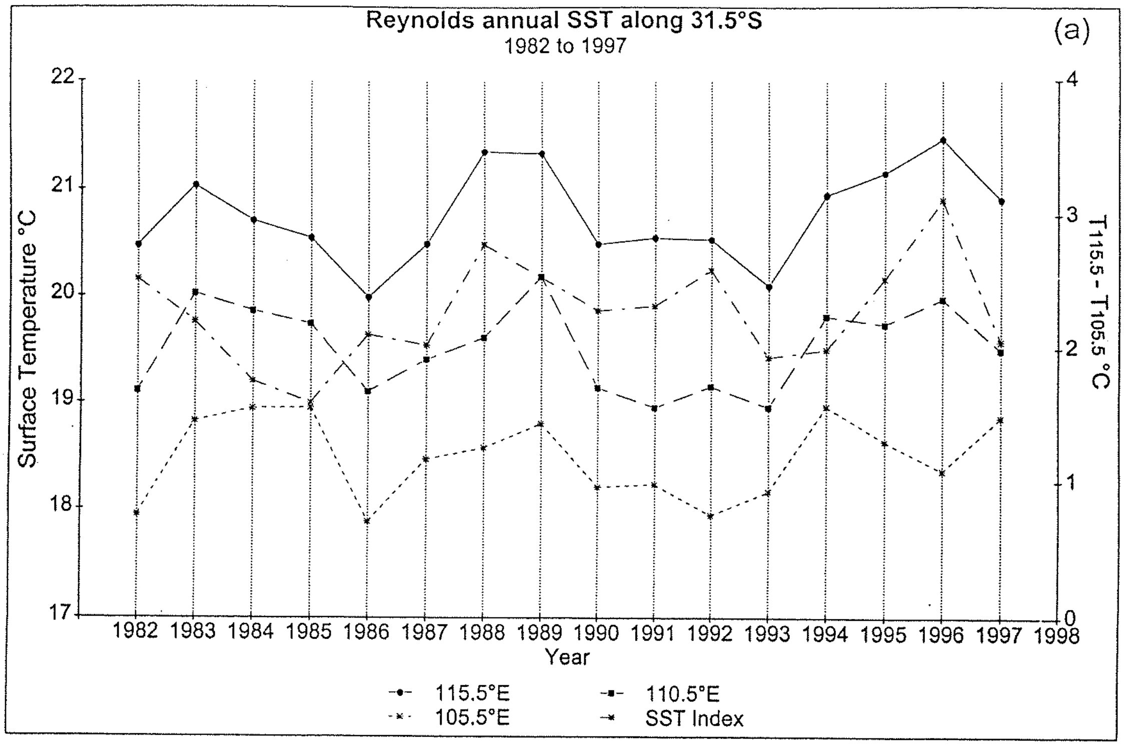


Figure 1.12: (a) Monthly mean SSTs at three longitudes along latitude band 31° to 32°S off Perth over the period 1982 to 1997 derived from the monthly Reynolds SST dataset; longitude 115.5°E (circles) represents the coastal block. (b) Monthly anomalies from the seasonal cycle at the three longitudes.



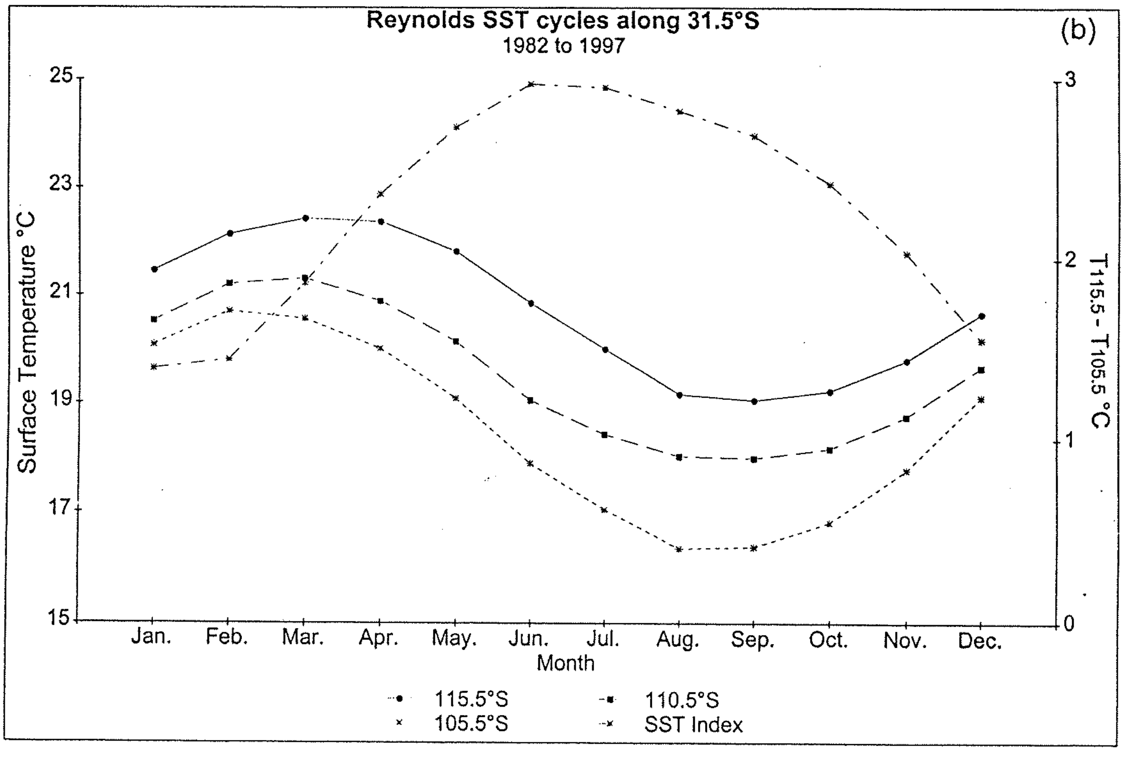


Figure 1.13: (a) Annual mean SSTs at three longitudes along latitude band 31° to 32°S (off Perth) over the period 1982 to 1997 derived from the monthly Reynolds SST dataset; longitude 115.5°E (circles) represents the coastal block. The dot-dashed line (lowest plot) is the SST gradient index calculated as the temperature difference between the coastal block and 105.5°E (asterisks). (b) Seasonal cycles of SST and the SST gradient index.

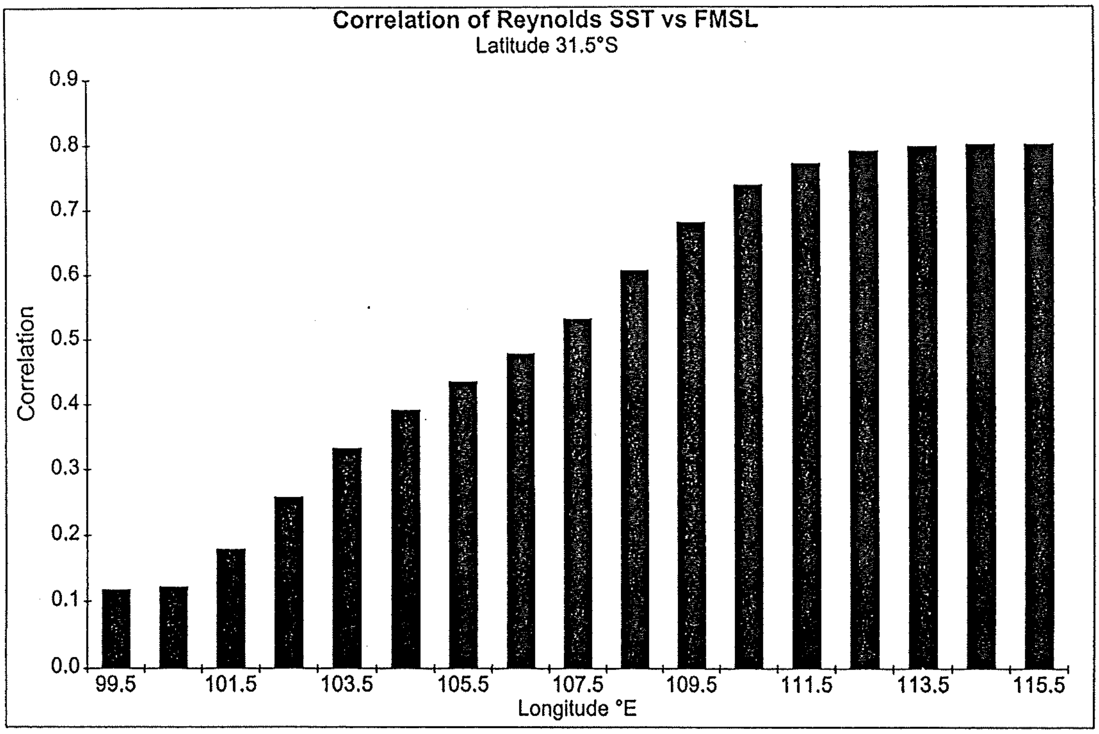
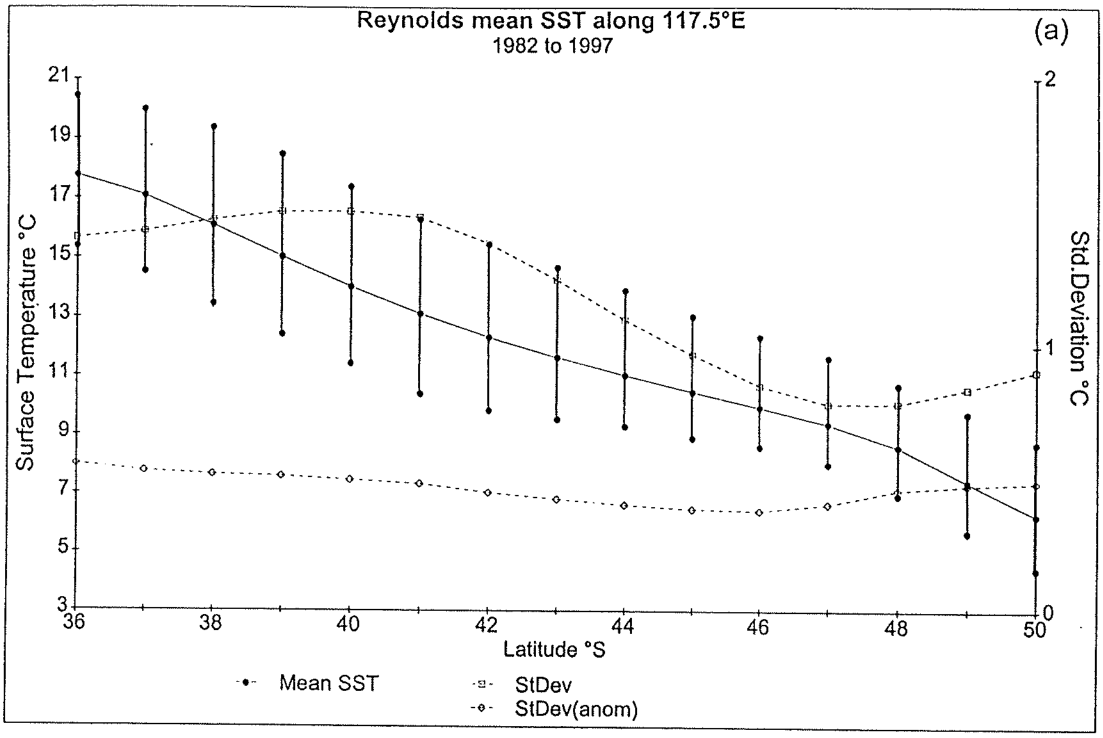


Figure 1.14: Correlation coefficient of annual Reynolds SSTs (from 99.5° to 115.5°E along latitude band 31° to 32°S, off Perth) with Fremantle sea level.



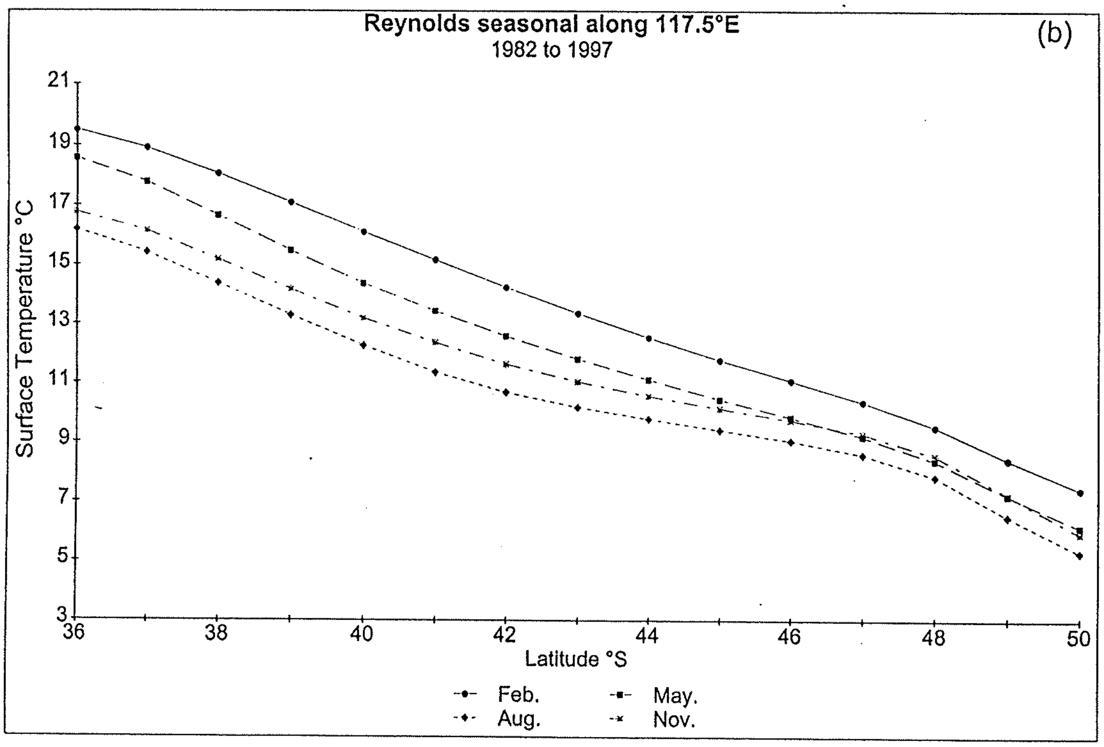
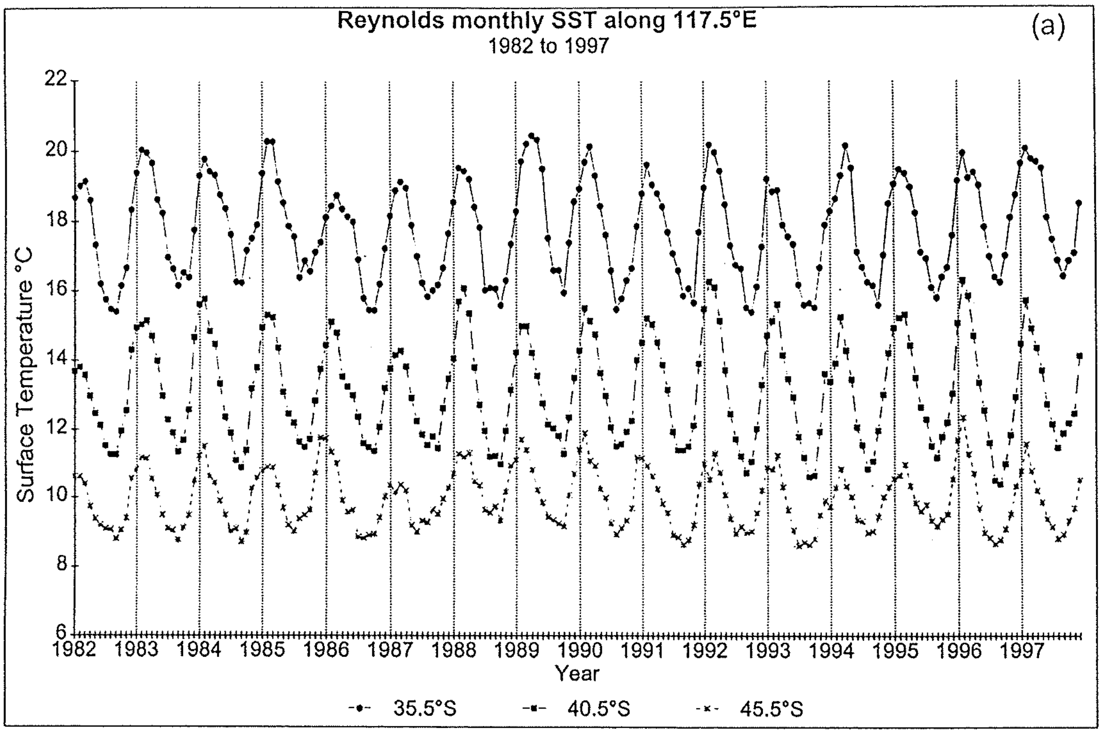


Figure 1.15: (a) Overall mean SST transect along longitude band 117° to 118°E (off Albany) between the Western Australian coast and 50°S from the Reynolds SST dataset 1982 to 1997. The mean is the solid line with filled circles, the vertical bars representing the overall monthly minimum and maximum over the 16-year period. The open squares are the standard deviations (right axis), and the open diamonds are the standard deviations of the anomalies after the mean seasonal cycle has been removed. (b) Seasonal SST transects along the same longitude band in February (circles, representing summer), May (squares, autumn), August (diamonds, winter) and November (asterisks, spring).



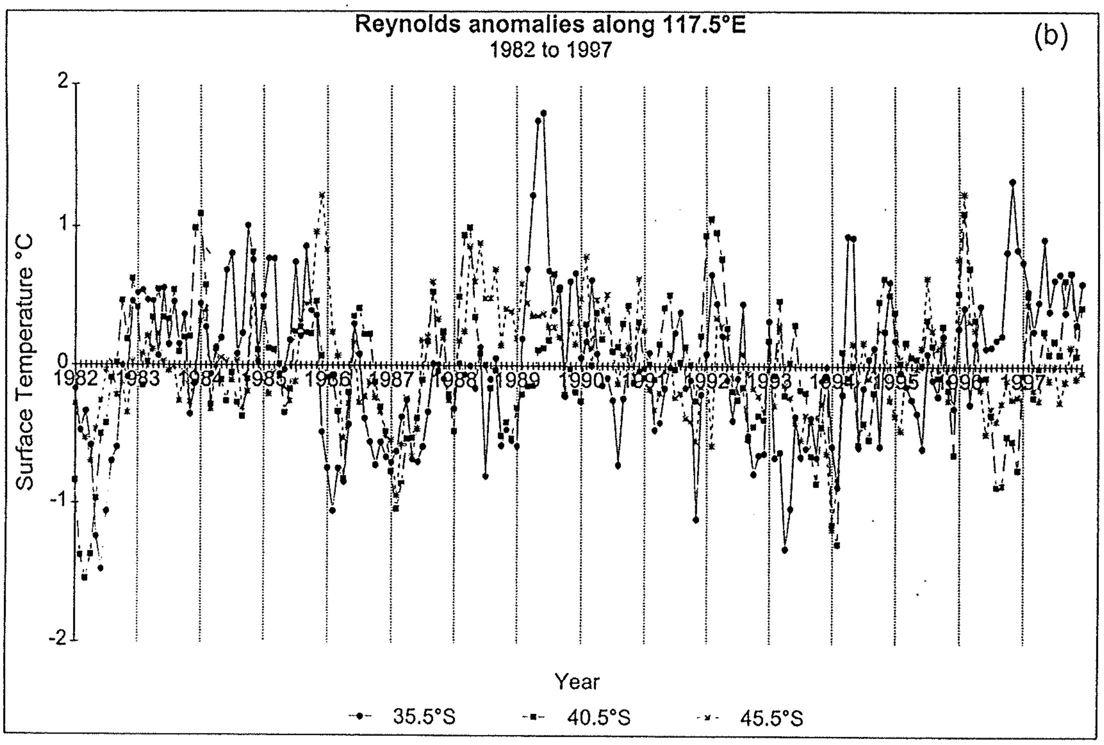
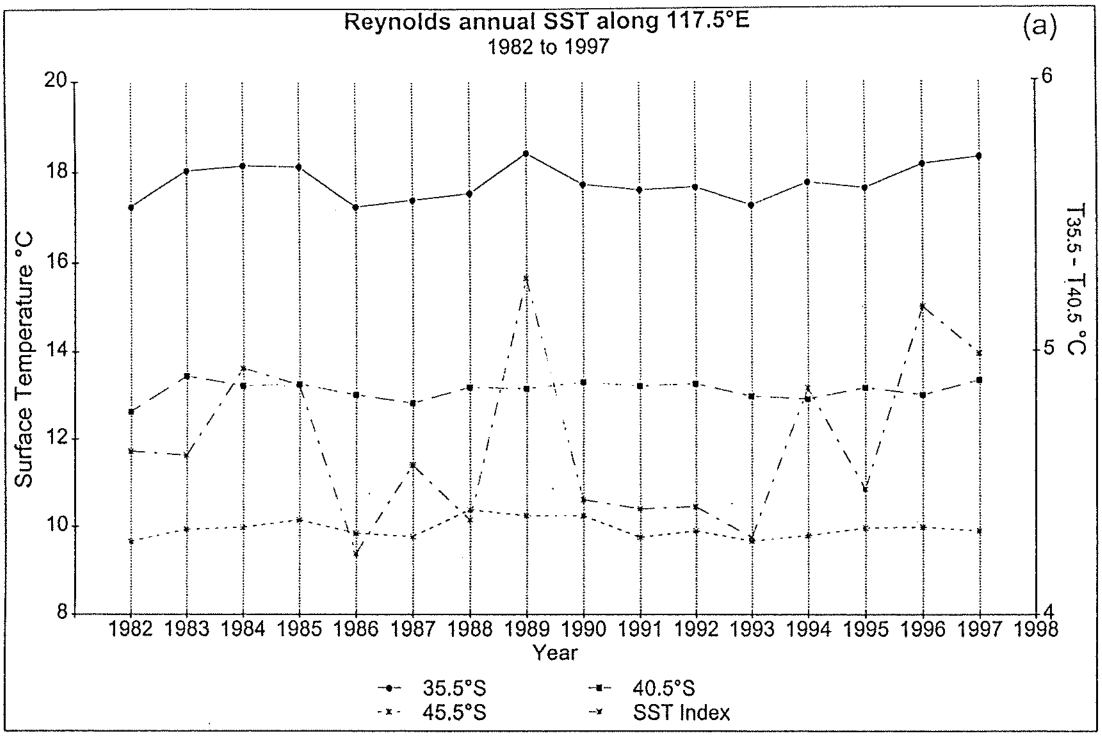


Figure 1.16: (a) Monthly mean SSTs at three latitudes along longitude band 117° to 118°E (off Albany) between the Western Australian coast and 50°S over the period 1982 to 1997 derived from the monthly Reynolds SST dataset; latitude 35.5°S (circles) represents the coastal block. (b) Monthly anomalies from the seasonal cycle at the three latitudes.



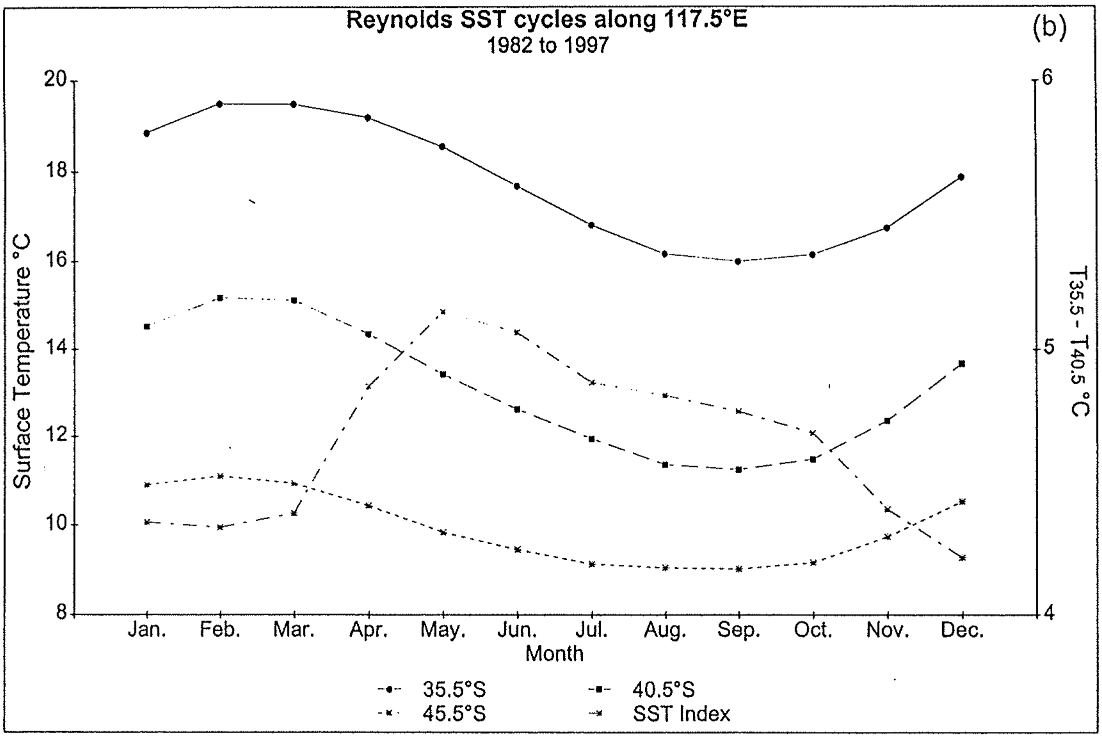
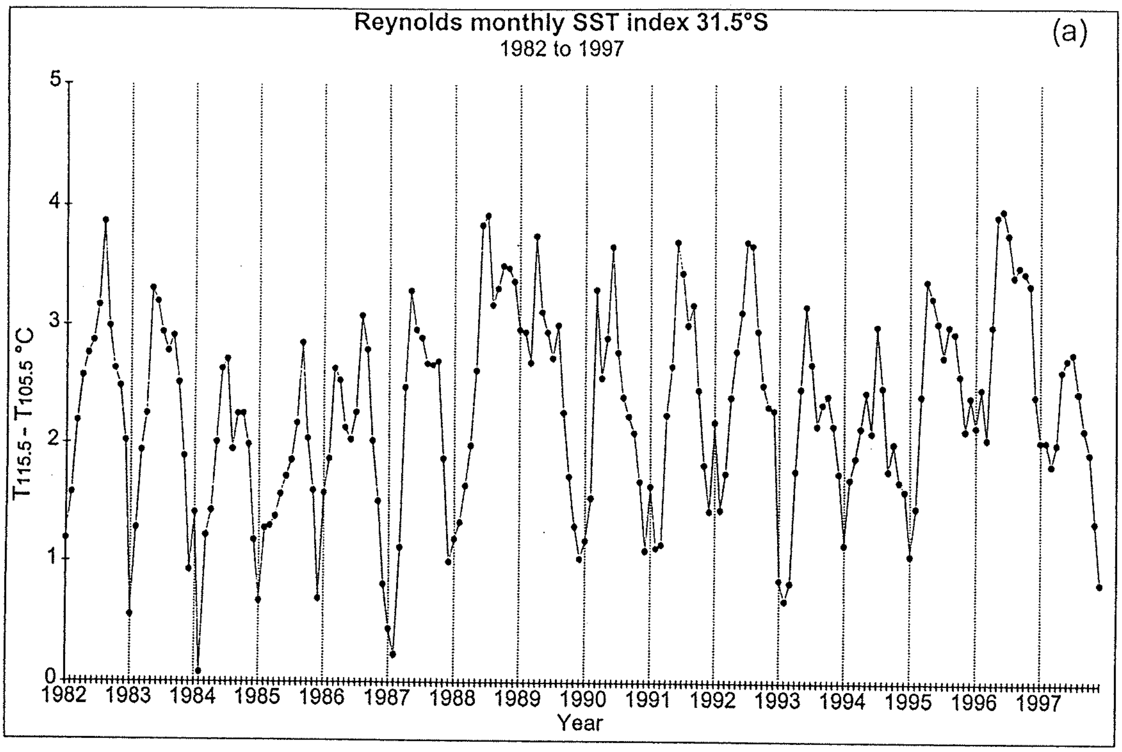


Figure 1.17: (a) Annual mean SSTs at three latitudes along longitude band 117° to 118°E (off Albany) between the Western Australian coast and 50°S over the period 1982 to 1997 derived from the monthly Reynolds SST dataset; latitude 35.5°S (circles) represents the coastal block. The dot-dashed line (lowest plot) is the SST index gradient calculated as the temperature difference between the coastal block and 40.5°S (asterisks). (b) Seasonal cycles of SST and the SST gradient index.



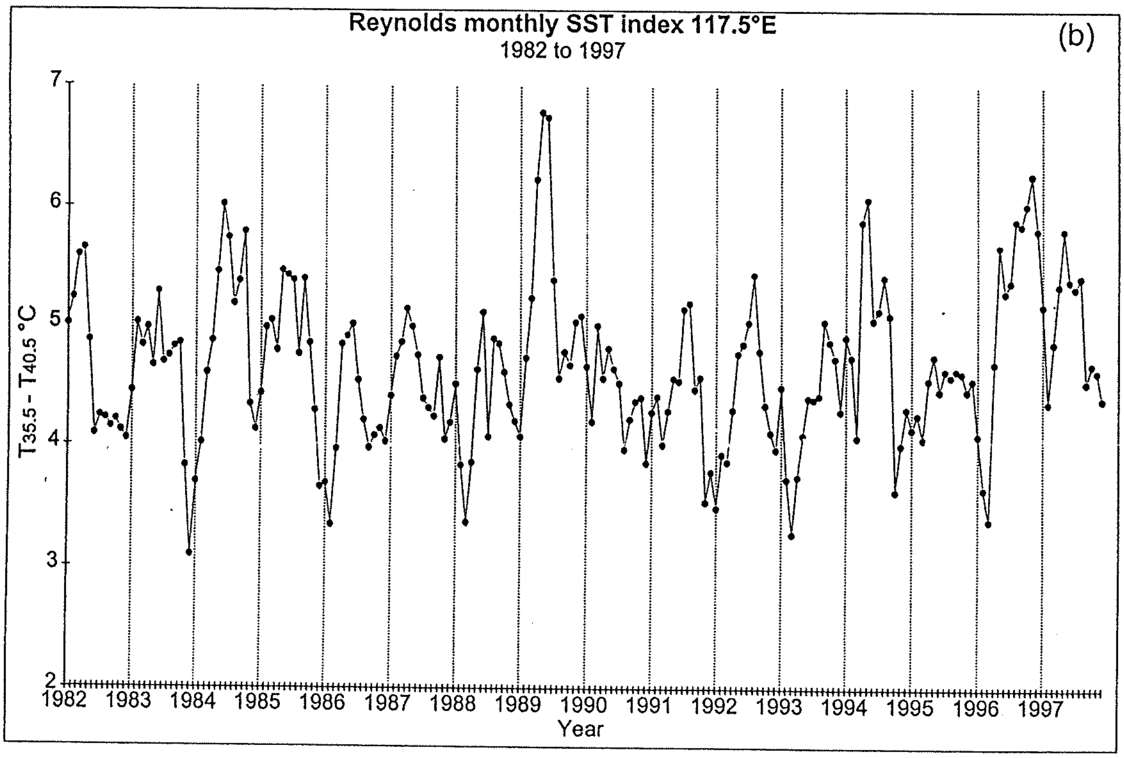


Figure 1.18: Monthly SST gradient indices off (a) Fremantle and (b) Albany, derived from the Reynolds SSTs as described in the text.

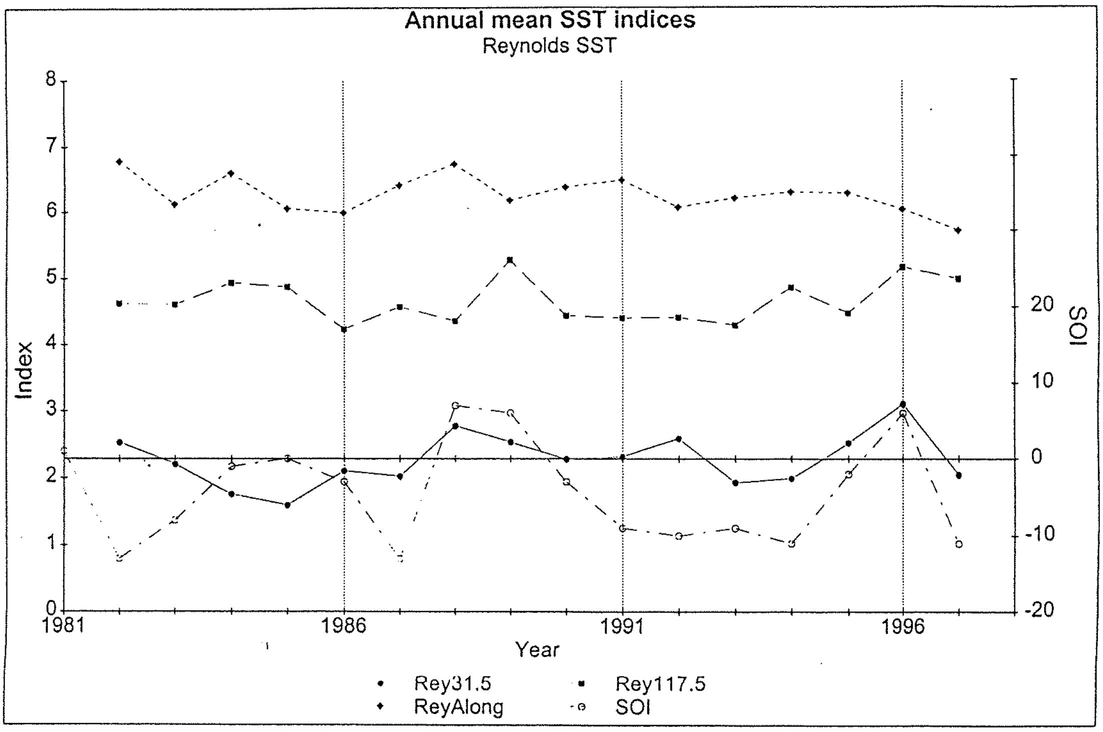
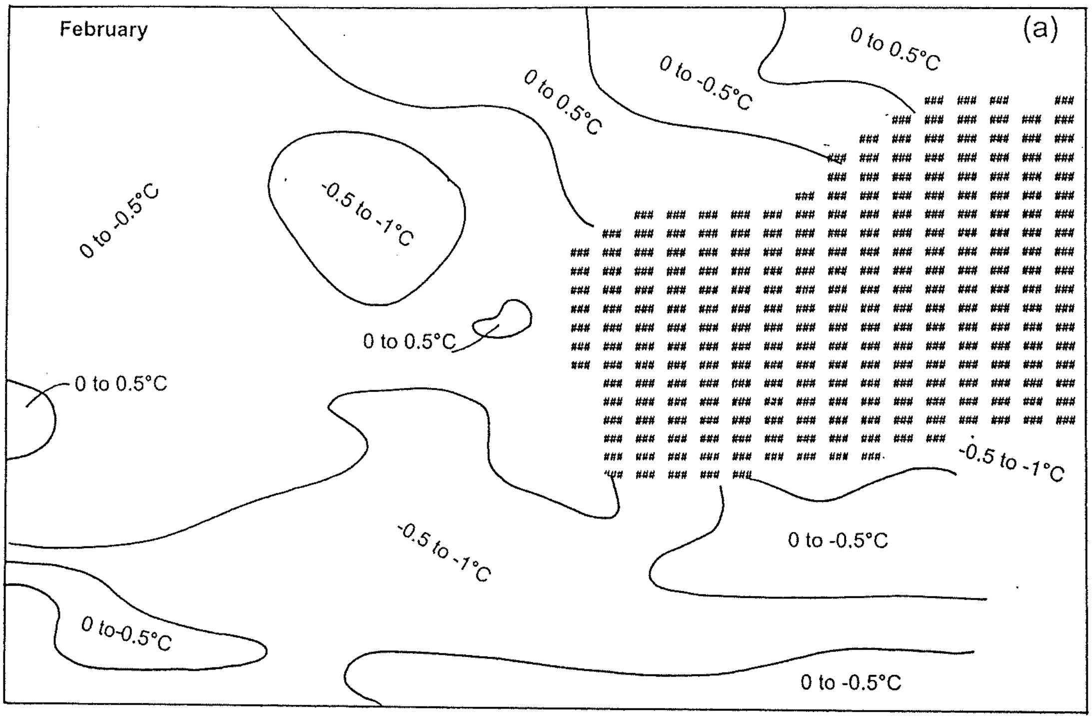


Figure 1.19: Annual SST gradient indices off Fremantle (solid line and circles) and Albany (dashed line and squares) derived from the Reynolds SSTs as described in the text, as well as the alongshore gradient index (dotted line and diamonds) and the SOI (dot-dashes with open circles).



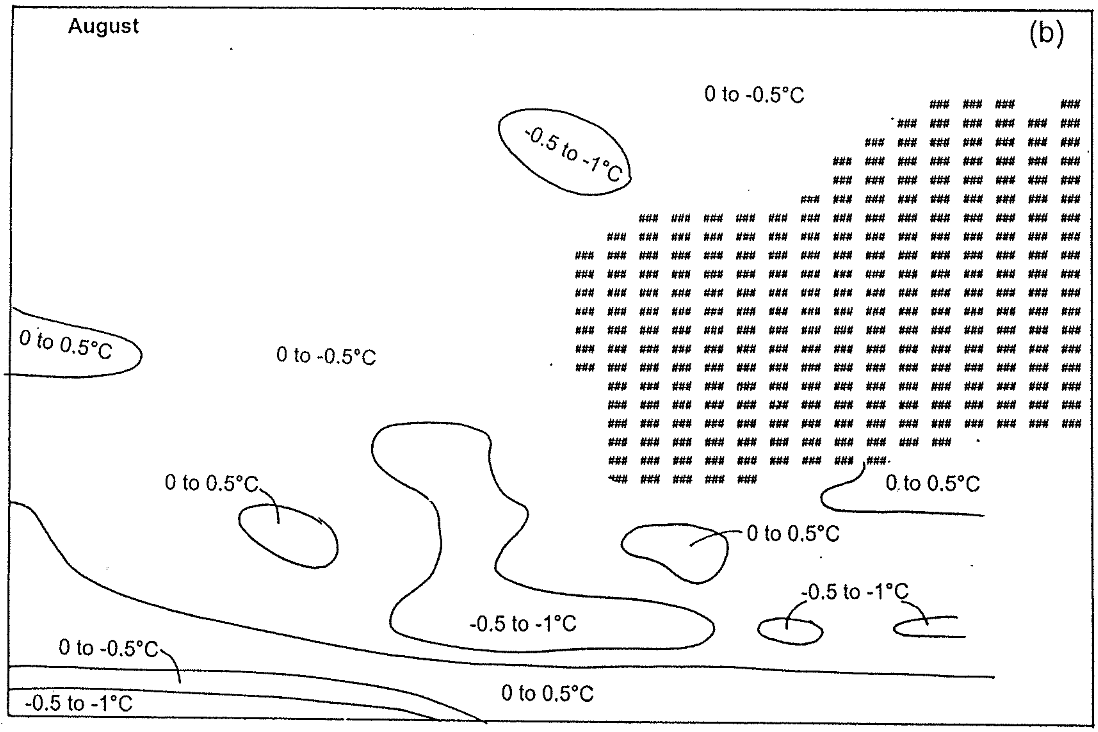
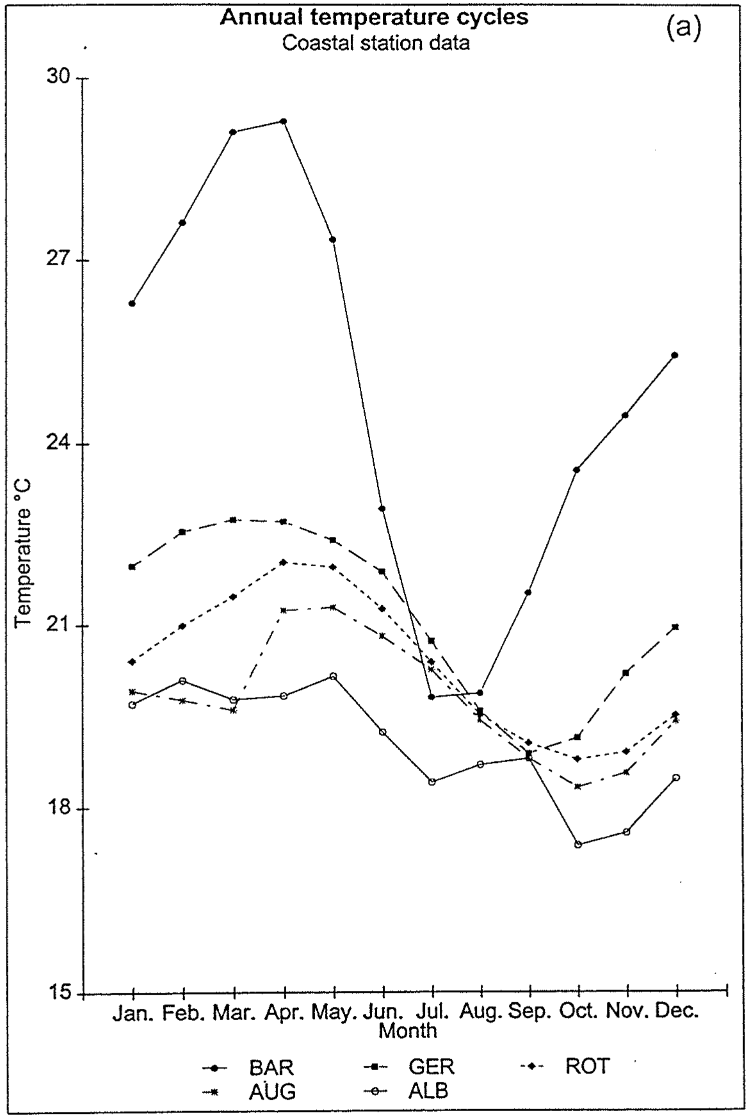


Figure 1.20: Monthly SST differences (Reynolds - COADS) for the south-eastern Indian Ocean derived from both data sets for the overlapping 8-year period 1982 to 1989, for February (a, representing summer) and August (b, winter). Land is coded ###, and the contours have been hand-smoothed.



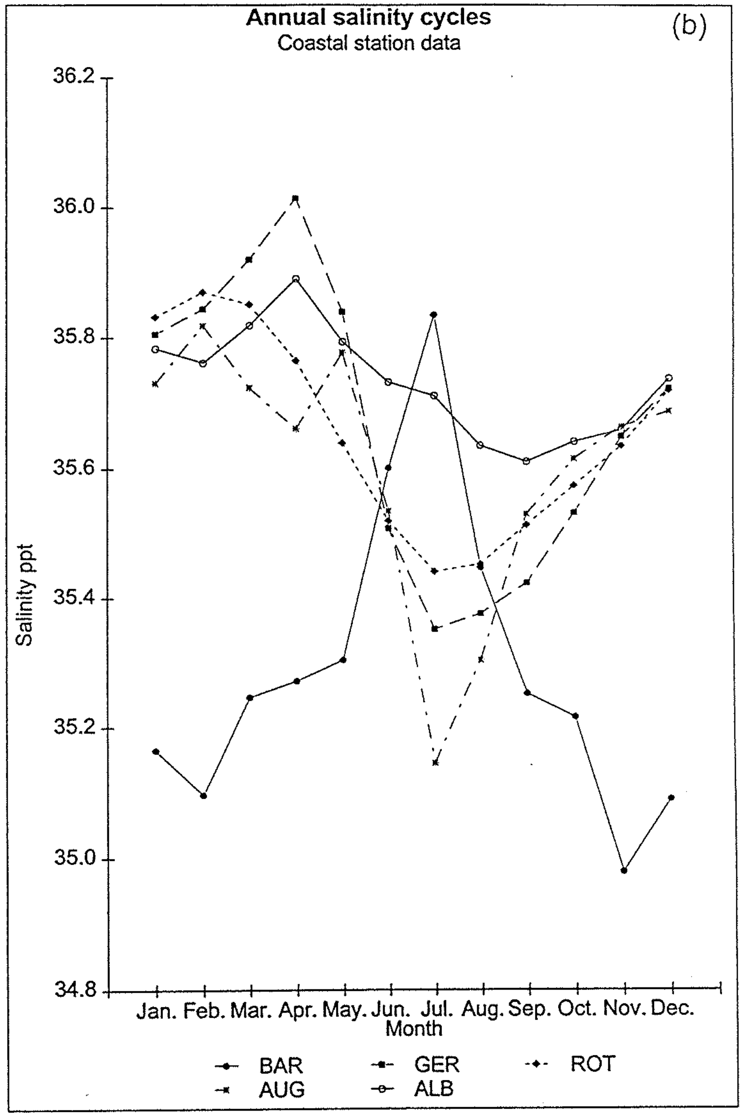
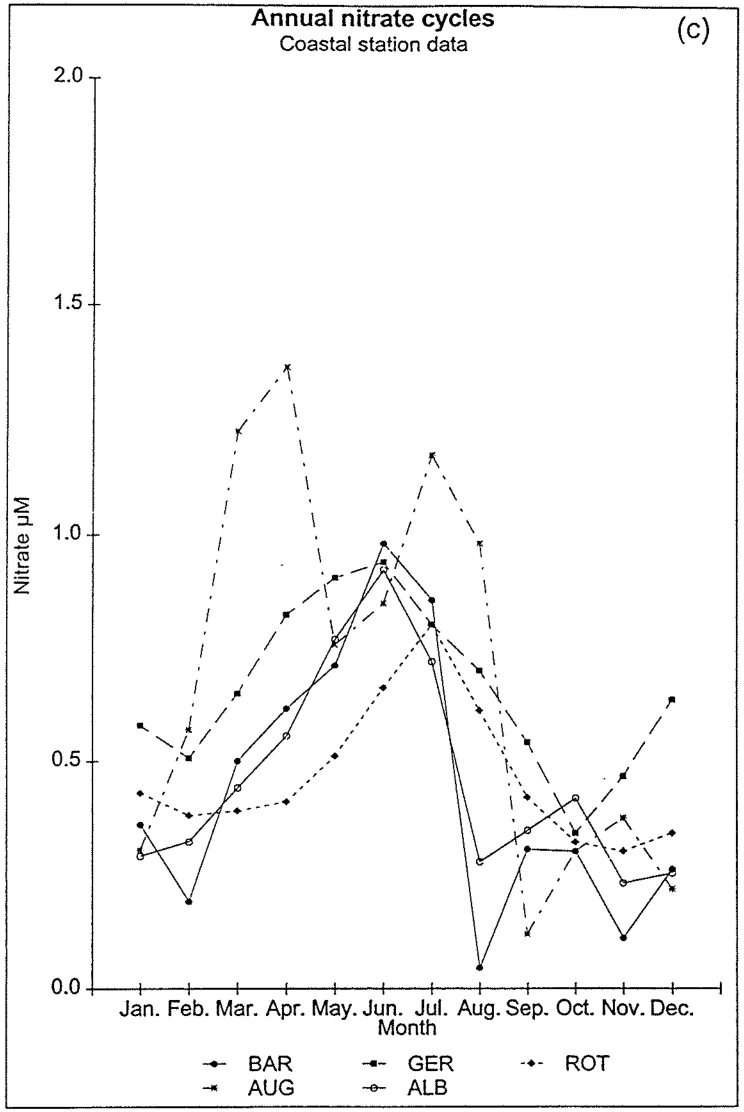
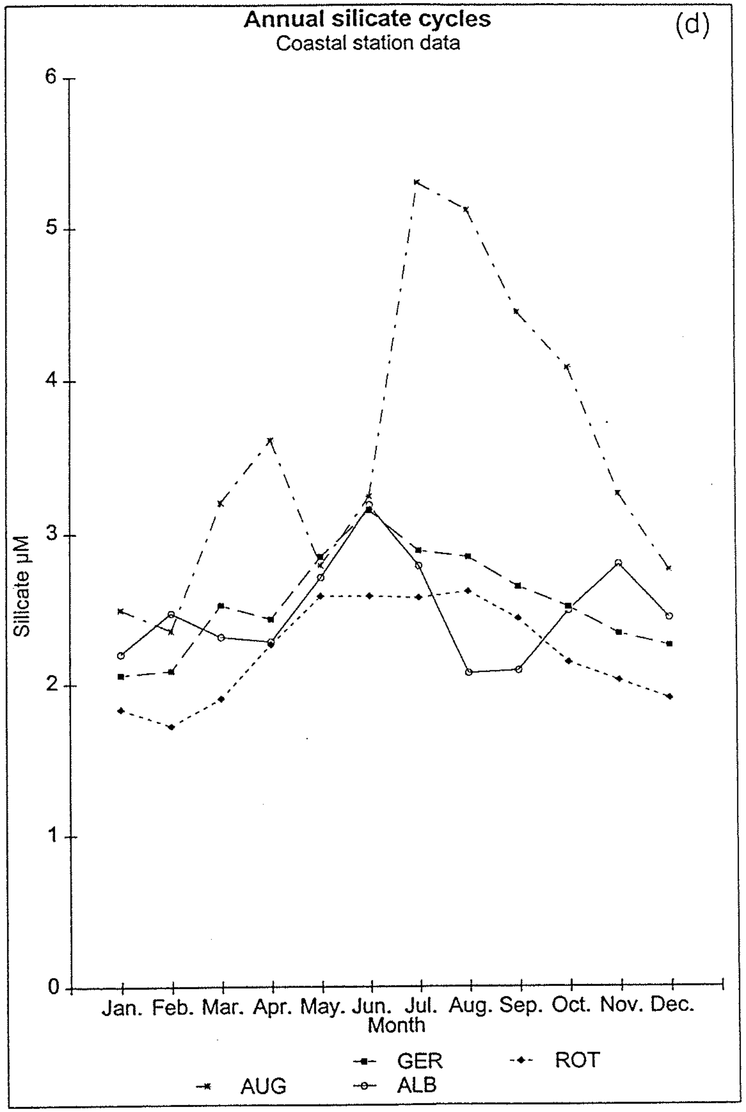


Figure 1.21: Annual cycles of depth-averaged (a) temperature, (b) salinity, (c) nitrate and (d) silicate at the 5 coastal monitoring stations off Western Australia: Barrow Island BAR (circles), Geraldton GER (squares), Rottnest Island ROT (diamonds), Augusta AUG (asterisks) and Albany ALB (open circles).


Annual nitrate cycles
Coastal station data
(c)
Nitrate µM
2.0
1.5
1.0
0.5
0.0
Jan. Feb. Mar. Apr. May. Jun. Jul. Aug. Sep. Oct. Nov. Dec.
Month
BAR
GER
ROT
AUG
ALB


Annual silicate cycles
Coastal station data
(d)
Silicate µM
6
5
4
3
2
1
0
Jan. Feb. Mar. Apr. May. Jun. Jul. Aug. Sep. Oct. Nov. Dec.
Month
GER
ROT
AUG
ALB

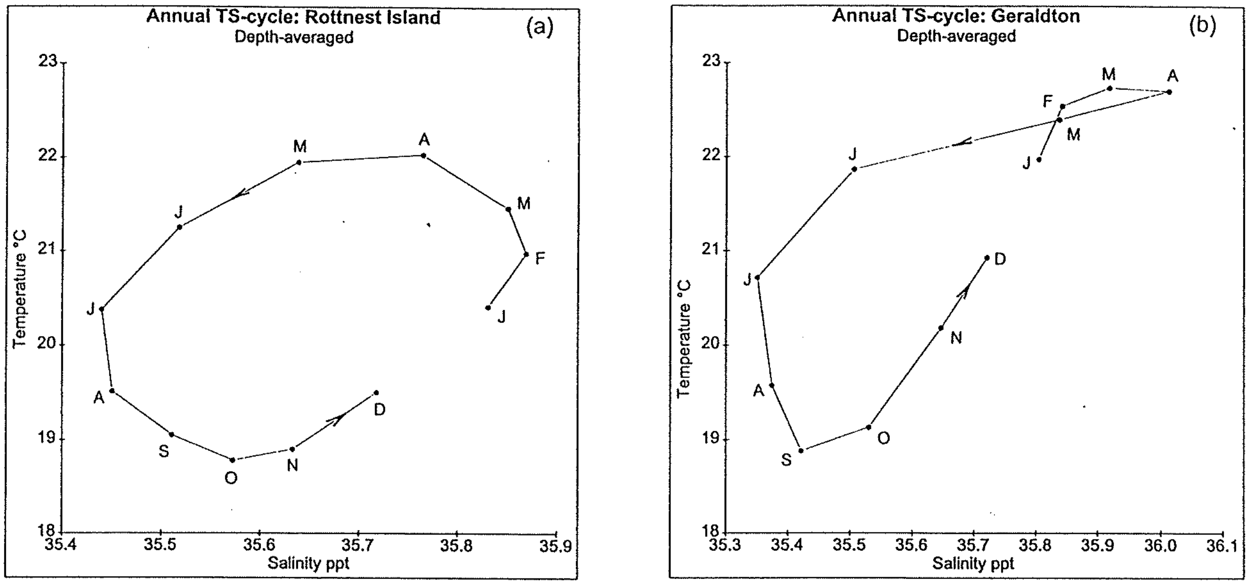
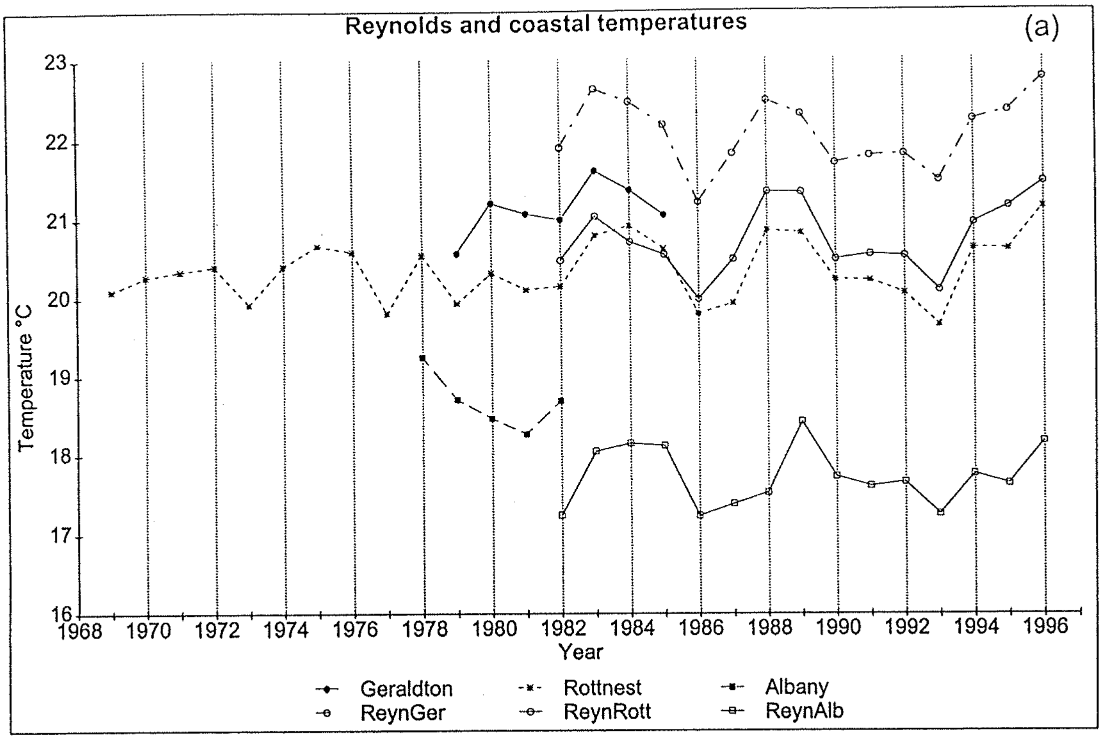


Figure 1.22: TS-plots of monthly mean depth-averaged temperatures and salinities off (a, left panel) Rottnest Island station and (b, right panel) Geraldton, from the optimum interpolated data analysis. Symbols J to D refer to the months January to December.



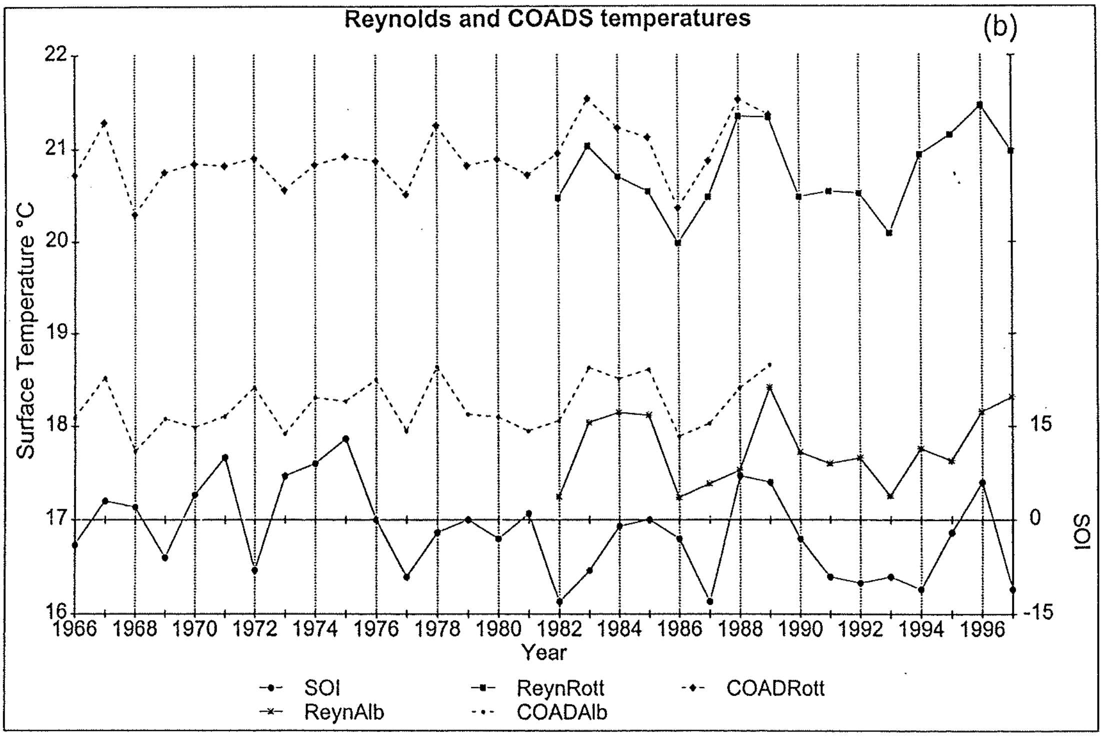
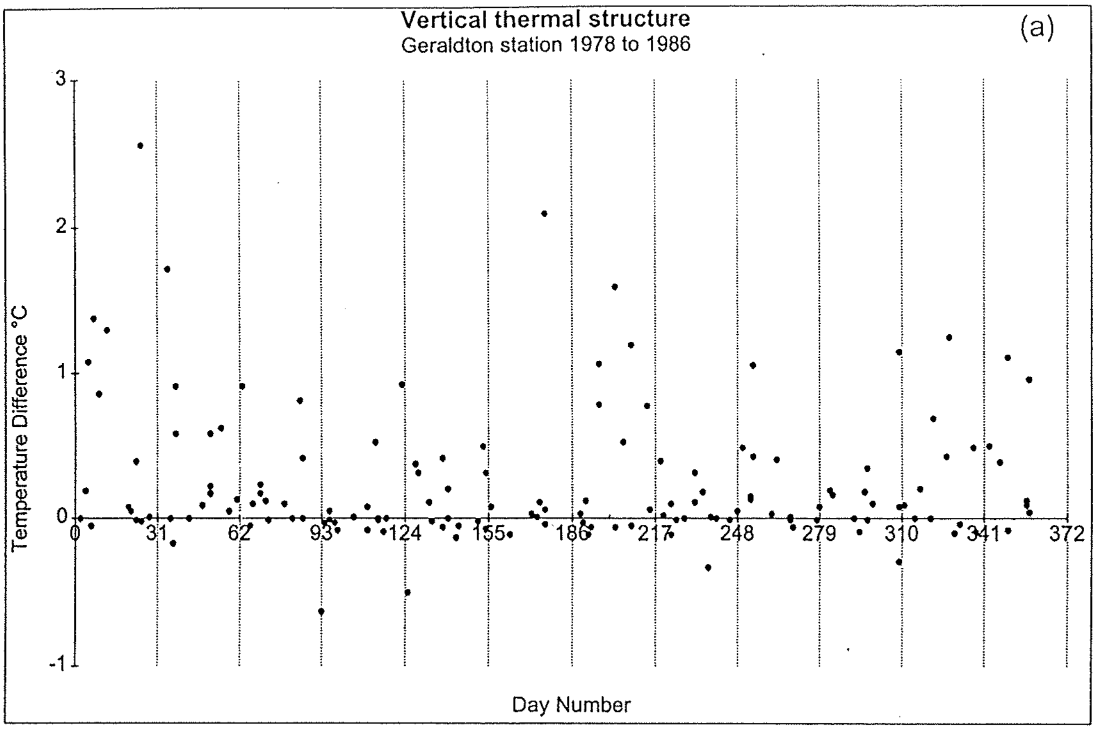


Figure 1.23: (a) Annual mean depth-averaged temperatures derived from the optimal interpolation time-series for Geraldton (circles), Rottnest (asterisks) and Albany (squares), together with the corresponding Reynolds satellite-derived SSTs for the appropriate 1 degree latitude/longitude squares. (b) Annual mean surface temperatures for areas off Rottnest Island (upper pair of curves) and Albany between 1968 and 1996 from the Reynolds and COADS datasets, and the annual SOI (lowest curve). The Reynolds data started in 1982 and the available COADS dataset ended in 1989.



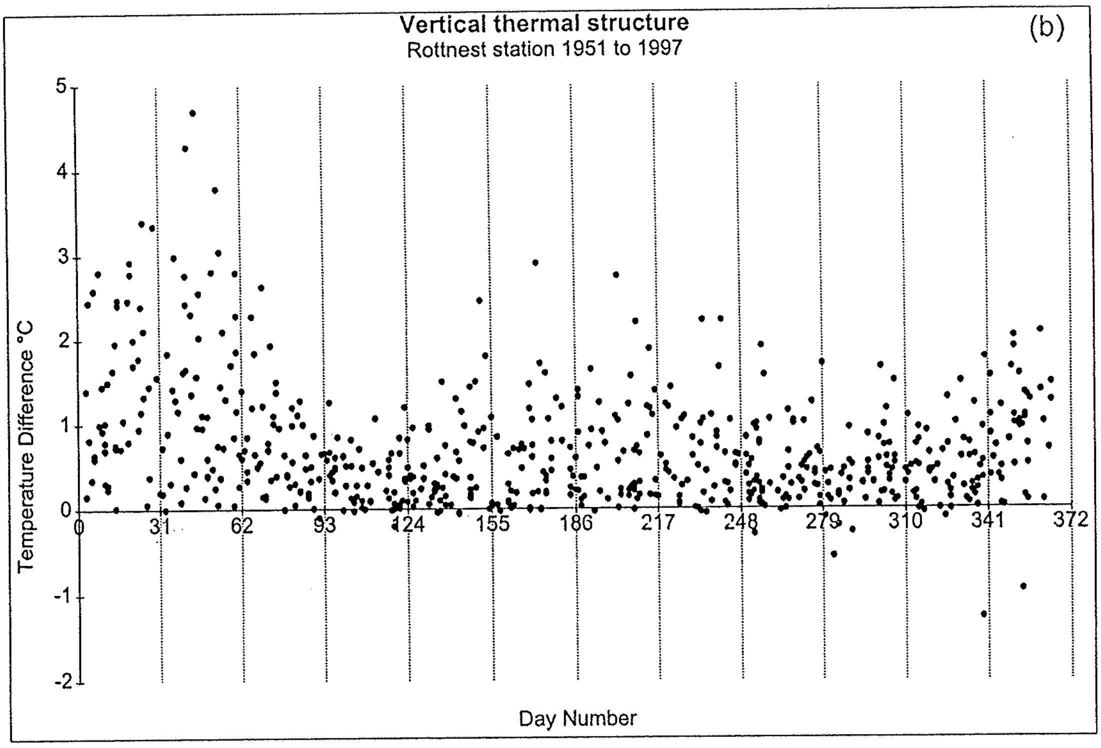
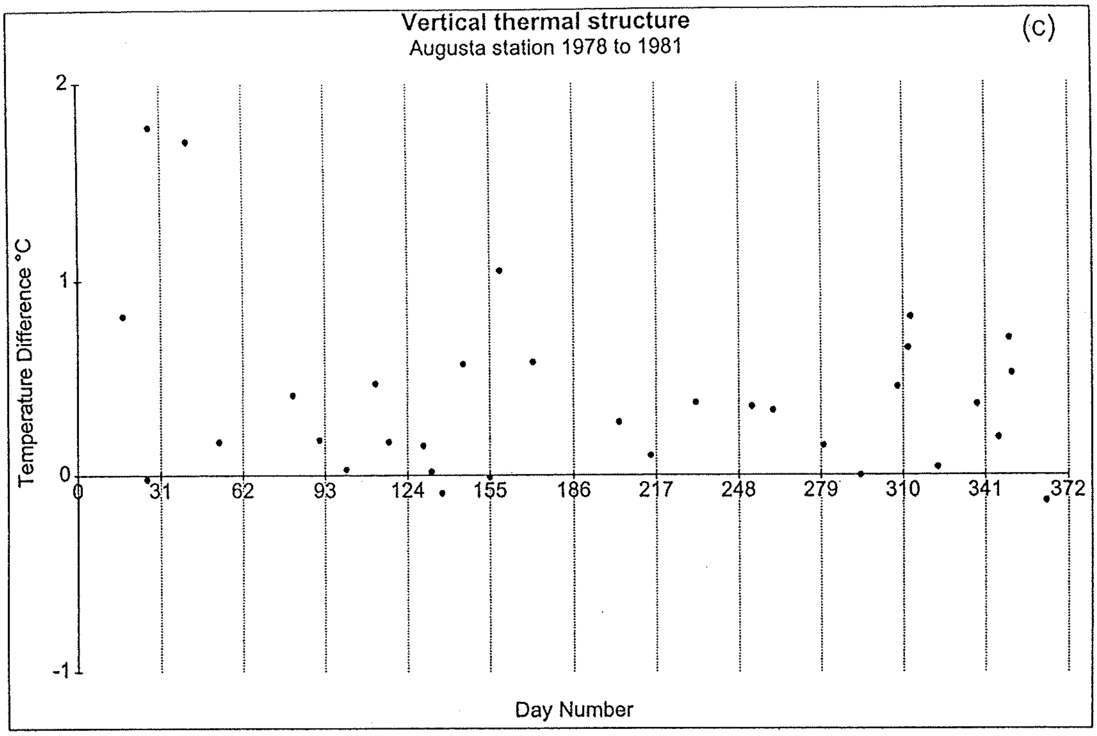
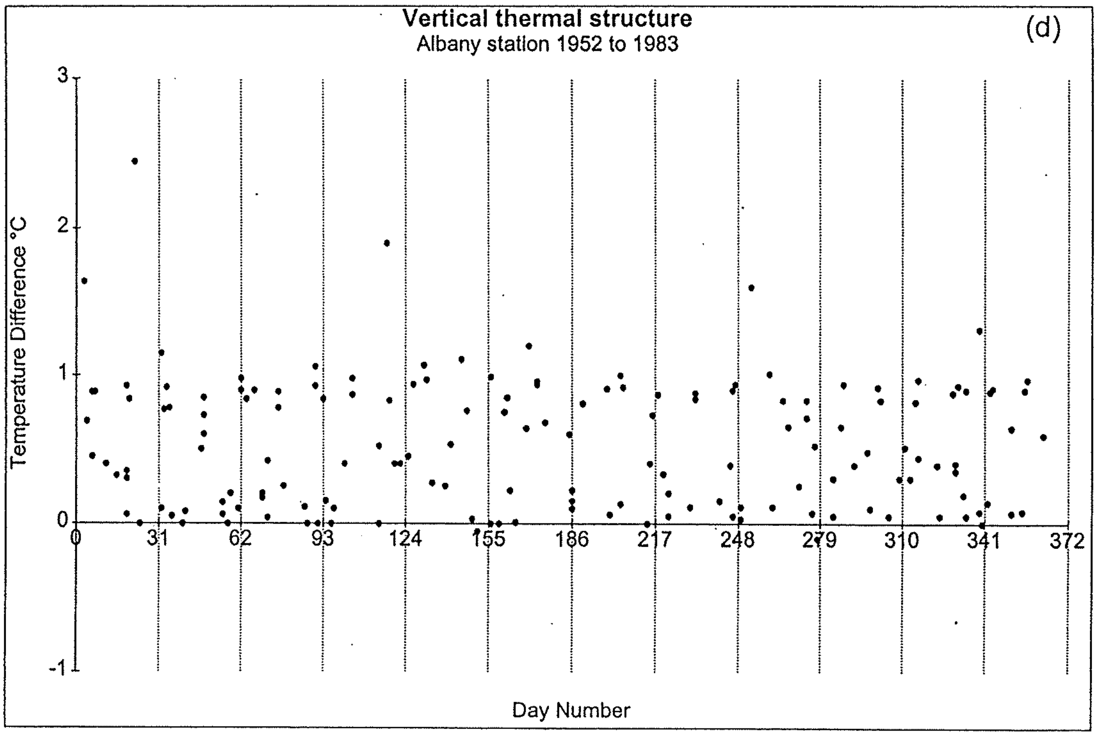


Figure 1.24: Temperature differences between the surface (upper 1 m layer) and near the seabed at the four coastal monitoring stations (a) Geraldton, (b) Rottnest Island, (c) Augusta and (d) Albany, over the calendar year; the vertical grid-lines approximately indicate the months.


Vertical thermal structure
Augusta station 1978 to 1981
(c)
Temperature Difference °C
2
1
0
-1
0
31
62
93
124
155
186
217
248
279
310
341
372
Day Number


Vertical thermal structure
Albany station 1952 to 1983
(d)
Temperature Difference °C
3
2
1
0
-1
0
31
62
93
124
155
186
217
248
279
310
341
372
Day Number

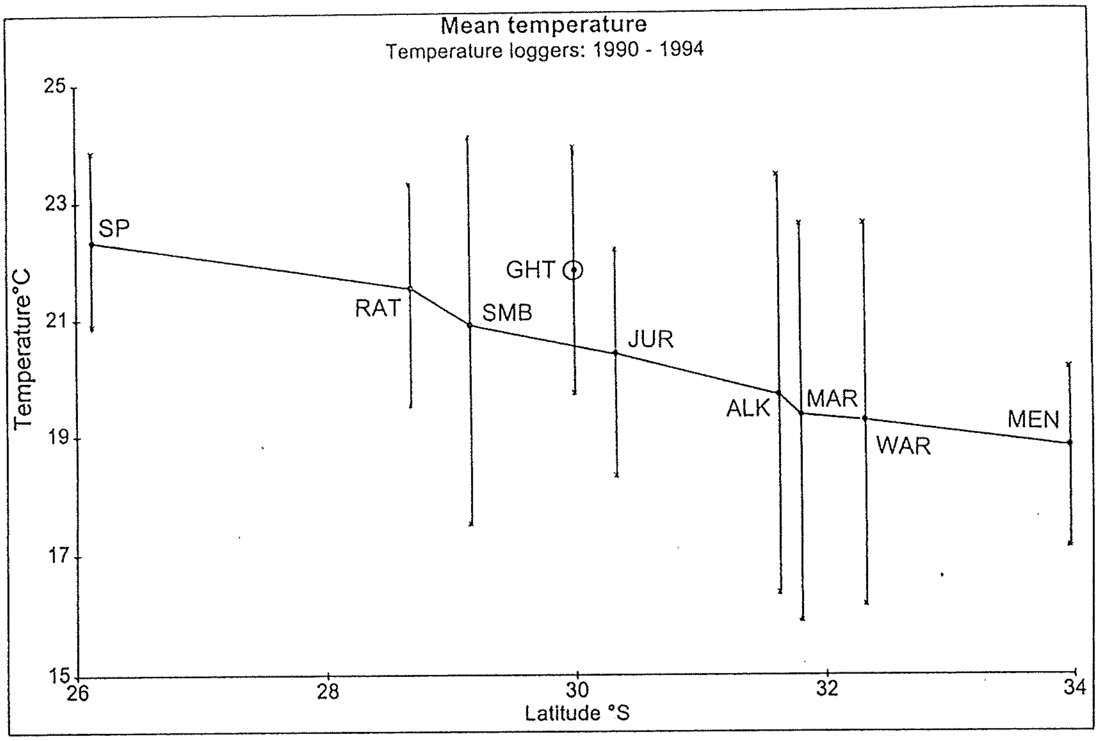


Figure 1.25: Overall mean temperatures (solid circles) with monthly minimum and maximum values (asterisks joined by vertical lines) at the puerulus collector sites along the west coast, derived from the temperature logger data (courtesy Fisheries WA). For the site abbreviations, refer to Table 1.3.

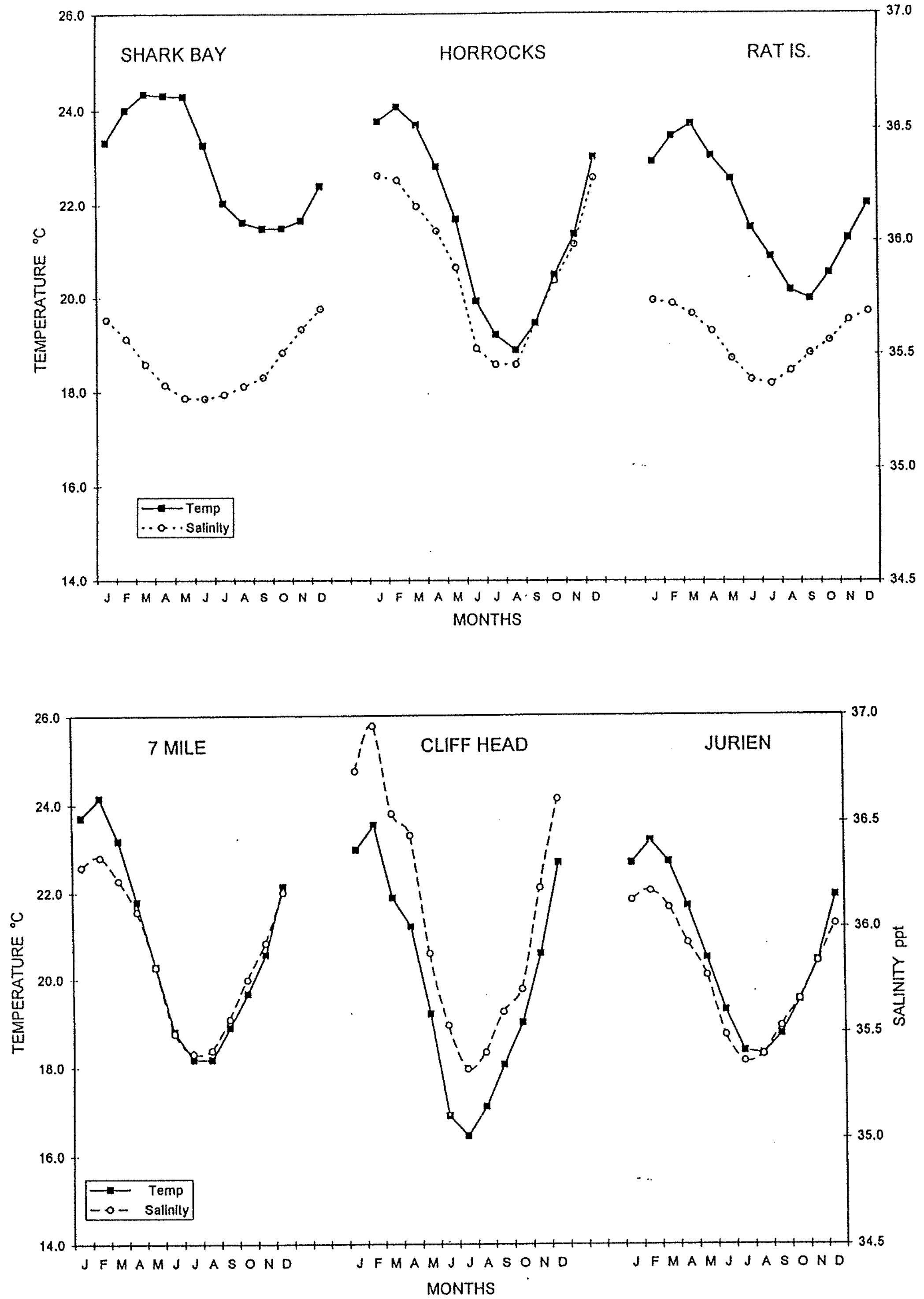
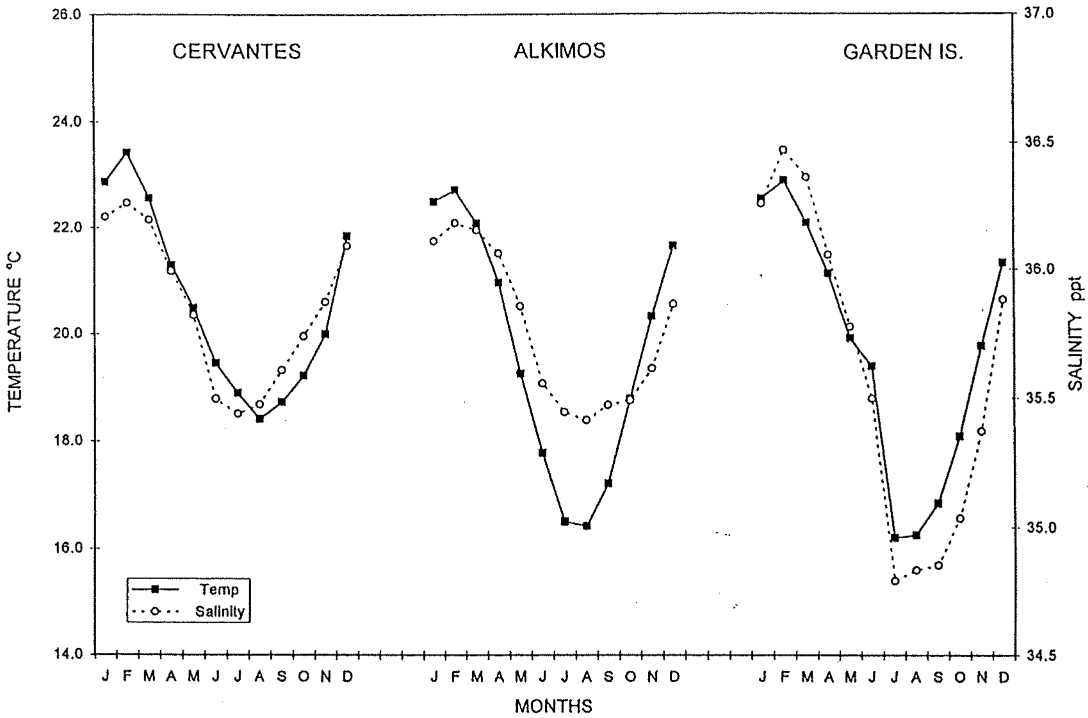
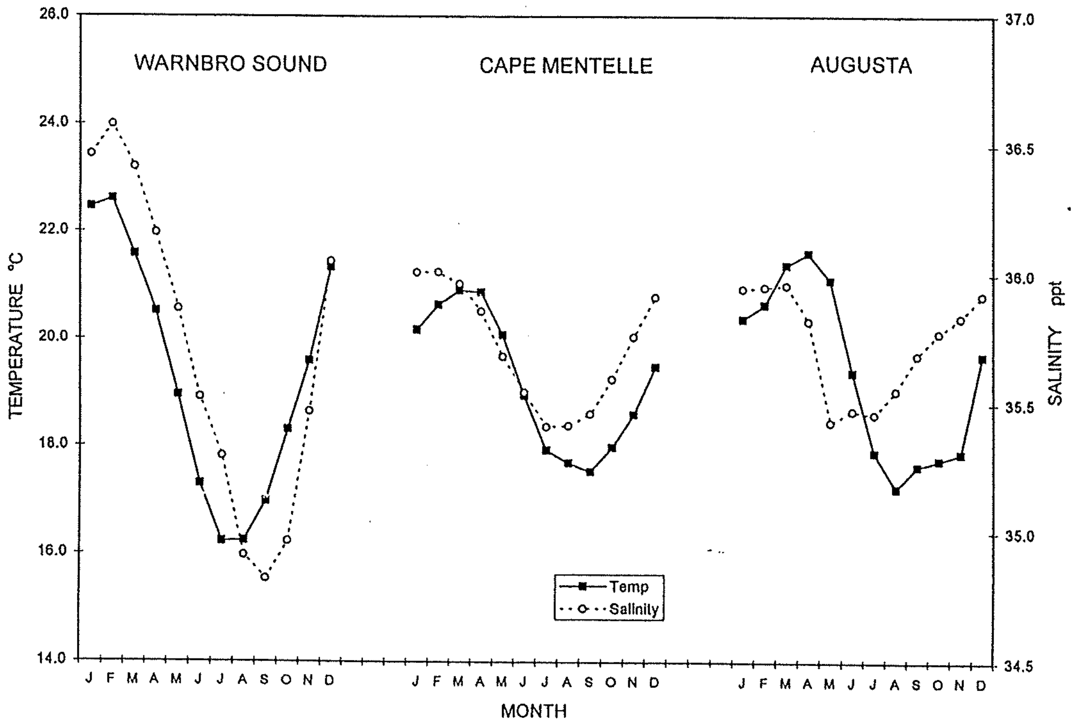
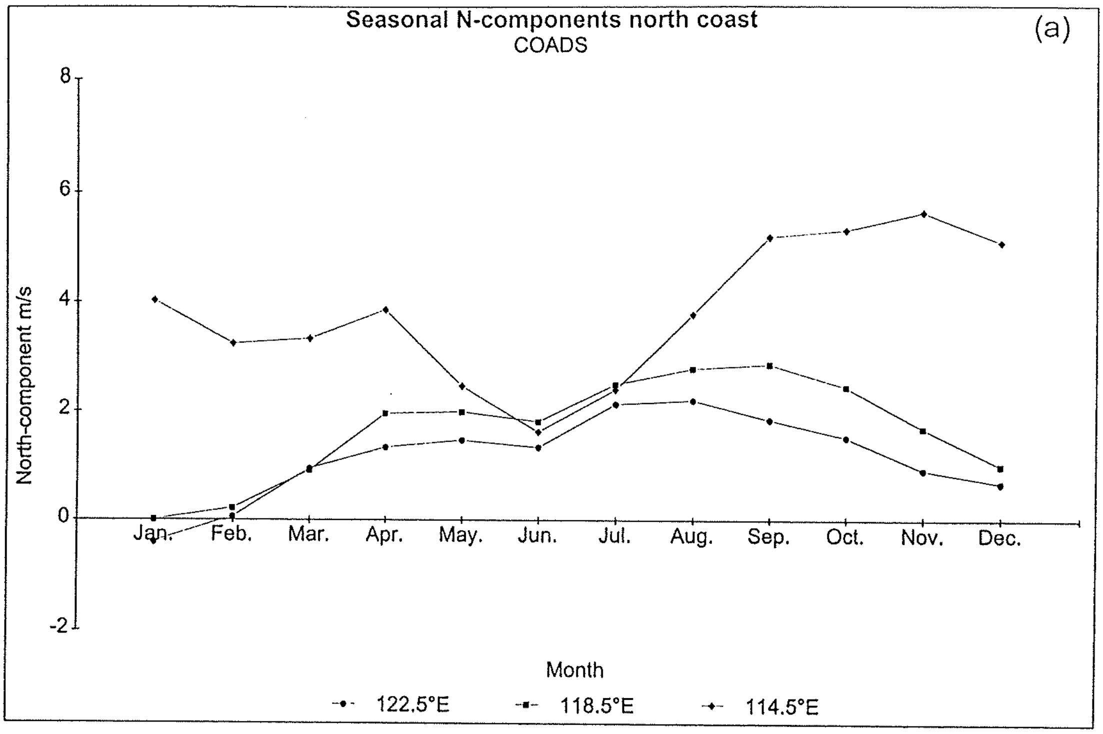


Figure 1.26: Annual temperature and salinity cycles at 12 puerulus collector sites along the west coast, derived from the monthly spot samples (Pearce 1998 unpublished data, courtesy Fisheries WA). For each site, the monthly mean temperature (solid, left axis) and salinity (dashed, right axis) are shown for the months of January (J) to December (D).


26.0
24.0
22.0
20.0
18.0
16.0
14.0
37.0
36.5
36.0
35.5
35.0
34.5
CERVANTES
ALKIMOS
GARDEN IS.
TEMPERATURE °C
SALINITY ppt
Temp
Salinity
J F M A M J J A S O N D
MONTHS


26.0
24.0
22.0
20.0
18.0
16.0
14.0
37.0
36.5
36.0
35.5
35.0
34.5
WARNBRO SOUND
CAPE MENTELLE
AUGUSTA
TEMPERATURE °C
SALINITY ppt
Temp
Salinity
J F M A M J J A S O N D
MONTH



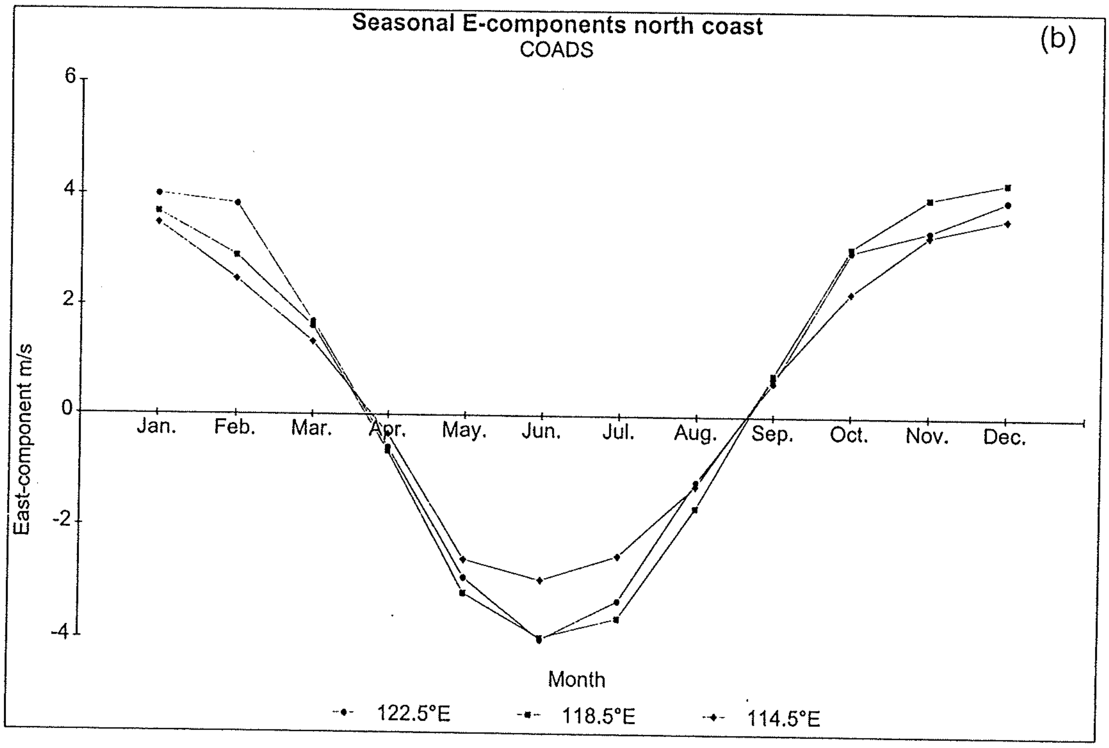


Figure 1.27: Seasonal (a) northwards and (b) eastwards wind components for the three coastal blocks off Broome (122.5°E), Port Hedland (118.5°E) and Exmouth (114.5°E) on the Northwest Shelf derived from COADS winds over the period 1945 to 1989.

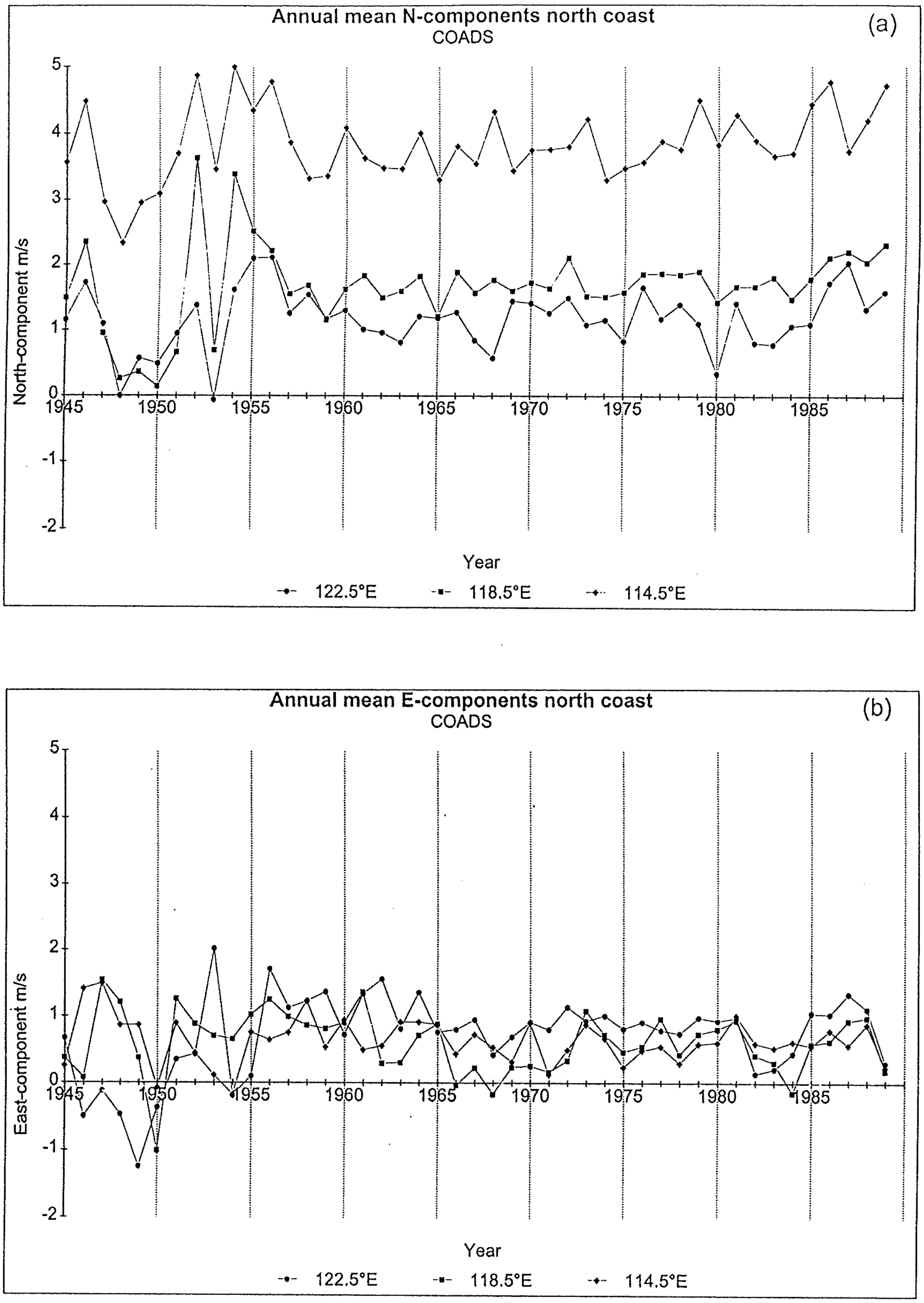


Figure 1.28: Annual mean (a) northwards and (b) eastwards wind components for the three coastal blocks off Broome (122.5°E), Port Hedland (118.5°E) and Exmouth (114.5°E) derived from COADS winds over the period 1945 to 1989.

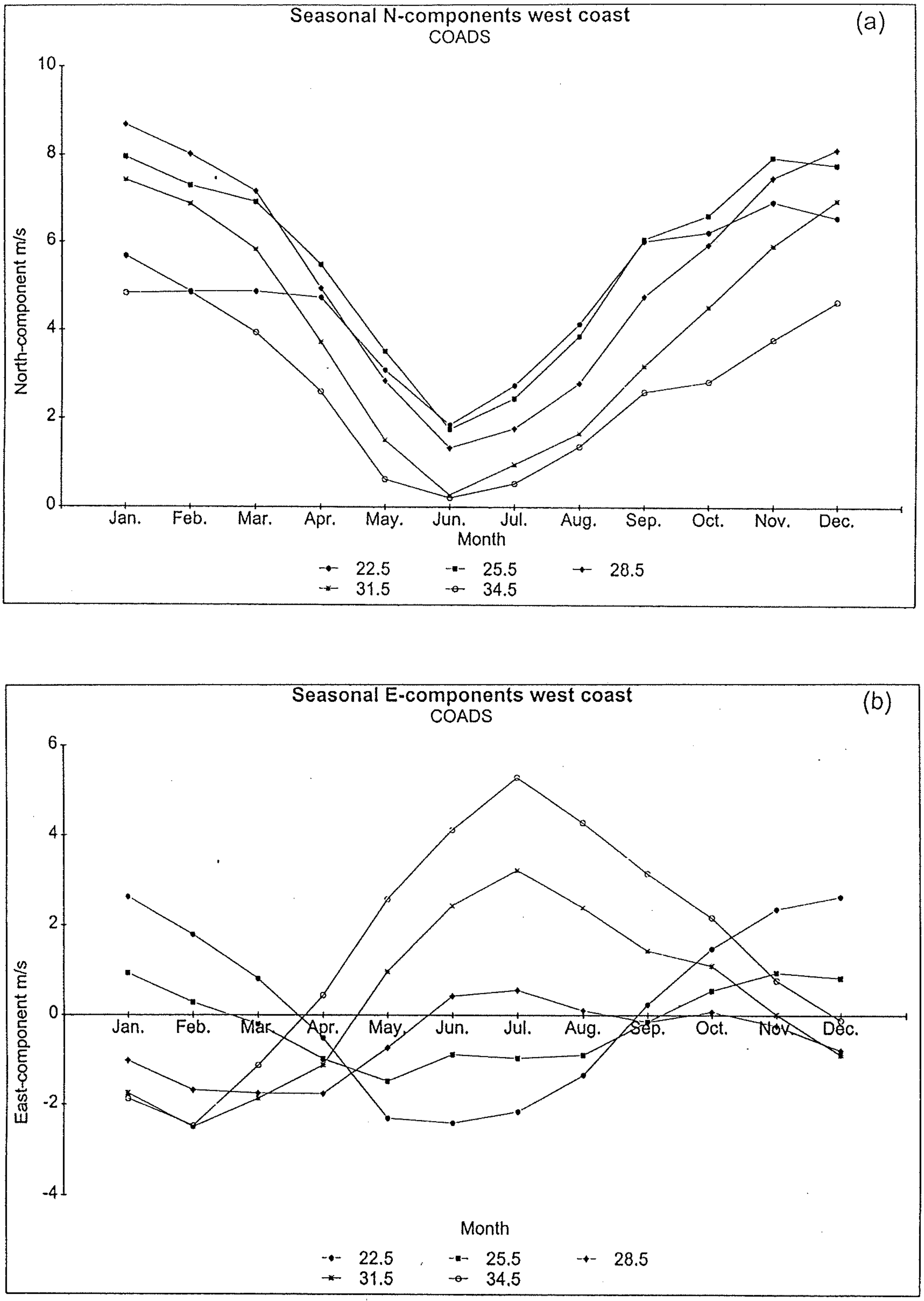
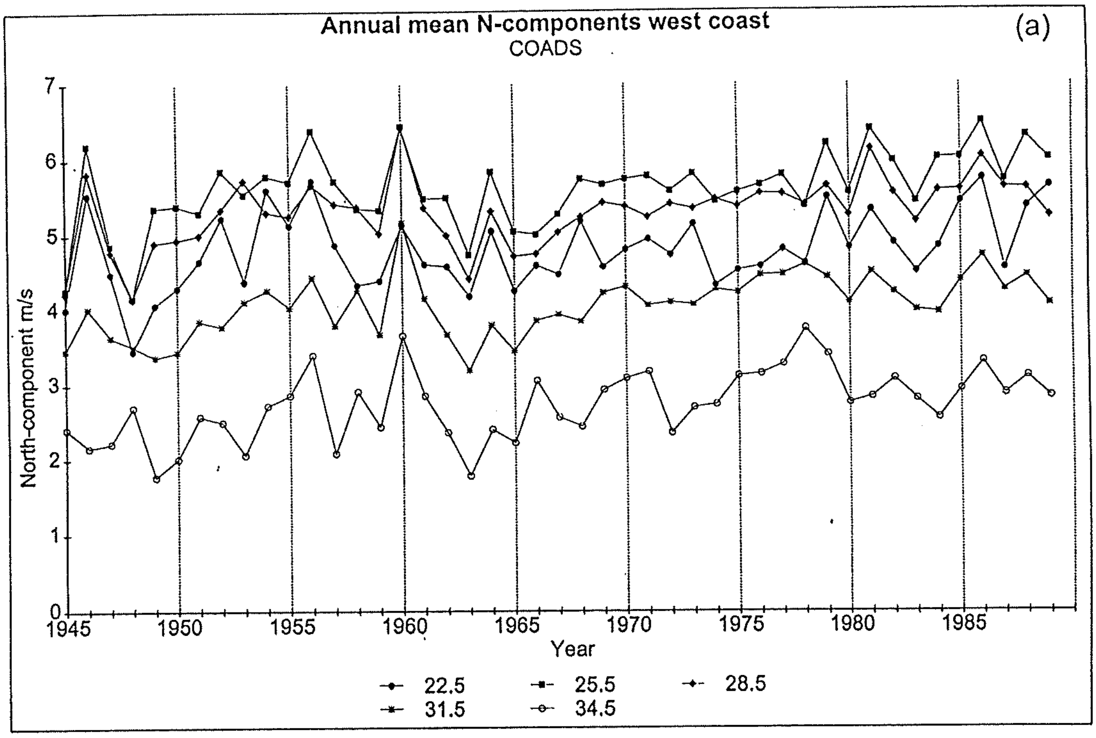


Figure 1.29: Seasonal (a) northwards and (b) eastwards wind components for the five coastal blocks off Exmouth (22.5°S), Shark Bay (25.5°S), Abrolhos Islands (28.5°S), Rottnest Island (31.5°S) and Cape Leeuwin (34.5°S) on the west coast derived from COADS winds over the period 1945 to 1989.



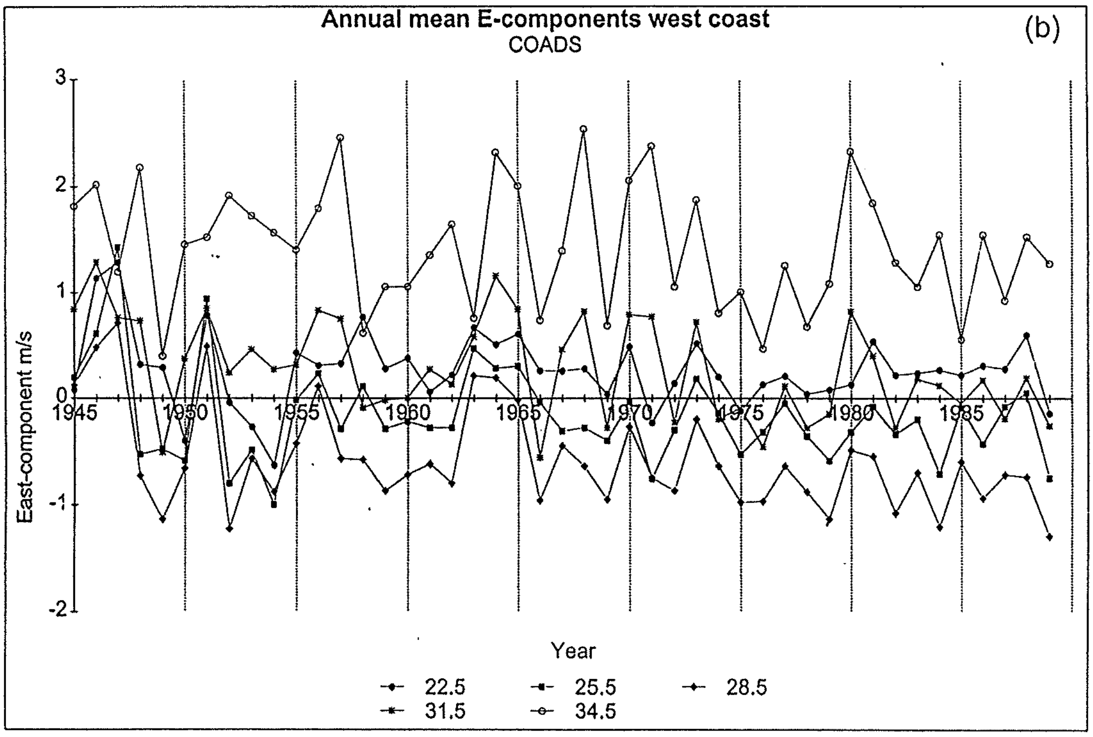
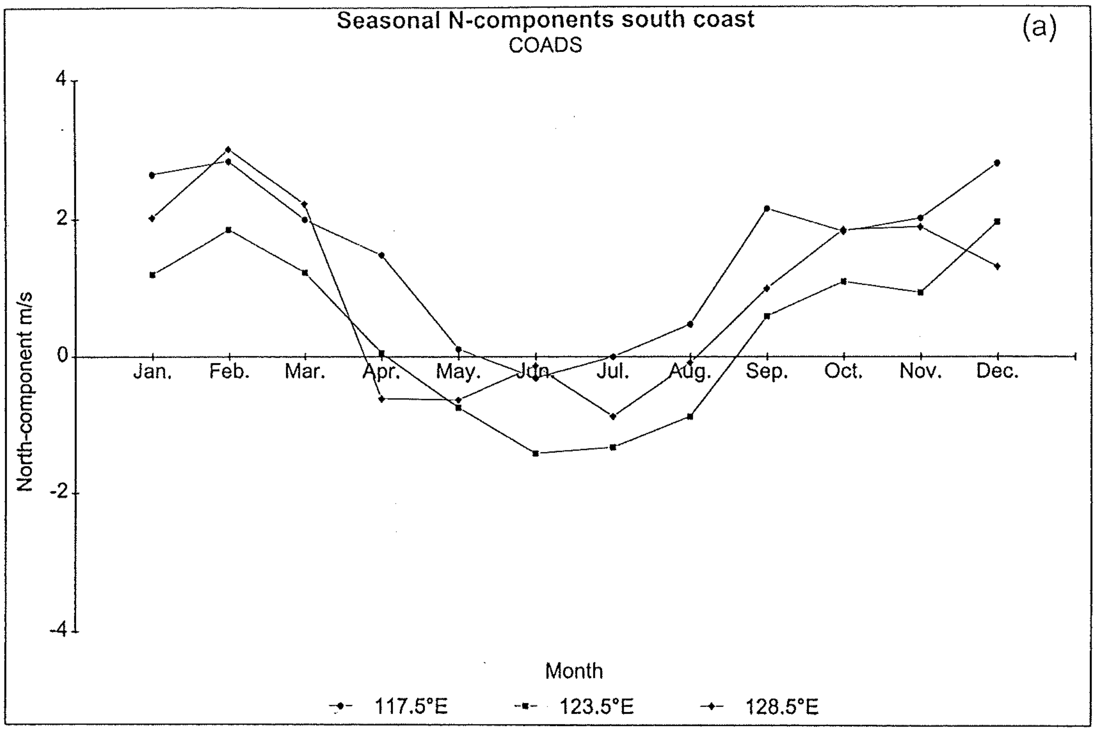


Figure 1.30: Annual mean (a) northwards and (b) eastwards wind components for the five coastal blocks off Exmouth (22.5°S), Shark Bay (25.5°S), Abrolhos Islands (28.5°S), Rottnest Island (31.5°S) and Cape Leeuwin (34.5°S) on the west coast derived from COADS winds over the period 1945 to 1989.



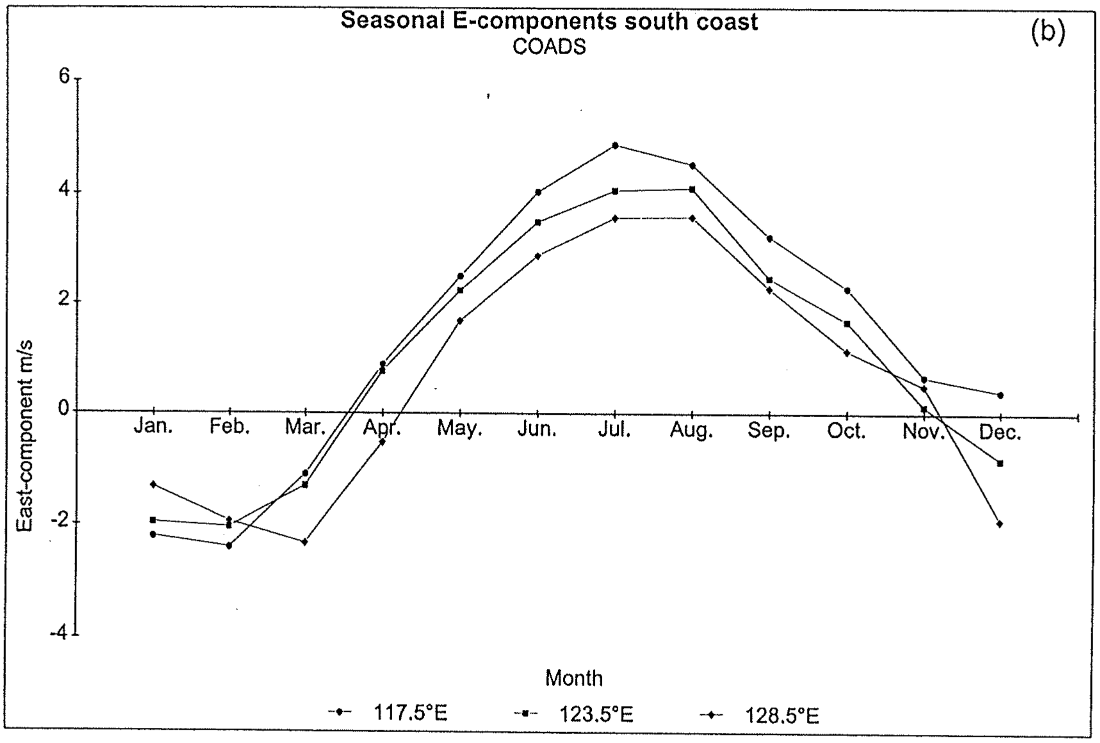
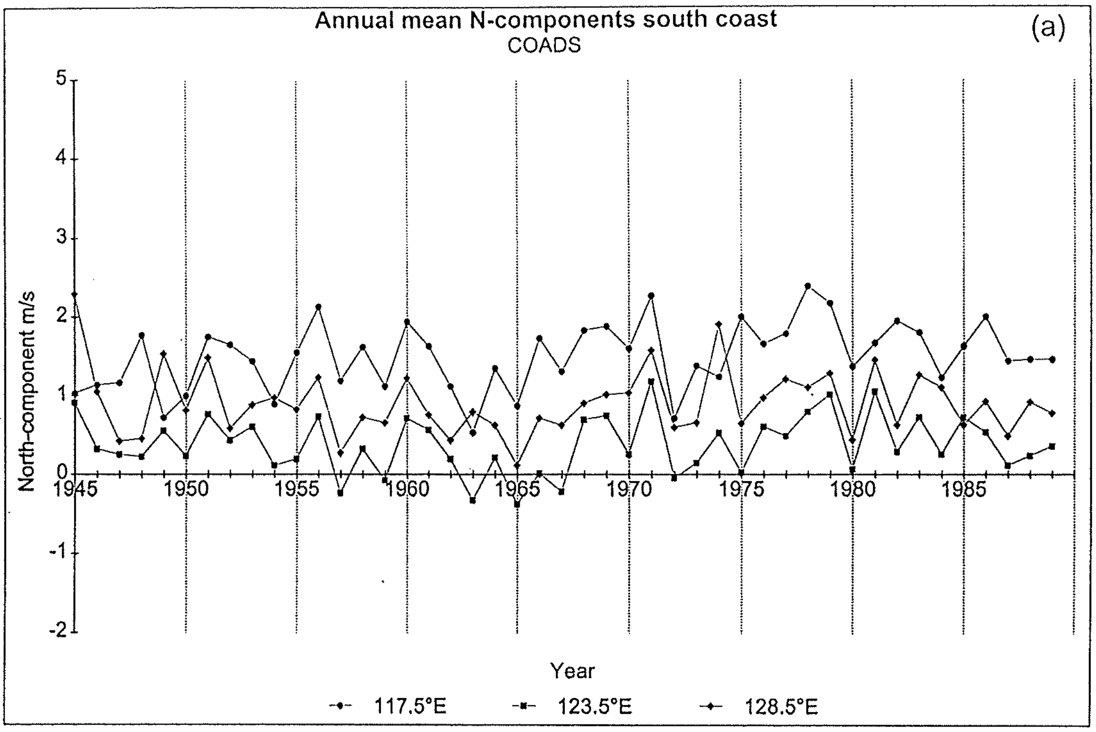


Figure 1.31: Seasonal (a) northwards and (b) eastwards wind components for the three coastal blocks off Albany (117.5°E), Cape Pasley (123.5°E) and Eucla (128.5°E) on the south coast derived from COADS winds over the period 1945 to 1989.



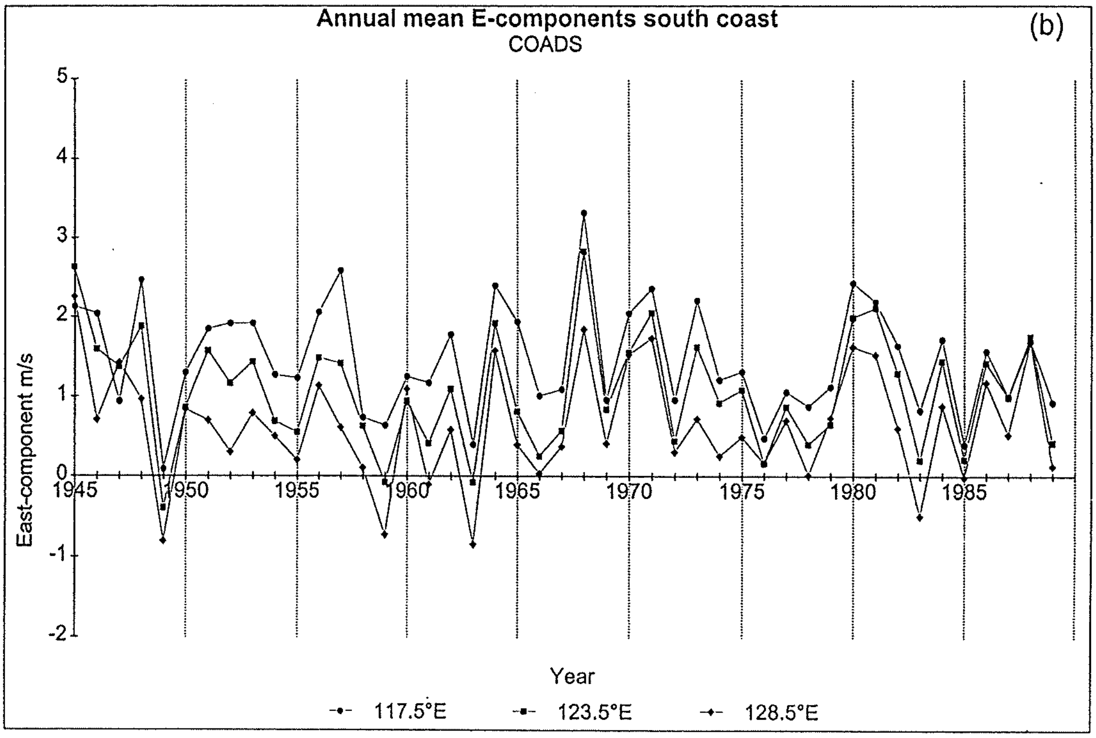
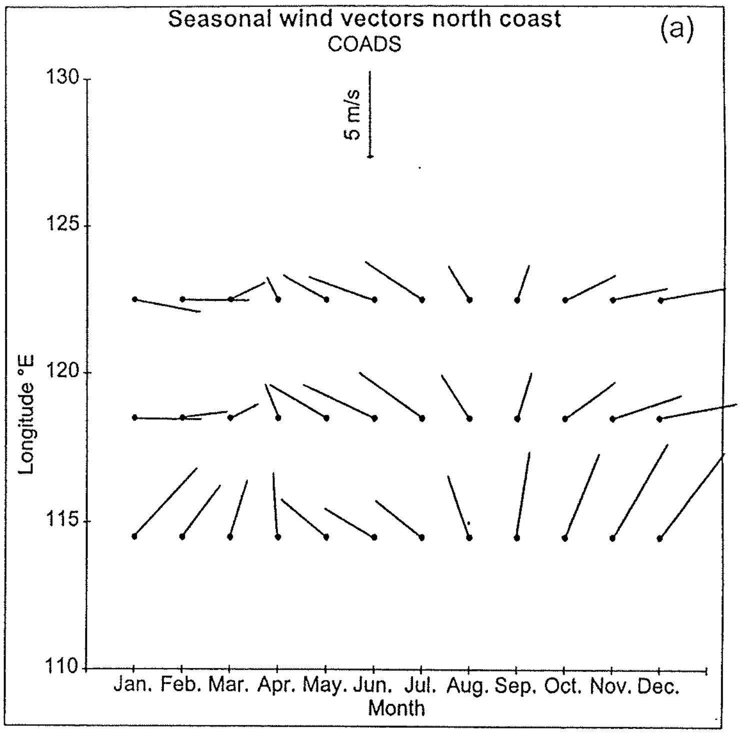


Figure 1.32: Annual mean (a) northwards and (b) eastwards wind components for the three coastal blocks off Albany (117.5°E), Cape Pasley (123.5°E) and Eucla (128.5°E) on the south coast derived from COADS winds over the period 1945 to 1989.



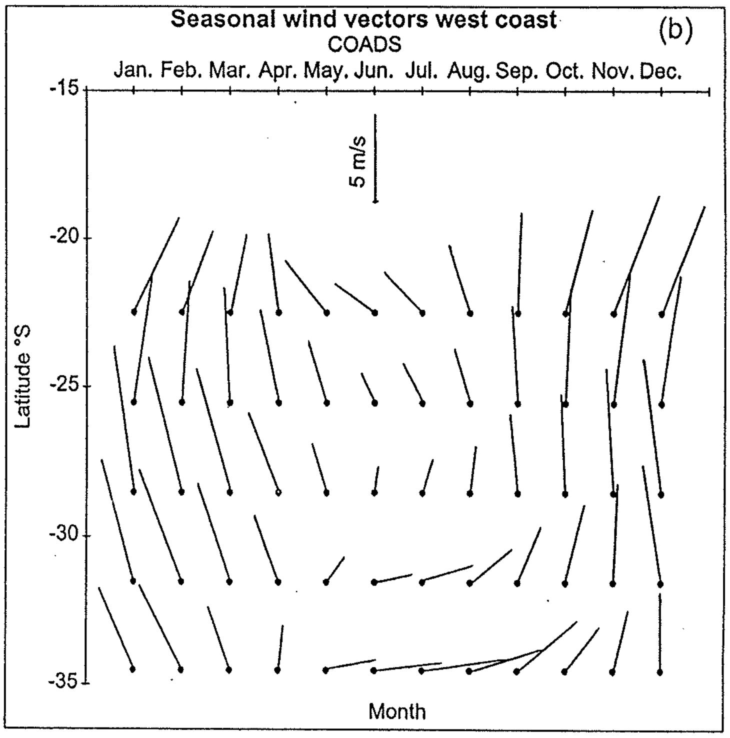
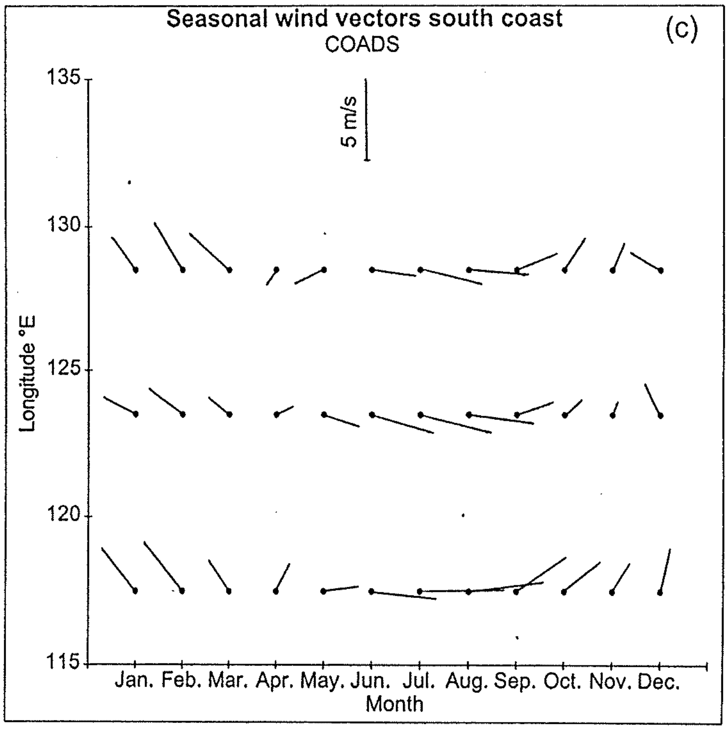
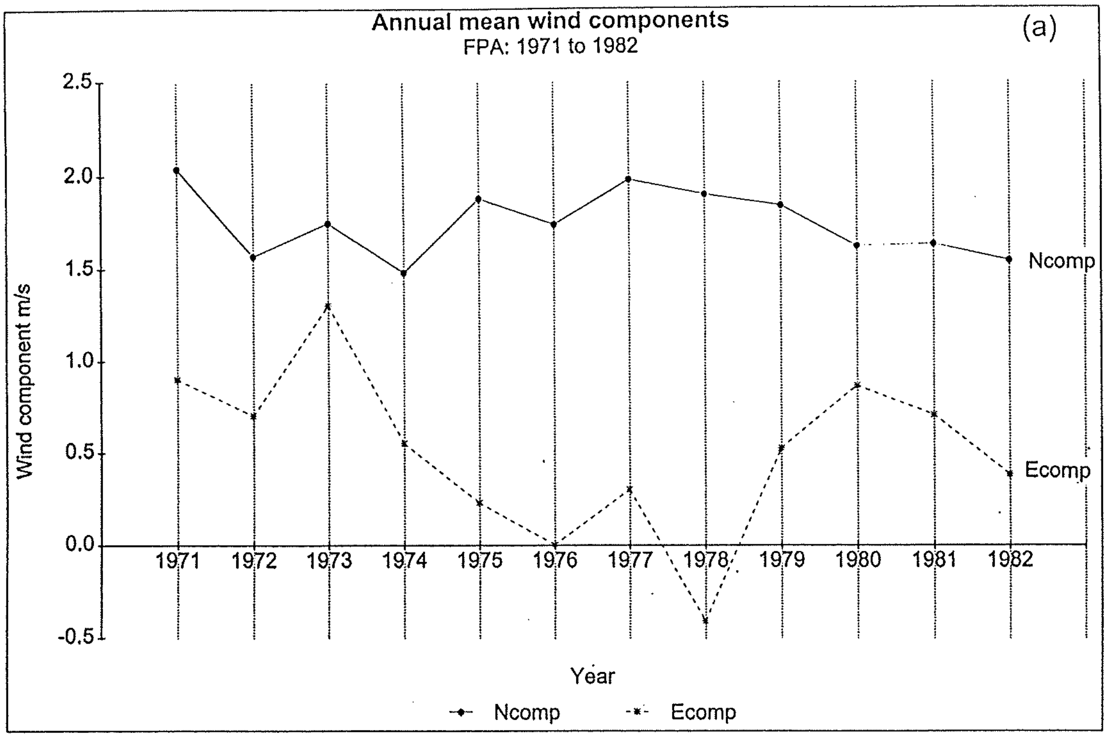


Figure 1.33: Seasonal mean wind vectors for the selected sites along the north (left panel), west (central panel) and south (right panel) coasts, derived from COADS winds over the period 1945 to 1989.



Seasonal wind vectors south coast
COADS
(c)
5 m/s
Longitude °E
135
130
125
120
115
Jan. Feb. Mar. Apr. May. Jun. Jul. Aug. Sep. Oct. Nov. Dec.
Month



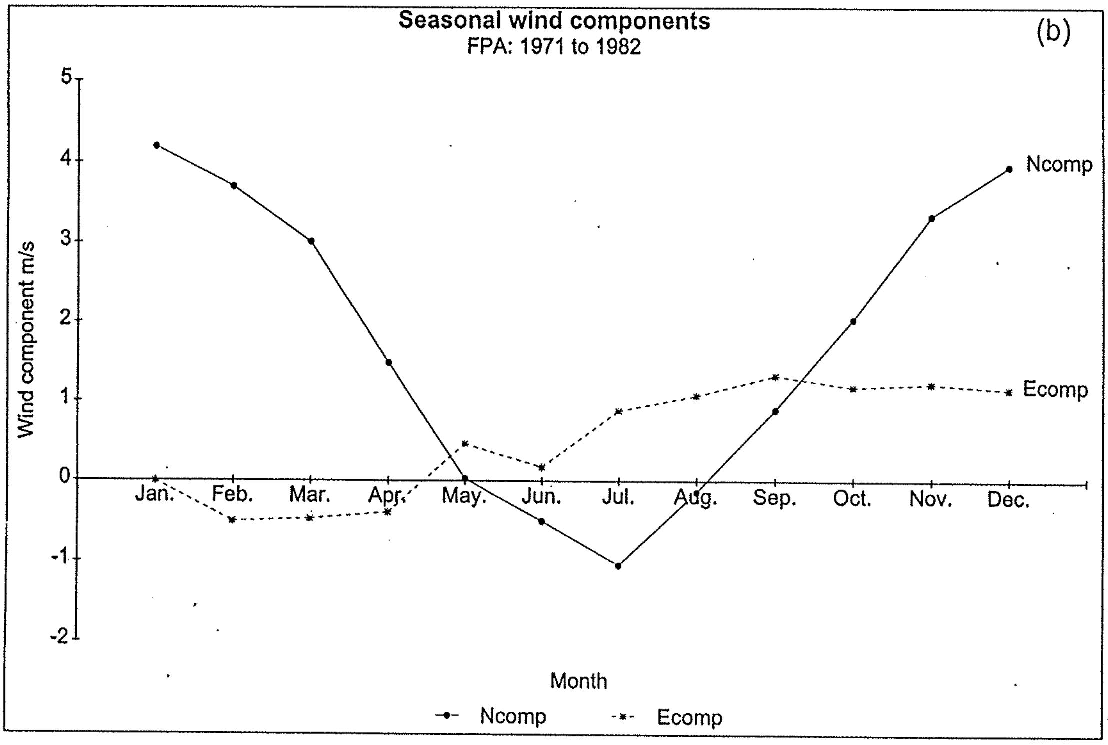


Figure 1.34: (a) Annual mean alongshore (filled circles and solid lines) and onshore (asterisks, dashed) wind components at Fremantle Port Authority, and (b) seasonal wind components.

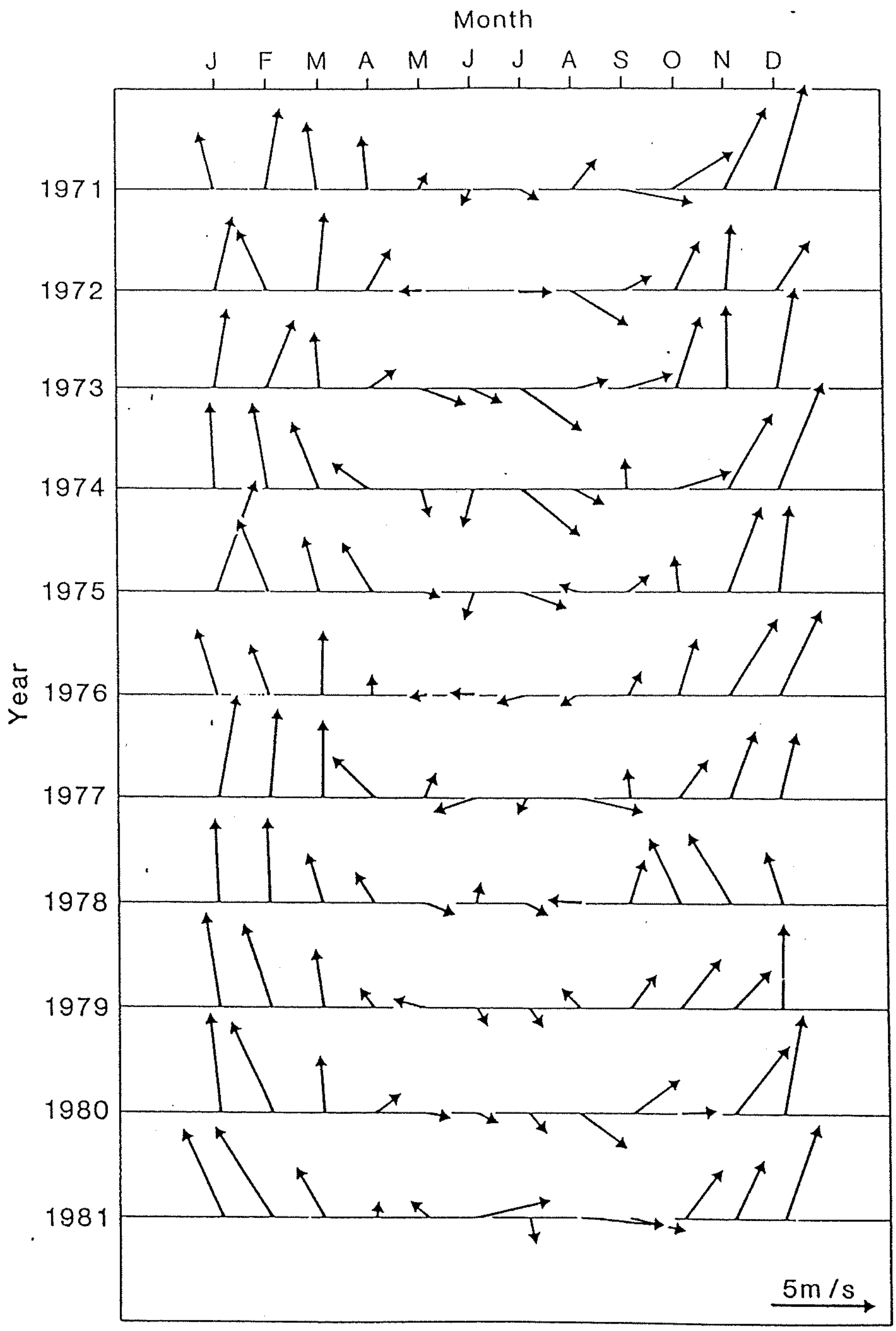


Figure 1.35: Monthly mean wind vectors at Fremantle Port Authority over the period 1971 to 1981 (Pearce, unpublished data).

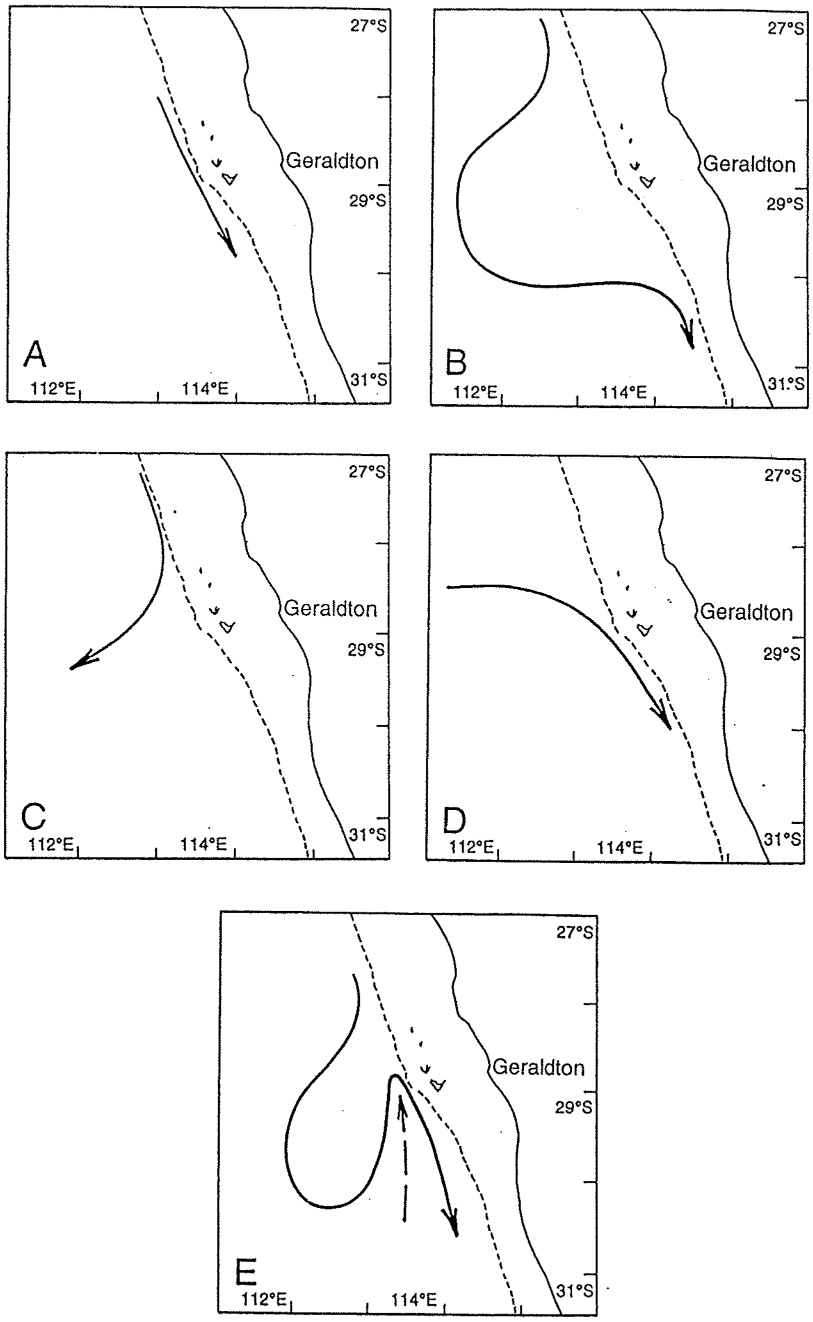


Figure 1.36: Classification of Leeuwin Current patterns off the Abrolhos Islands from AVHRR imagery between 1990 and 1995 (after Pearce 1997).

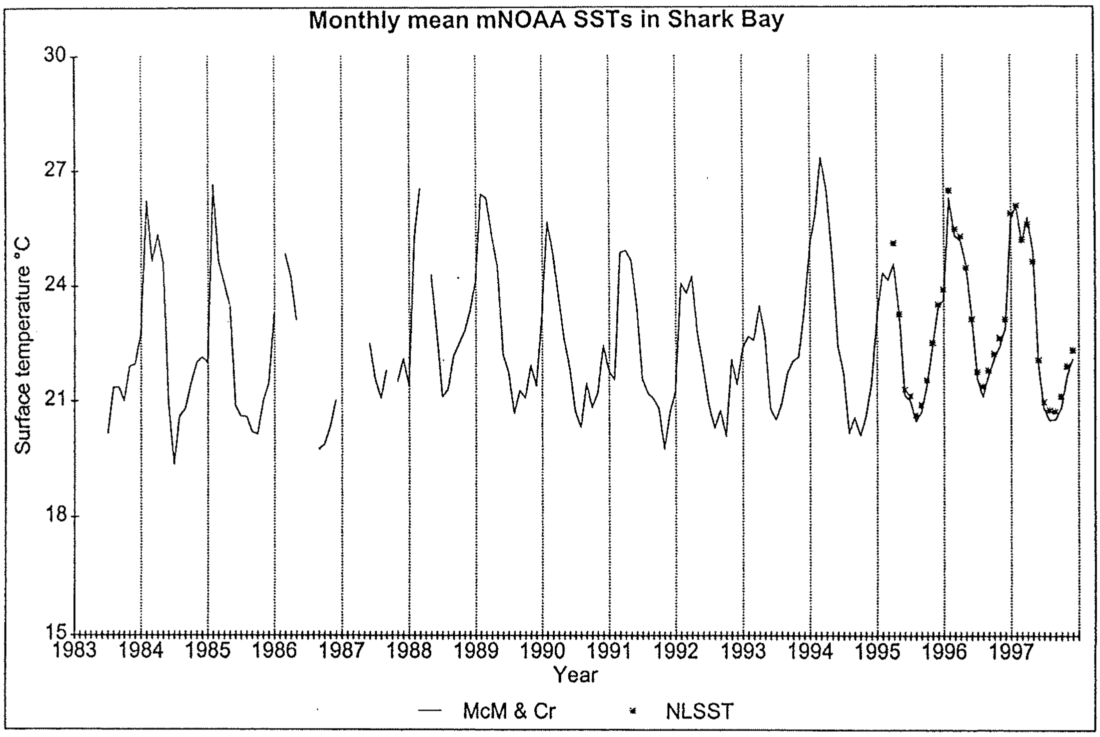
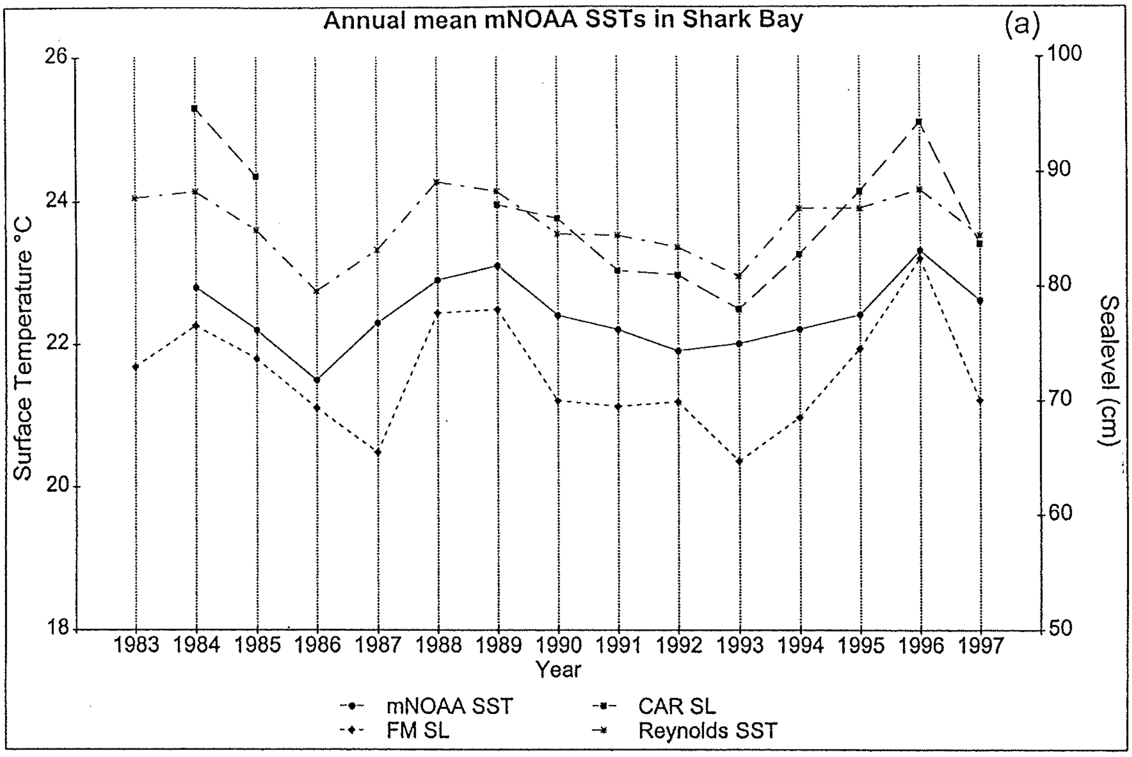


Figure 1.37: Monthly mean SSTs at a site roughly mid-way between Cape St.Cricq and Cape Peron North in Shark Bay derived from NOAA-AVHRR satellite imagery. The McMillin and Crosby SST is the solid line and the NLSST (from 1995) the asterisks (see text).



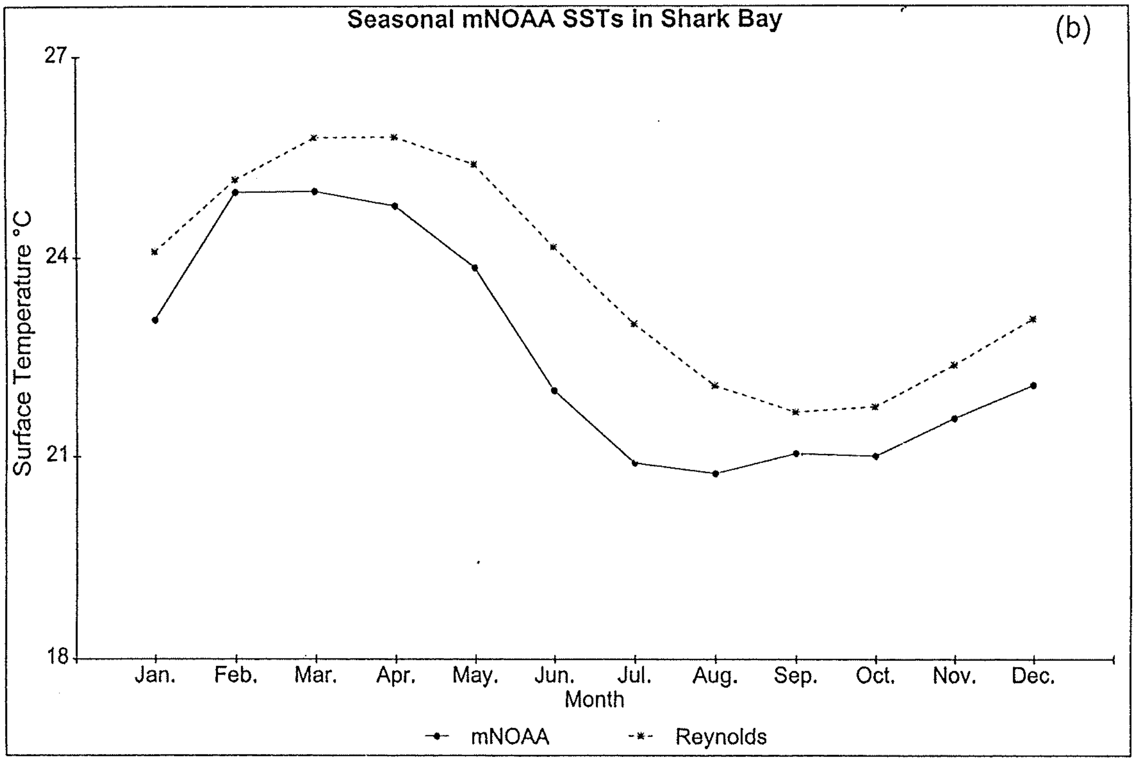
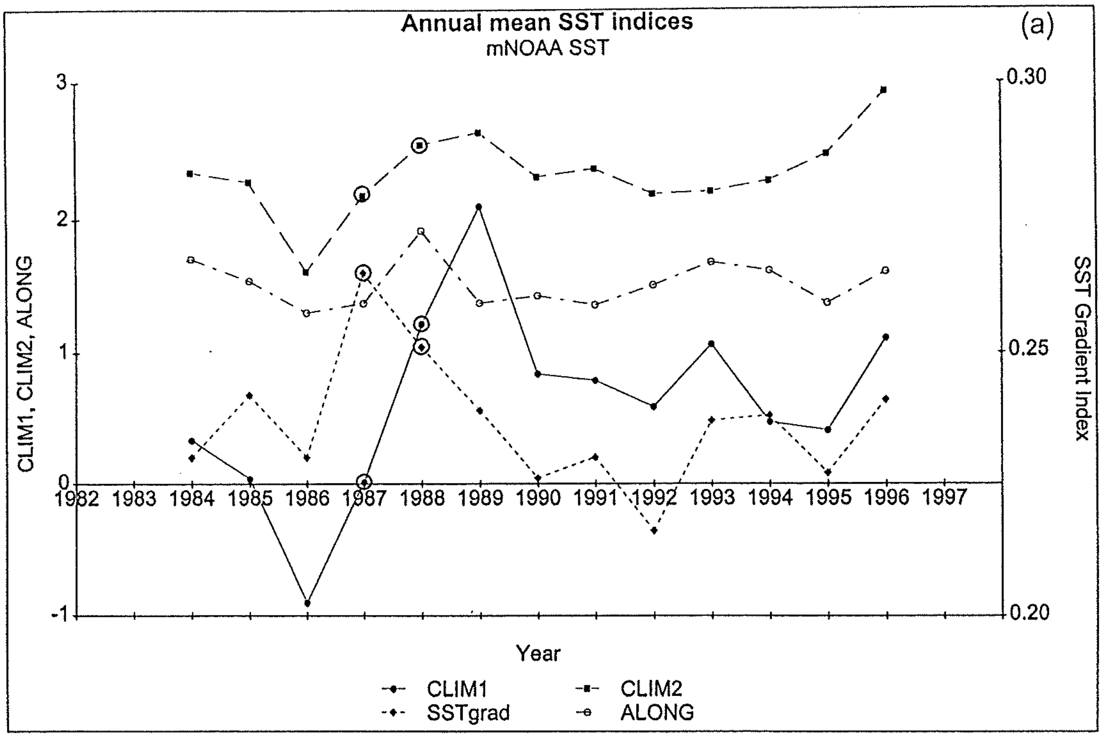


Figure 1.38: (a) Annual mean AVHRR-SSTs (solid circles) at the site described in Figure 1.37, the Reynolds SST in Shark Bay (asterisks), Carnarvon sea level (squares) and Fremantle sea level (diamonds), and (b) the mean seasonal AVHRR-SST pattern at the site in Shark Bay (solid line and circles) compared with that from Reynolds SST (dashed line and asterisks).



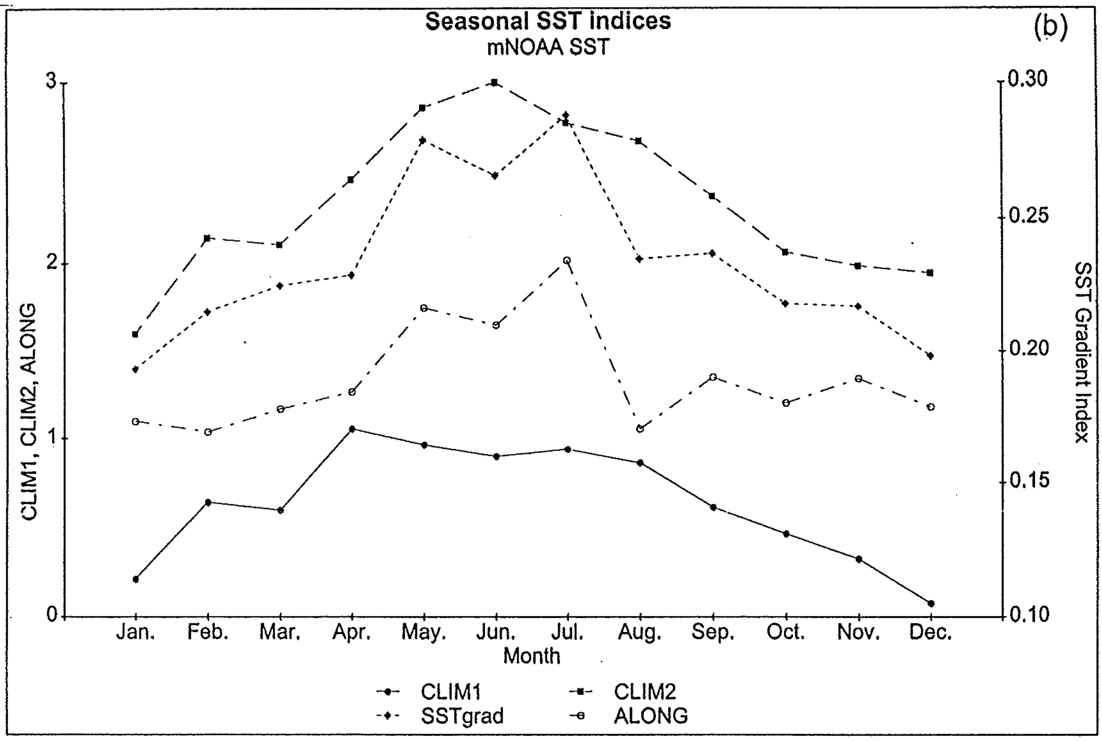


Figure 1.39: (a) Annual and (b) seasonal mean SST mNOAA indices as defined in the text. The points for 1987 and 1988 in (a) are circled because they are based on less than 8 months of data in those years.

2. Western Rock Lobster (N. Caputi, C. Chubb and A. Pearce)

Introduction

The western rock lobster (*Panulirus cygnus*) fishery is Australia's most valuable single species fishery with an average catch of about 11 000 t, valued at about $250 million (1996/97). The Leeuwin Current has been shown to have a positive correlation with the level of puerulus settling in the inshore coastal regions (Pearce and Phillips 1988, 1994; Phillips *et al.* 1991). Caputi *et al.* (1995) investigated the combined impact of environmental conditions, Leeuwin Current strength and westerly winds (Caputi and Brown 1993), and spawning stock in their assessment of the variation of puerulus settlement at Dongara, Alkimos and the Abrolhos Islands. These assessments examined the impact of the current strength (using the annual Fremantle sea level as an index) in explaining the puerulus settlement which mostly occurs during September to January. It is not clear whether the Leeuwin Current assists in the retention of the larvae due to its eddy system and transportation of pueruli to areas of settlement and/or provides conditions which are favourable to survival such as warmer waters. Westerly winds have a positive correlation with puerulus settlement, probably assisting in the transportation of larvae to the coast. Spawning stock was not significant at the coastal locations, although it may have influenced the puerulus settlement at the Abrolhos Islands

Understanding the factors which affect puerulus settlement is important in the management of the fishery, especially as reliable forecasts of the catches are based on the puerulus settlement 3-4 years before. This section examines the effect of the SST on the puerulus settlement and also investigates the relationship between the monthly variation in Leeuwin Current strength, westerly winds and SST, and the annual puerulus settlement using the environmental data described in Section 1.

Methods

Pueruli are caught on collectors of artificial seaweed (Phillips 1972) moored in shallow water locations along the Western Australian coast. Puerulus settlement is seasonal with the peak generally occurring during September to November. The annual index of abundance of puerulus settling is based on the mean number of puerulus caught per collector (Phillips 1972) for the period May to April each year. Currently there are nine collector sites, Shark Bay to Cape Mentelle, throughout the range of the western rock lobster fishery. This study focuses on the coastal sites, Dongara (established 1968) and Alkimos (1982), and the offshore Abrolhos Islands. Collectors were stationed at the Abrolhos Islands between 1971/72 and 1978/79 and then removed but re-installed again in 1984. This study analyses Abrolhos data from four collectors that were repositioned in the same locations to those used in the 1970s.

An index of the strength of the Leeuwin Current is provided by mean annual Fremantle sea level over the calendar year (Pearce and Phillips 1988). Alternative satellite-derived indices of the annual strength of the Leeuwin Current (described in Section 1) are also examined. Monthly rainfall at five locations in the southern part of the fishery is used as an index of the strength of westerly winds over the winter - early spring (July-September) and spring (October-November) periods (Caputi and Brown 1993). The periods are just prior to and during the periods of peak settlement. To assess the impact of westerly winds on the settlement at the Abrolhos, rainfall from three northern locations, Jurien to Geraldton, during July-November has been used. A more direct measure of westerly winds has been obtained using the east-west component of winds at Perth and Geraldton. However this is only recorded 3-hourly and may not accurately reflect the wind conditions offshore.

The average Reynolds SST based on satellite thermal imagery (see section 1) for the region 27°-34°S and 105°-117°E in the south-eastern Indian Ocean has been examined as this region is where most of the western rock lobster phyllosoma larvae are found (Phillips 1981).

Results

The annual puerulus settlement time series at Dongara which provides the longest sequence of puerulus settlement (Figure 2.1) indicates regular cycles of the order of 4-6 years. A feature of the Alkimos time series is that three of the highest puerulus settlements in its 15 year data have occurred over the period 1994/95 to 1996/97 which should result in very good catches in 1998/99 and 1999/2000.

Puerulus settlement at Dongara and the Abrolhos Islands was very similar during the 1970s (Figure 2.1) and was one of the reasons the collectors at the Abrolhos were removed. However the settlement since 1984 has been well below that at Dongara, particularly during the 8 year period 1986/87 to 1993/94, with 1993/94 settlement being the lowest in 21 years of sampling. The good settlements in 1984/85 and 1989/90 at Dongara did not occur in the Abrolhos Islands.

The monthly distribution of puerulus settlement at Dongara indicates the peak settlement occurs during August to November while at the offshore Abrolhos Islands the peak occurs about 2 months later over the period October to January (Figure 2.2). It is also evident that there was good settlement occurring in October at the Abrolhos Islands in the 1970s whereas this is not evident since 1984. Alkimos and other coastal sites are generally similar to Dongara.

The influence of the Leeuwin Current on the puerulus settlement continues the pattern described by Pearce and Phillips (1988, 1994) with the annual variation in the current being influenced by the impact of ENSO events (Figure 2.3). Also, the strength of the westerly winds (rainfall) continues to be significantly related to the strength of the puerulus settling on the coastal sites (Caputi and Brown 1993, Caputi *et al.* 1995) . The multiple correlation of 0.74 between puerulus settlement at Dongara and the Leeuwin Current strength and rain (Oct.-Nov.) is significantly greater than for sea level alone (0.66). Thus both of these environmental factors contribute to the variation in puerulus settlement (Caputi *et al.* 1995).

The above assessment of the Leeuwin Current has focused on the annual sea level, however, the current strength during certain months may be more critical than others on the level of puerulus settlement (Caputi *et al.*1996a). The correlation between the monthly Leeuwin Current index and the annual puerulus settlement shows a consistent pattern over each location with a peak in the correlation for April followed by a second peak in August or later, during the time of settlement (Figure 2.4). This pattern is consistent for settlement data collected in the 1970s at Garden Island, since the early 1980s at Alkimos and Cape Mentelle, and for data collected over both periods at Dongara, Jurien and Abrolhos Islands.

By April the larvae have generally moved off the continental shelf (Phillips *et al.* 1979) after hatching during the late spring/summer period (Nov.-Feb.) and this is also the period when the Leeuwin Current is strengthening. The correlation using the April sea level with the annual puerulus settlement is generally as good as when using the average sea level for the whole year. Hence the April sea level enables an early estimator of the puerulus settlement strength later in the year. Figure 2.5 shows the relationship of the puerulus settlement at Dongara with the April sea level and the impact of westerly winds, measured using rainfall, near the period of peak settlement (Caputi *et al.* 1996b).

The effect of the monthly variation in the Leeuwin Current on the puerulus settlement in the southern-most sampling location, Cape Mentelle, shows a similar pattern in the correlation to other locations (Figure 2.4). However, in this case, annual sea level has a higher correlation (r=0.93) with puerulus settlement at Cape Mentelle than any individual month. At this location little or no settlement occurs unless the Leeuwin Current strength is above average (Figure 2.6). Phillips *et al.* (1991) suggested that the proximity of the Leeuwin Current to the coast off Cape Mentelle during the settlement period may also be important, with better settlement occurring when the current is close inshore than when it is offshore. The timing of the settlement in the southern locations is consistent with the transport mechanism (Chubb unpublished data). The extended ENSO event which occurred in the early 1990s has caused particular concerns for fishermen in this area as little or no settlement was recorded over four years.

At the Abrolhos Islands the overall correlation between monthly sea level and settlement is generally lower as other environmental factors (negative impact of westerly winds) and the level of the spawning stock may also be affecting settlement (Caputi *et al.* 1995, 1998). However the peak correlations in April and August are still evident as well as a strong peak in December which needs further assessment. For most of the coastal locations over 75% of settlement occurs up to November so that environmental variables after this period would not be expected to have any major effect on the overall puerulus settlement. However peak settlement at the Abrolhos Islands lags coastal settlement by about two months (Figure 2.2) with about 50% of settlement occurring from December onwards; factors contributing to the variation in sea level during December may be having an impact on the overall settlement. The sea level during December is generally low (Figure 1.9) indicating that the Leeuwin Current is not flowing strongly during this period and, in fact, a net northerly movement of the alongshore drift occurs along the shelf during November to March (Cresswell *et al.* 1989). The multiple correlation of the puerulus settlement at the Abrolhos with the sea level in December and the westerly winds in October-November is 0.78 (Figure 2.7). Since this correlation with the December sea level was first observed (Caputi *et al.* 1996b), the very good puerulus settlement for 1995/96 was associated with a very strong December sea level and the very low puerulus settlement for 1997/98 was associated with a very low December sea level (Figure 2.7). However until further information is available on reasons for the later settlement period at the Abrolhos Islands and the significance of current movements in the December period, this correlation will only be used as the basis for generating a possible hypothesis.

The temperature anomaly for the Reynolds SST based on satellite thermal imagery for the lower west coast region, 27°-34°S and 105°-117°E, indicates below average temperatures for the

1982, 1986 and 1990-94 which generally follows the trend in the Leeuwin Current and ENSO events (Figure 2.3). The relationship between the mean annual sea level and the Reynolds temperature in the lower west coast shows a correlation of 0.76 (Figure 2.9). However some years such as 1994 have an above average SST despite a weak Leeuwin Current occurring that year. This may explain the good puerulus settlement which occurred that year, particularly in the Alkimos region.

The impact of the SST by month on the annual puerulus settlement was undertaken. This showed that SST between February and April at the coastal locations of Dongara, Jurien and Alkimos, appeared to have the highest correlation with the annual puerulus settlement which peaked in September-October later that year (Figure 2.10). The Abrolhos Islands showed a similar pattern but the peak correlations occurred with the SST a month later, March to May.

The correlation between the SST over the February-April period and the puerulus settlement at Dongara was 0.83 for the period 1982/83 to 1995/96 and the multiple correlation is 0.89 after including the effect of westerly winds during October-November (Figure 2.11).

The Leeuwin Current thermal indices CLIM1, SSTgrad and ALONG were not significantly related to the puerulus settlement at the coastal sites (Dongara and Alkimos) nor at the Abrolhos. Only CLIM2 was significantly related to Alkimos puerulus settlement ($r=0.79$, $p=0.001$, $n=13$). Alkimos puerulus settlement has a similar correlation using the SST (February-April).

Discussion

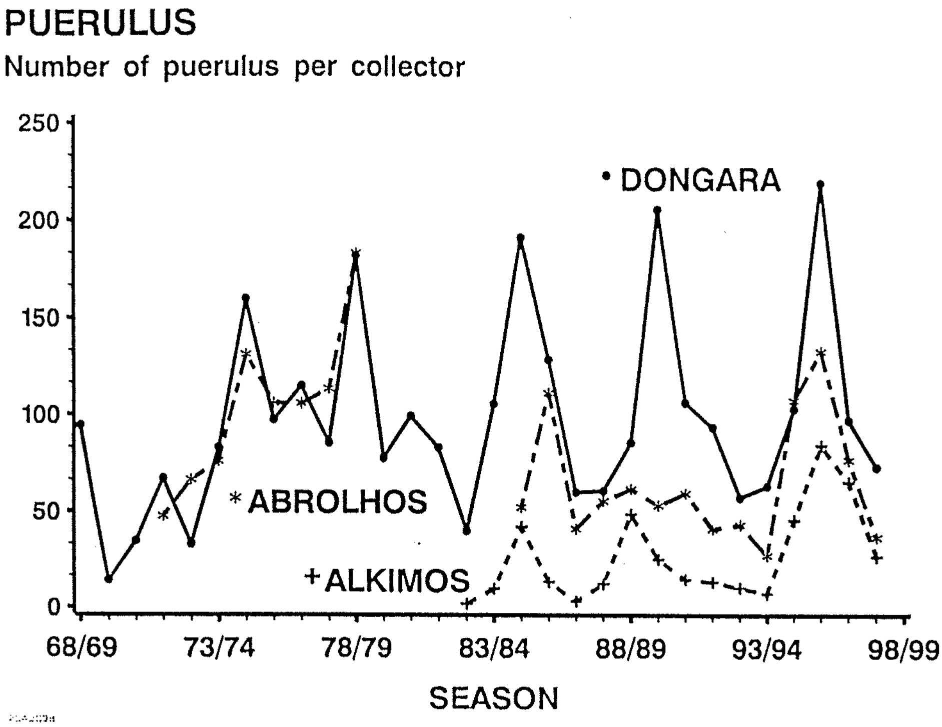
This study shows that the environment is the main cause of the fluctuations in the puerulus settlement in the coastal sites of Dongara and Alkimos over the time period examined. This confirms the results of Pearce and Phillips (1988), Caputi and Brown (1993), and Caputi *et al.* (1995) on the influence of the Leeuwin Current and westerly winds on the coastal puerulus settlement; the latter study also showed that the spawning stock was not significant. This study shows that the effect of the Leeuwin Current when it begins to strengthen during the February to April period may be critical and that the effect of the SST during this period may be influential in the level of puerulus settlement

While the processes that determine how the Leeuwin Current affects puerulus settlement are not clear, it is evident that more puerulus settle in non-ENSO (La Nina) years when the Leeuwin Current is flowing strongly (as measured by the sea levels) and the SST is above average than during ENSO periods. The influence of the current on the larval life could be two fold. Firstly, the increase in temperature associated with a stronger Leeuwin Current in April may improve growth and survival of the larvae. Laboratory examination of factors affecting larval survival and growth indicate the warmer waters could help reduce intermoult periods, increase the incremental growth and survival of the larvae (Baldo Marinovic pers. comm.). While the current flows generally along the edge of the continental shelf, it also penetrates offshore where the larvae are at this time (see Figure 1.14). Secondly, the current may also help through larval retention by eddies and in the transport of the latter stages of larvae across the continental shelf into coastal reef nursery areas (Pearce and Phillips 1994), especially for the southern locations like Cape Mentelle (Phillips *et al.* 1991, Chubb unpublished).

The decline in puerulus settlement at the Abrolhos between 1986/87 and 1993/94 may have been caused by two factors - environmental and/or spawning stock. That is, the environmental conditions may have changed between these periods causing an adverse effect at the Abrolhos but not for the coastal locations. Caputi *et al.* (1995) showed that this decline in puerulus settlement at the Abrolhos Islands coincided with the decline in the spawning stock. They hypothesised that the Abrolhos being situated off-shore and closer to regions where the pool of larvae occurs, there may be a more direct relationship between the spawning stock and puerulus settlement with the environment contributing less to the variation in puerulus settlement.

The inverse relationship between the Abrolhos settlement and the strength of the westerly winds is opposite to the effect shown for coastal locations. Thus the westerly winds which help the return of the late stage larvae to the coast may be providing a negative impact for the Abrolhos Islands (60 km off-shore). The very low rainfall associated with the good puerulus settlement in 1994/95 helps to confirm the effect of this environmental variable. Nevertheless, this environmental factor does not explain the major decline in puerulus settlement. The sea level in December, which may reflect the northerly current flow at this time of year, appears to explain some of decline in puerulus settlement in the late 1980s and early 1990s and may also explain the recent good settlement in 1995/96 and poor settlement in 1997/98.

An FRDC project is in progress which may assist in understanding the mechanism which is causing this significant correlation of December sea level. This project involves using satellite altimeter to measure surface currents to help develop a three-dimensional data-assimilating model of the ocean dynamics off Western Australia which should help provide some insight into the environmental factors affecting puerulus settlement. This may assist in resolving the relative importance of larval transport by the Leeuwin Current compared to the influence of SST on larval survival.



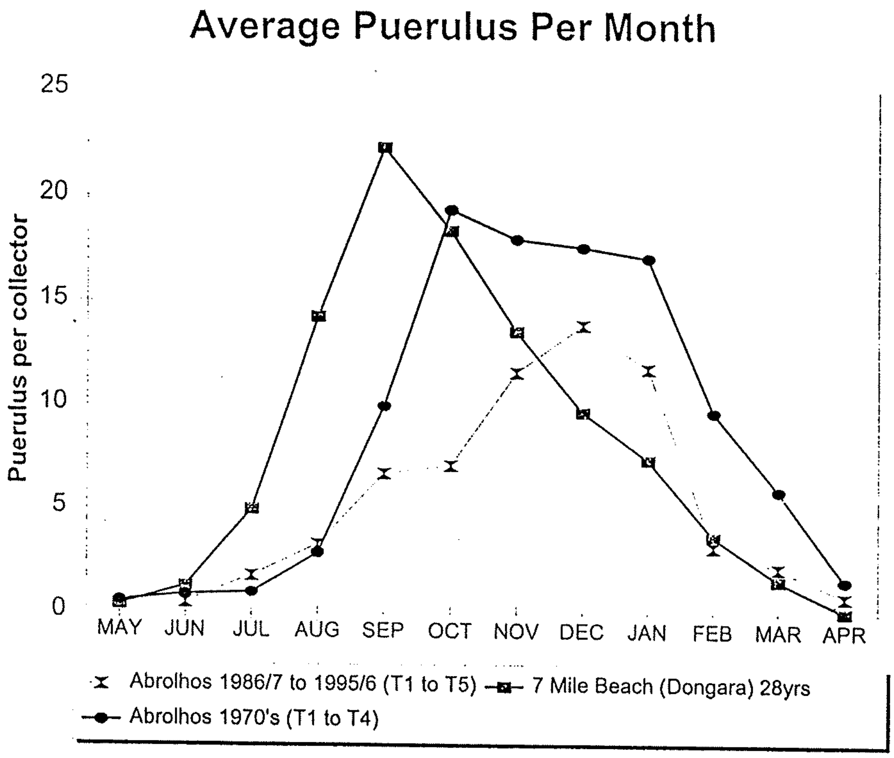


Figure 2.1 (top): Time series of annual puerulus settlement at Dongara, Alkimos and Abrolhos Islands

Figure 2.2 (bottom): Average monthly puerulus settlement at Seven Mile Beach (Dongara, squares) and Rat Island (Abrolhos Islands, for 2 different periods, circles and triangles)

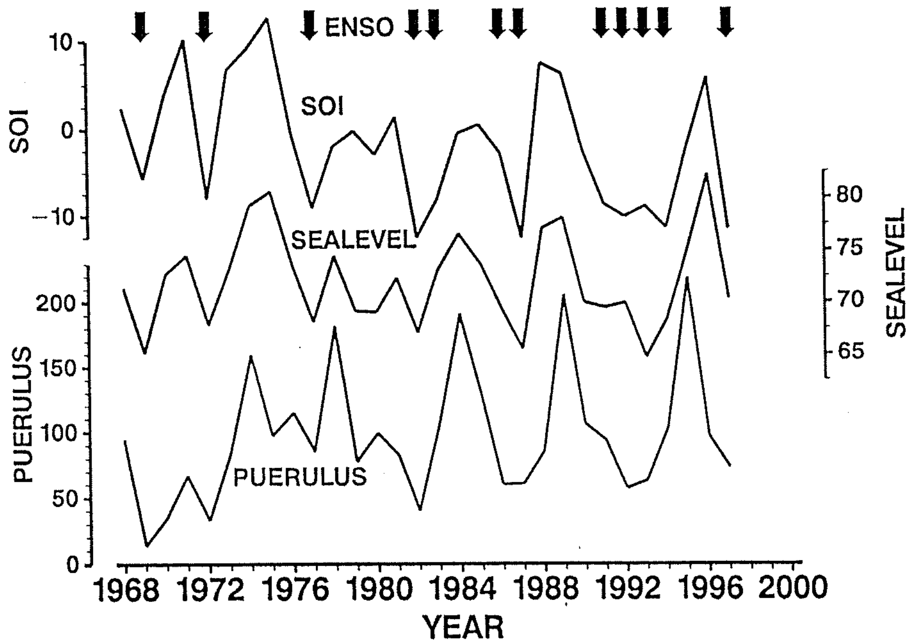


Figure 2.3: Annual mean values of the Southern Oscillation Index (SOI), Fremantle mean sea level, and puerulus settlement at Seven Mile Beach, Dongara, between 1968 and 1997. ENSO periods are indicated with arrows.

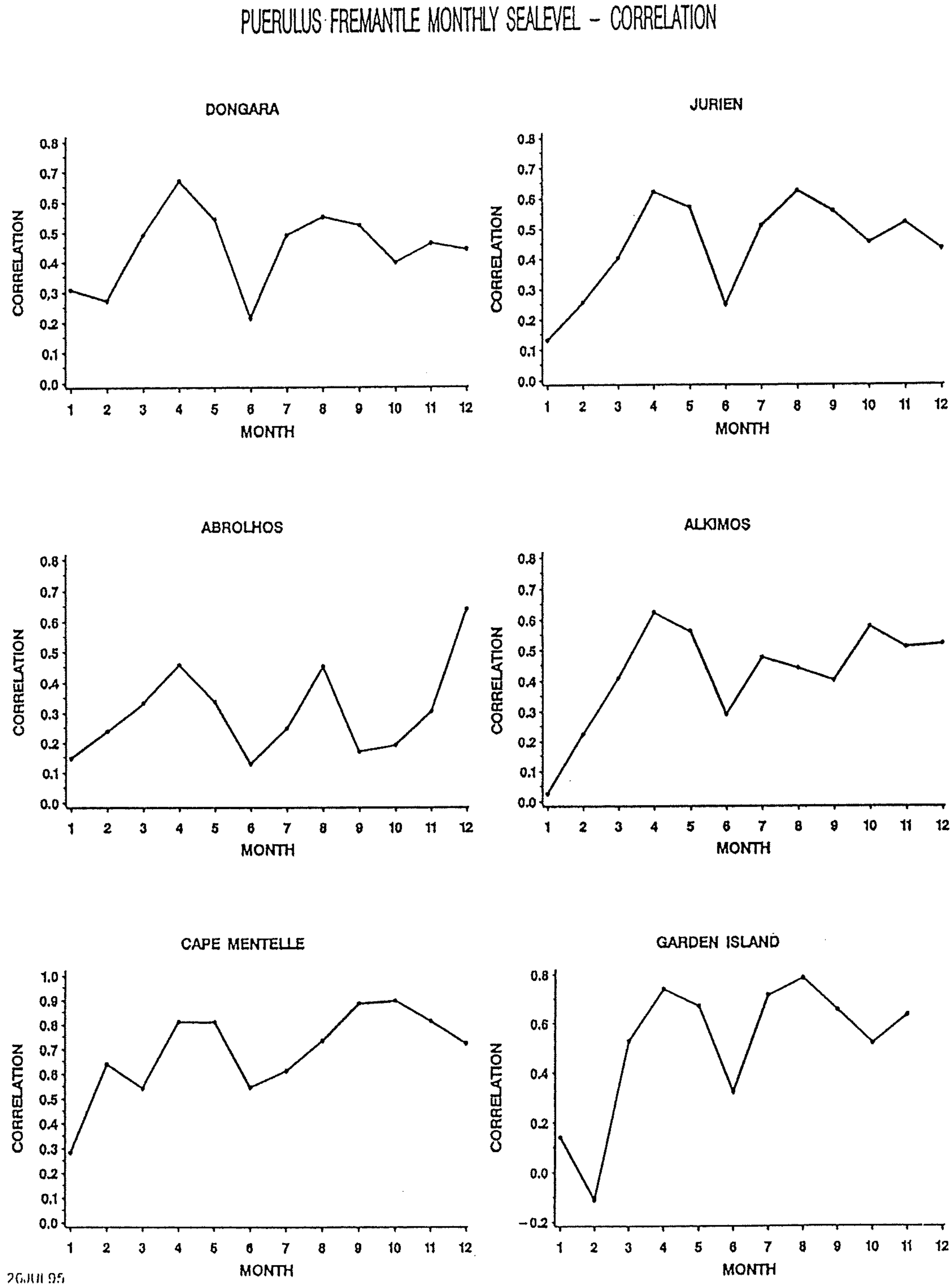
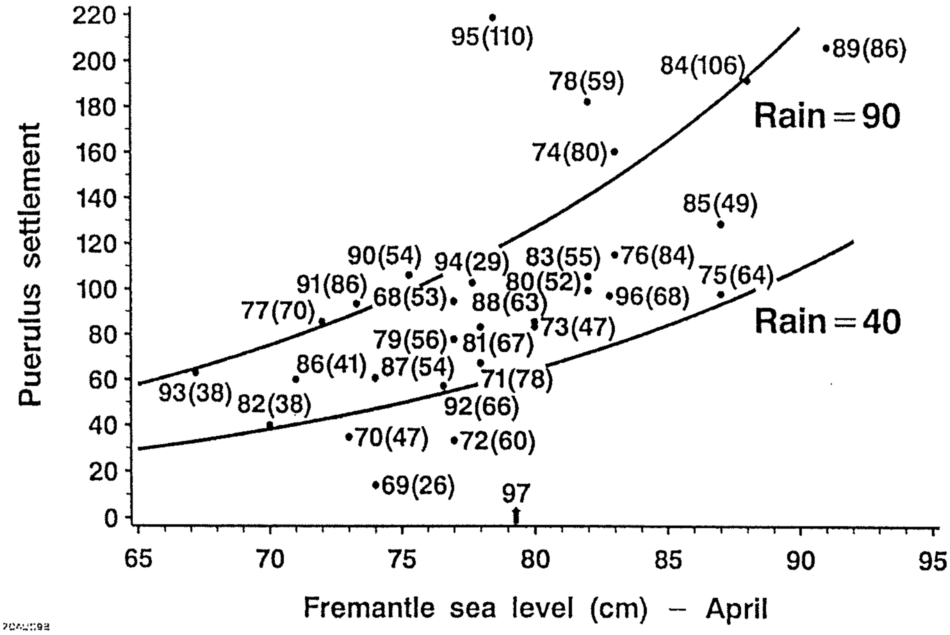


Figure 2.4: Correlations between the monthly Fremantle sea level (an index of the strength of the Leeuwin Current) and the annual puerulus settlement for six locations. The settlement occurs mostly between September and January.

Puerulus Dongara – Sea level (April)

(Rain South Oct–Nov)



PUERULUS (CAPE MENTELLE) – LEEUWIN CURRENT

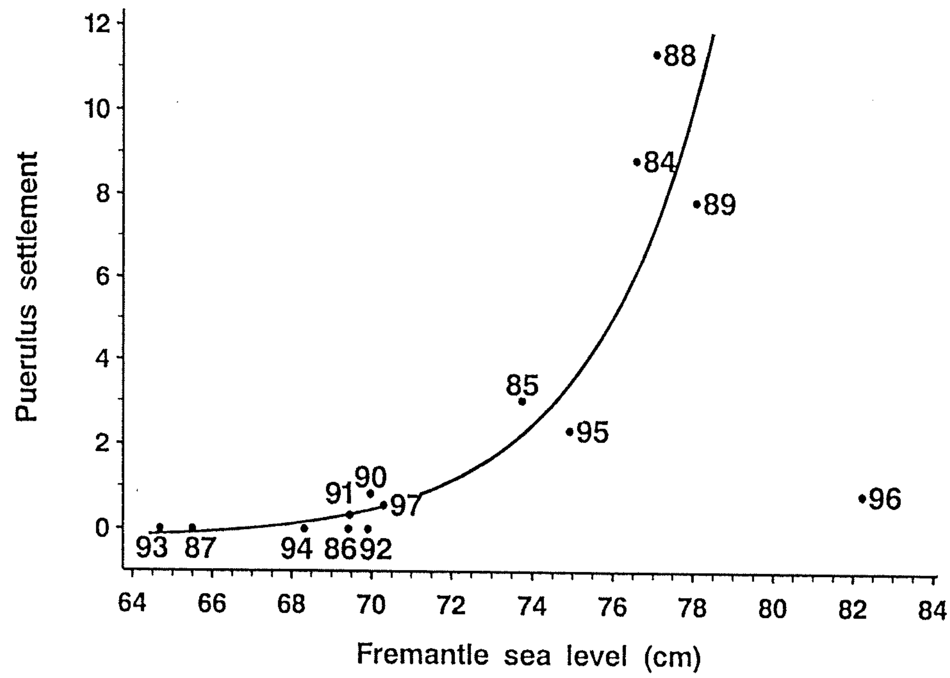
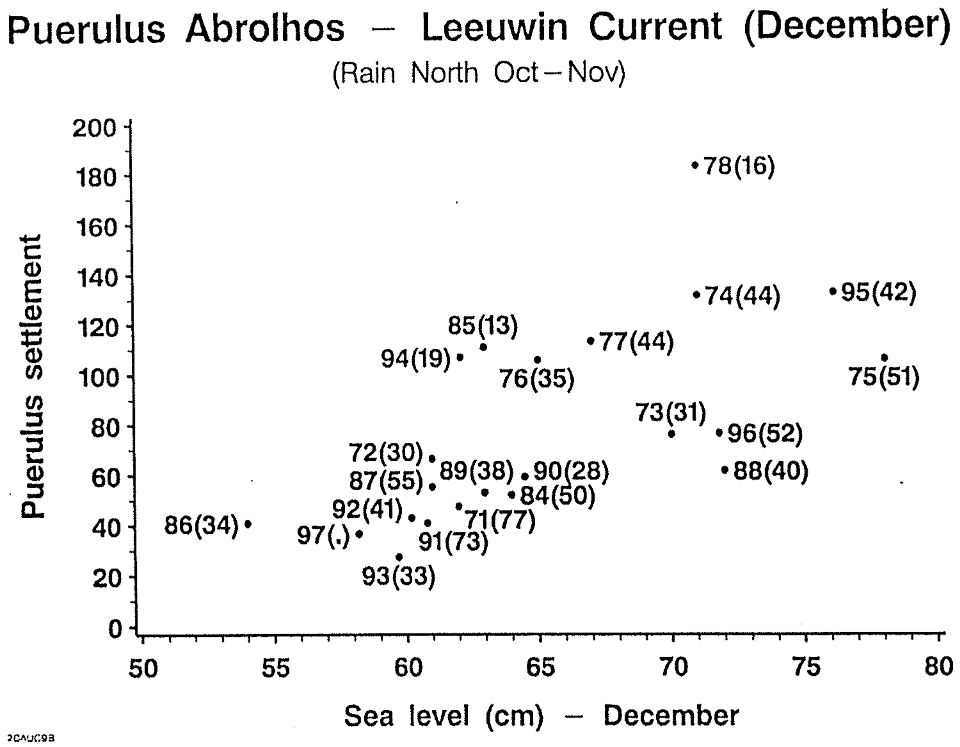


Figure 2.5 (top): Multiple regression relationship between the annual puerulus settlement (mean number per collector) at Dongara which peaks during September-January and the Fremantle sea level (an index of the strength of the Leeuwin Current) in April, at two levels of rainfall (in mm, an index of the strength of westerly winds) in October-November. The year and rainfall (in brackets) are indicated.

Figure 2.6 (bottom): Relationship between annual Fremantle sea level (an index of the strength of the Leeuwin Current) and the annual puerulus settlement at Cape Mentelle (mean number per collector) which commences later in the same year. The year is indicated.



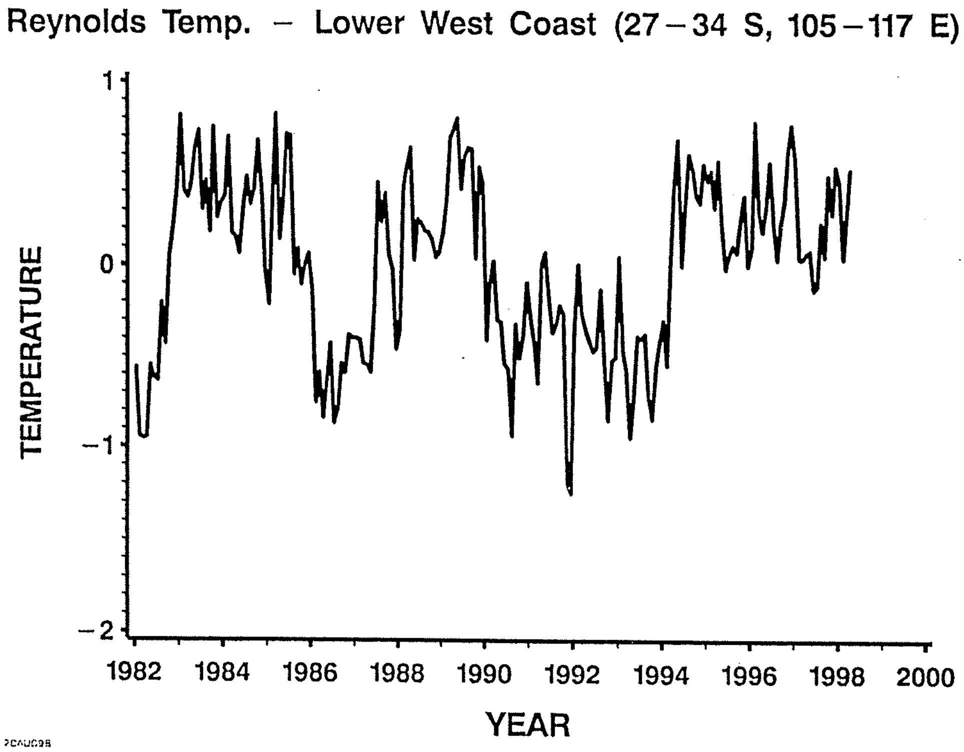


Figure 2.7 (top): Relationship between the annual puerulus settlement (mean number per collector) at the Abrolhos Islands and Fremantle sea level in December. The year and rainfall (in mm, an index of the strength westerly winds, in brackets) in October-November are indicated.

Figure 2.8 (bottom): Monthly Reynolds SST for the block 27° to 34°S, 105° to coast of Western Australia.

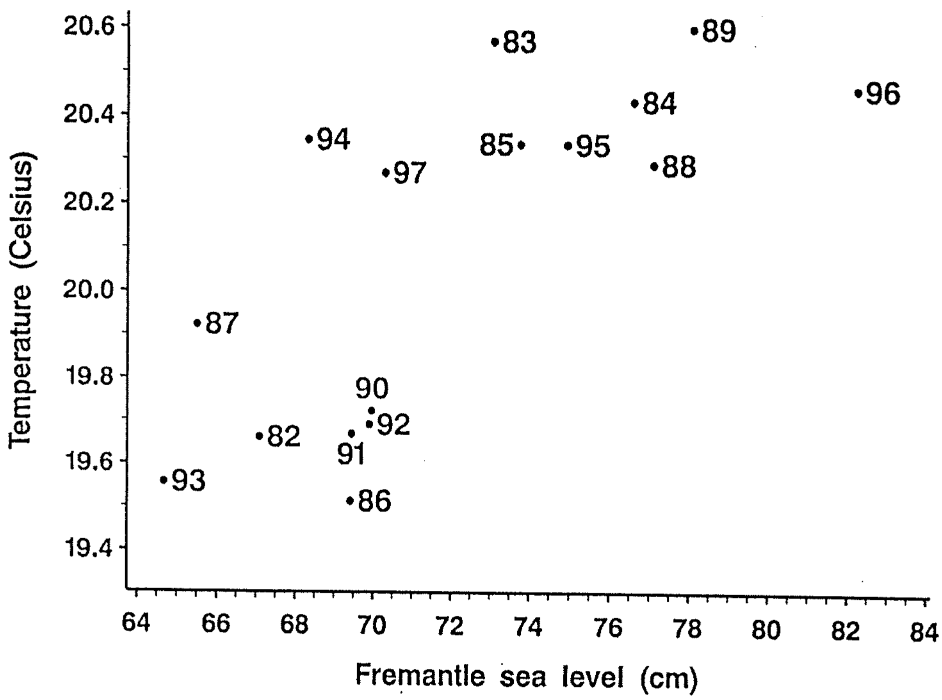


Figure 2.9: Relationship between annual Fremantle sea level and Reynolds SST for the lower west coast of Western Australia.

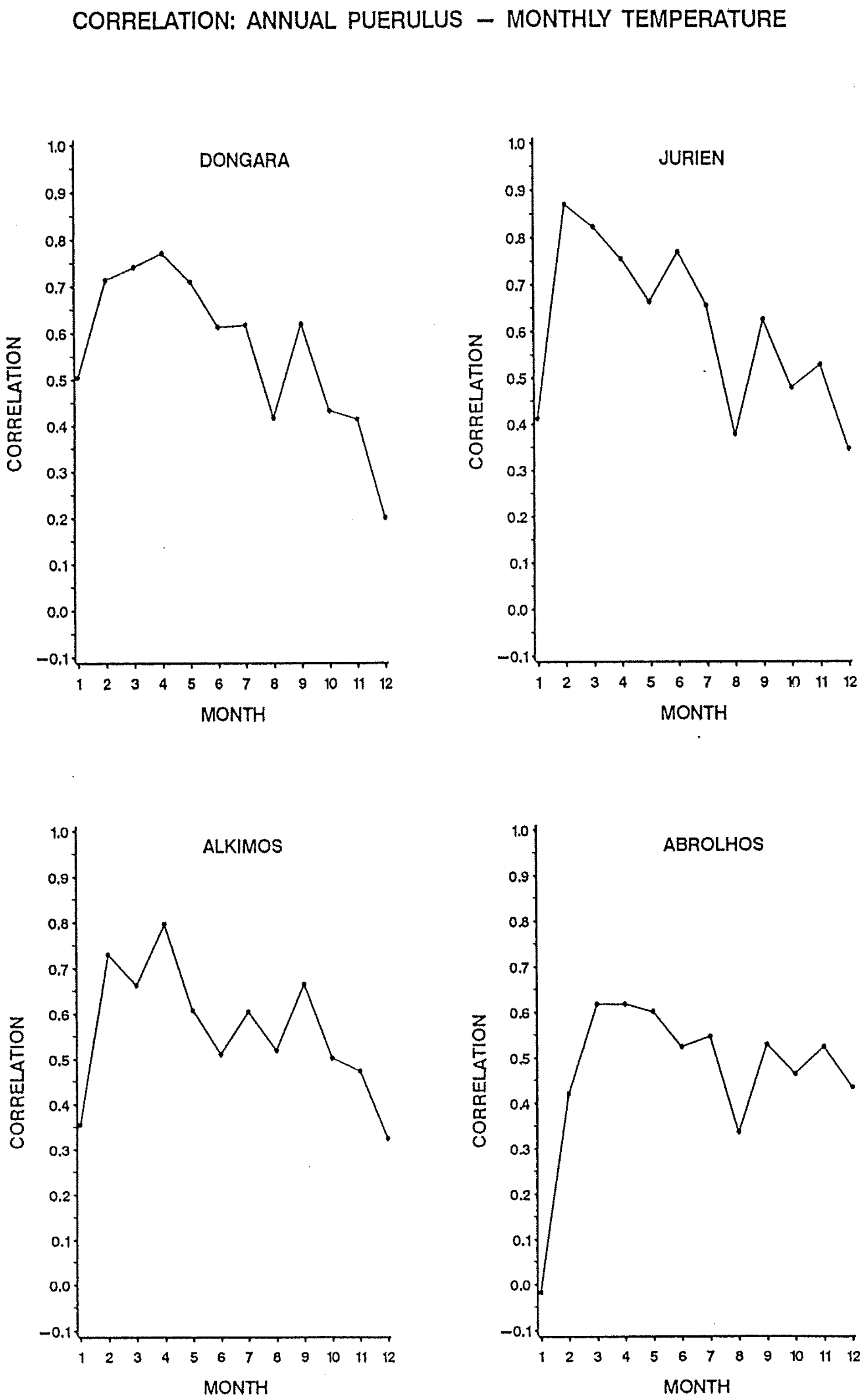


Figure 2.10: Correlations between the monthly Reynolds SST for the lower west coast and the annual puerulus settlement for six locations. The settlement occurs mostly between September and January.

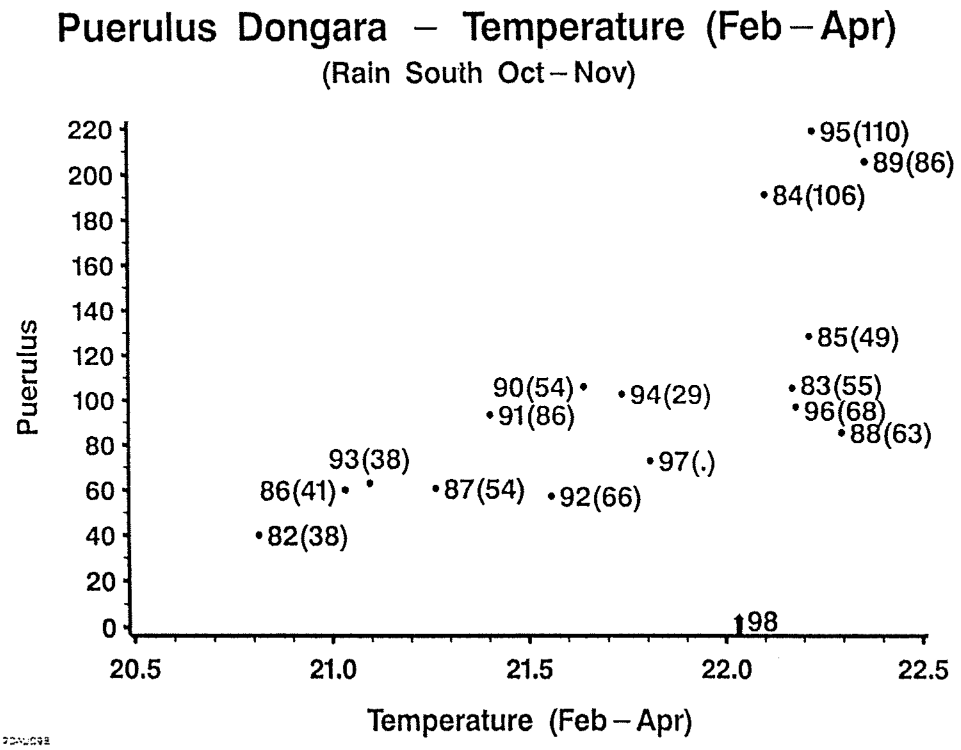


Figure 2.11: Relationship between the annual puerulus settlement (mean number per collector) at Dongara which peaks during September-January and the Reynolds SST for the lower west coast in February-April. The year and rainfall (in mm, an index of the strength westerly winds, in brackets) in October-November are indicated.

3. Scallops (N. Caputi, R. Watson, L. Joll and A. Pearce)

Introduction

Catches of the saucer scallop, *Amusium balloti* (Bernardi), in Shark Bay (Figure 3.1) have shown a greater than an order of magnitude difference in catches since 1984, ranging from 121 t. meat weight in 1989 to 4414 t in 1992. This trawl fishery began in 1966 as a by-catch of the trawl fishery for prawns. The fishery has been fully exploited since 1984, with current access being limited to 14 scallop-only vessels (using 100 mm minimum mesh size) and 27 vessels with prawn and scallop licences which use 50 mm mesh.

The scallop fishery at the Abrolhos Islands is generally smaller than Shark Bay with catches ranging from 10 to 528 t since 1983 when the fishery became heavily exploited. There are currently 16 licences in the fishery (Harris *et al.* in press).

Surveys designed to measure the abundance of pre-recruits to the Shark Bay scallop population each year have indicated that these catch variations were primarily the result of inter-annual variations in recruitment. Scallop populations throughout the world are acknowledged as having highly variable recruitment as a result of the influence of environmental factors (Hancock 1973). Environmental factors which may be responsible for the variations in recruitment in *A. balloti* in Shark Bay were therefore investigated. Also, to enable the proper assessment of the stock-recruitment relationship, the effect of the environment needs to be taken into account, especially during the vulnerable larval phase of the life history.

Observation of satellite imagery of Shark Bay showed that tongues of warmer water, derived from the south-flowing Leeuwin Current, enter the Bay during the critical spawning period; the current also flows near the Abrolhos Islands which are about 60 km offshore. This study updates the results of Joll and Caputi (1995a) on the inter-relationships between the strength of the Leeuwin Current and the abundance of pre-recruit scallops in Shark Bay (see also Caputi *et al.* 1998), and investigates the effect of the current on the scallop catch near the Abrolhos Islands

The life history of *A. balloti* has been described in Joll (1987, 1989) and Joll and Caputi (1995a). In Shark Bay, gametogenesis commences in late March/early April and spawning occurs from April/May until December. The planktonic larval life lasts 14 - 21 days (Rose *et al.* 1988). Growth of new recruits is rapid, with scallops spawned in at least the first 3 to 4 months of the spawning season reaching a size suitable for commercial harvest (90mm shell height) by March or April the following year (Joll 1987). The new recruits from a spawning season develop reproductively in the following year and enter the breeding stock.

At the Abrolhos Islands the spawning cycle is about three months behind Shark Bay, with spawning occurring between August and the following March (Joll 1989, Joll and Caputi 1995b). The fishery which occurs between April and June is based on 1+ year old scallops after they have spawned.

Methods

Pre-recruitment surveys have been conducted in Shark Bay in November each year since 1983 using the 20 m RV "Flinders". Because of the fast growth rate, much of the new recruitment is catchable by trawling at this time of year using 50 mm mesh nets. These surveys estimate the abundance of pre-recruits from the current spawning season and these pre-recruits enter the fishery in the following year.

Surveys are conducted using systematic sample trawling to cover the approximately 1000 km^2 of the two known fishing areas (Figure 3.1). Approximately 70 trawls of 20-30 min duration are carried out at night (to standardize for possible diurnal variations in catchability) using twin 11 m headrope trawls with 50 mm mesh nets and 45 mm codends. The catches are standardized for the distance travelled. The main grounds (the larger of the two survey areas in Figure 3.1) provide the most consistent area of fishing, with little fishing occurring on the Denham Sound ground from 1985 to 1990. Hence the indices of abundance have been determined separately for the main grounds and Denham Sound. Recruitment to the main fishing grounds has been separated into two parts: the Red Cliff (northern half) and North West Peron (southern half).

Survey data are separated into recruit and residual scallops. There is generally very little overlap between the two groups in size frequency distributions in November. The largest recruit scallops are rarely larger than 75 mm shell height, while the smallest residual animals are rarely smaller than 75 mm. Thus recruits have been defined as scallops less than or equal to 75 mm shell height. However, the upper limit of recruit sizes and the lower limit of residual sizes is checked each year by examining the daily growth rings present on the left valve (Joll 1988).

Regular surveys have not been conducted at the Abrolhos Islands and the annual catch taken by the fishery operating April to June is used as the abundance index since 1983 when the fishery could be regarded as fully exploited. The fishery is generally dominated by 1+ year old scallops.

Years of strong recruitment appear to be associated with successful spawning in the period April to July in Shark Bay (Joll and Caputi 1995a). Consequently, in considering the effects of the Leeuwin Current on scallop recruitment measured in the November survey, the strength of the current in these months is likely to be important. As the peak in the sea level at Fremantle occurs about a month after the peak at Carnarvon (Figure 1.9) as a result of the southward moving current, the sea level over the months of May to August at Fremantle was used to examine the influence of the Leeuwin Current in Shark Bay during April to July. Alternative satellite-derived indices of the annual strength of the Leeuwin Current (described in Section 1) are also examined.

At the Abrolhos the relationship was examined between the annual catch in April to June and the Leeuwin Current strength for the spawning period August, 2 years before, to March the previous year. This period encompasses the current strength over two cycles of the current as it weakens over the period August - September and then strengthens over the period February - March the following year (Figure 1.9). Unlike Shark Bay, the peak month in sea level between Fremantle and Geraldton (near the Abrolhos Islands) is the same, viz. June (Figure 1.9).

As the influence of the Leeuwin Current on the larval life may be due to the impact of the current on the SST, the Reynolds SST data was examined for the blocks just outside Shark Bay (24° to 26°S, 112° to 113°E) and the blocks inside Shark Bay (24° to 26°S, 113° to 114°E)

Results

The relationship between the average Fremantle sea level (cm) over the months of May to August for a given year and the subsequent abundance of recruits in the main fishing ground (log transformed) as measured by the November survey in Shark Bay of that year has a correlation of -0.58 ($P<0.05$) for the 15 years of data between 1984 and 1997 (Figure 3.2). The correlation was higher for the northern Red Cliff grounds, -0.69 ($P<0.01$), than for the North West Peron grounds, -0.42 ($P>0.05$), while the correlation with the Denham Sound ground was -0.30 ($p>0.05$).

The relationship between recruitment in the main fishing ground (log transformed) and the Reynolds SST in the blocks outside and inside Shark Bay resulted in a correlation of -0.47 ($P=0.07$) and -0.41 ($p>0.10$), respectively. As for the sea level, the correlation was higher for the northern Red Cliff grounds, -0.67 ($P<0.01$), than for the North West Peron grounds, -0.29 ($P>0.05$), and Denham Sound ground, -0.24 ($p>0.05$). The four satellite-derived Leeuwin Current indices described earlier were not significantly related to the scallop recruitment in Shark Bay.

At the Abrolhos Islands the correlation between the the annual catch (log transformed) and the Leeuwin Current strength during the spawning period August, 2 years before, to March the previous year was -0.61 ($p=0.15$, $n=15$) (Figure 3.3). Examination of the correlation between annual catch and the individual monthly sea levels over this spawning period resulted in correlations between -0.49 to -0.61 for each of the 8 months except for November ($r=-0.35$). The correlations for the months before and after this spawning period were generally lower indicating that this was the critical period which influenced recruitment. This relationship indicates that a low catch is expected in 1998 and that the 1999 catch should improve.

Discussion

Irregular recruitment as a result of environmental variation was considered by Hancock (1973) to be a general characteristic of scallop populations. Massive increases in the abundance of the Chilean scallop *Argopecten purpuratus* were noted to be associated with the El Nino event of 1982/83 (Arntz 1984; Wolff 1987). Wolff considered that factors improving the survival of recruits may include a shortened larval period due to increased temperatures, maintenance of adequate oxygen levels and reduction in the abundance of many predators.

Dickie (1955) observed that the recruitment of *Placopecten magellanicus* in the Bay of Fundy area was related to water temperature. He discussed the influence of water temperature on the duration of the larval period and found that low water temperatures reflected a high level of exchange between the Bay of Fundy and outside water masses. This high level of exchange was considered to lead to heavy losses of larvae. Caddy (1979) noted nine year cycles in landings of *P. magellanicus* from the Bay of Fundy, which corresponded to similar cycles in tidal features. He hypothesized that these tidal influences controlled the degree of retention of larvae within a gyre and this influenced recruitment to scallop grounds in its vicinity.

Hydrological flushing was considered by Caddy (1989) as an important environmental influence on recruitment success in sedentary molluscs. Retention of larvae within the water mass is of particular importance to the recruitment success of estuarine species (Andrews 1983) but has also been shown to be important for pelagic fish (Iles and Sinclair 1982).

In this study, the inverse relationship between the sea level and subsequent recruitment indicates that the recruitment will be highest during years when the Leeuwin Current is weak and the coastal sea levels are low. This corresponds to years of El Nino/Southern Oscillation (ENSO) events. During the period on which this model is based, 1983 to 1997, there was one ENSO event in 1987 and this corresponded to a high recruitment in the November surveys in Shark Bay (Figure 3.2) and a good catch of 731 t in the following year. Another ENSO event occurred in 1982, the year before the November surveys began, and this also corresponded to a high catch of 703 t in 1983. The strong recruitment in 1990 was responsible for record catches in 1991 and 1992, with a record catch in 1992 of 20 000 t. live weight which was five times greater than the highest catch prior to this recruitment (Joll 1994). Thus years of good recruitment in 1982, 1987 and 1990 in Shark Bay have all corresponded to ENSO periods which have been shown to be associated with years of weaker Leeuwin Currents (Pearce and Phillips 1988). However the weak Leeuwin Current in 1993 has only produced an average recruitment.

At the Abrolhos Islands the years of good catches 1983-84 and 1993-96 are also associated with ENSO years and years of weak Leeuwin Current strength during the spawning period (Figure 3.3). However some years of weak Leeuwin Current strength were not associated with good catches in subsequent years (1988-89 and 1992). This indicates that while the weaker Leeuwin Current appears be required for good recruitment to occur there are other environmental factors which may prevent this good recruitment from occurring. These could include local wind conditions affecting the current in the region of the scallop fishery

The relationship of the environmental factors was better with the recruitment in the northern part of the main fishing ground indicating that the influence of the Leeuwin Current entering Shark Bay from north of Bernier Island may be greater than the effect of the current entering from south of Dorre Island.

The mechanism of action of the environment on recruitment success has yet to be identified; it may refer to hydrological flushing in years of strong Leeuwin Currents or a temperature effect on spawning or fertilization because of warmer waters. Examination of the satellite SST did not result in an improvement of the relationship, however, this may be due to the reliability of the satellite SST within an enclosed region like Shark Bay. At this stage general environmental indicators such as Leeuwin Current strength and SST from satellite data have been used to assess the effect on recruitment and these explain the level of recruitment for most but not all years. However the effect of local environmental conditions such as wind strength and current strength in Shark Bay and the Abrolhos may provide more direct environmental measures. These may explain the recruitment in the years which are not currently being explained.

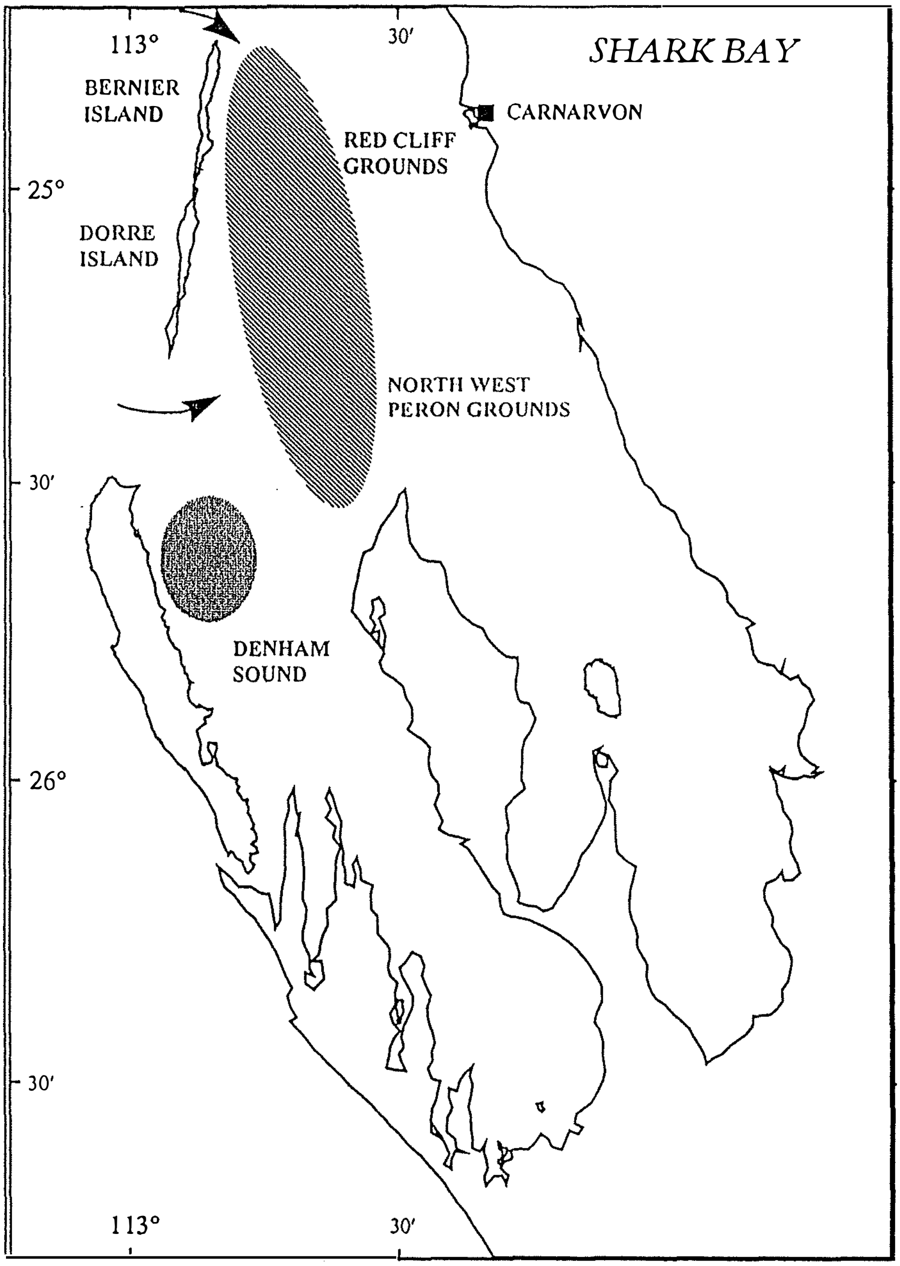
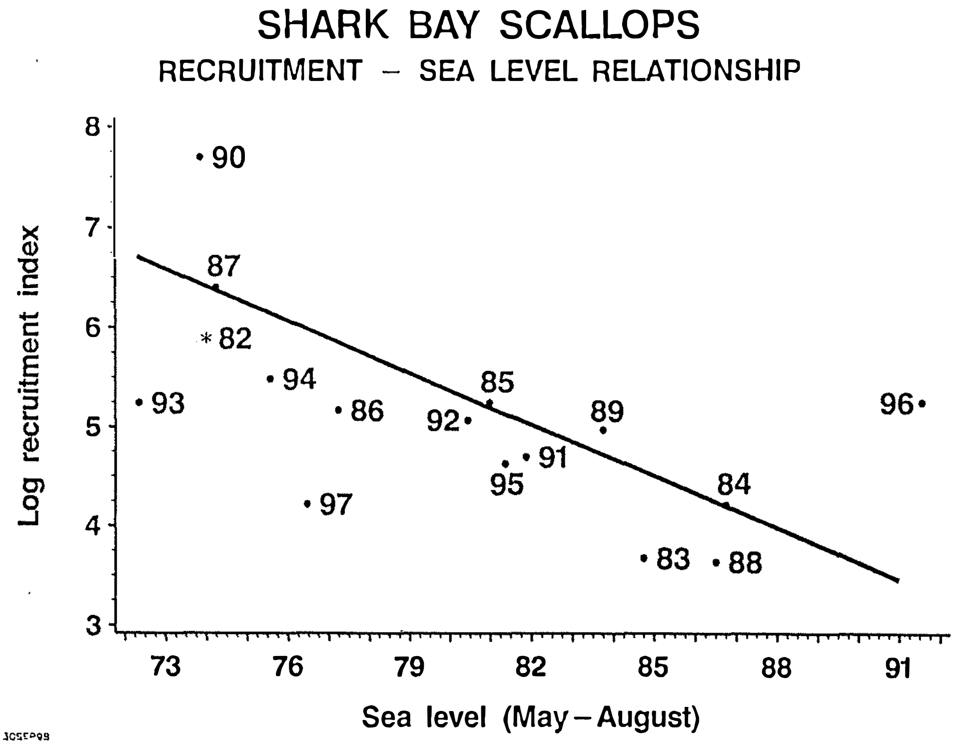


Figure 3.1: The major scallop fishing locations in Shark Bay; the arrows indicate Leeuwin Current water entering Shark Bay.



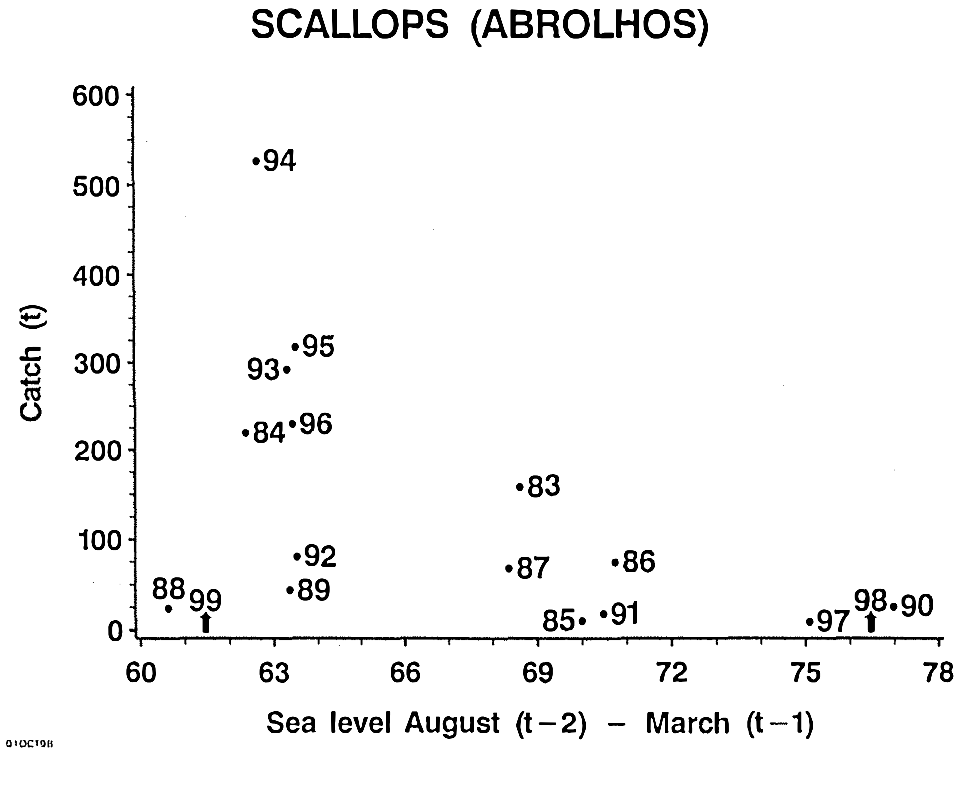


Figure 3.2 (top): Relationship between the log transformed recruitment in the Shark Bay scallop fishery and the strength of the Leeuwin Current during May-August (measured by the Fremantle sea level in cm). The year is indicated. The recruitment index for 1982 was estimated from the catch data.

Figure 3.3 (bottom): Relationship between the catch in the Abrolhos Islands scallop fishery and the strength of the Leeuwin Current (measured by the Fremantle sea level in cm) during the spawning period between August 2 years before the catch year (t-2) to March 1 year before (t-1). The catch year is indicated.

4. Western King Prawn (N. Caputi, R. Watson, J. Penn and A. Pearce)

Introduction

The Shark Bay prawn fishery is the largest prawn fishery in Western Australia with the king prawn (*Penaeus latisulcatus*) being the major species in the fishery. Lenanton *et al.* (1991) identified a positive relationship between the strength of the Leeuwin Current on the recruitment of the western king prawn fishery in Shark Bay. The present study provides an update of this relationship.

Methods

The recruitment of king prawns occurs during the period March to May. However the catch rates during this recruitment period cannot be used because of changes in management such as area closures during March and April to prevent the taking of the smaller prawns. Only the catch rates in May have been consistent in the recruitment area over the years and are used as the basis for determining the recruitment index. This catch rate in May is adjusted for the catches taken in March and April and correcting for the different levels of effort in May (Caputi 1989).

As the influence of the Leeuwin Current on the prawn recruitment may be due to the impact of the current on the SST, the Reynolds SST data was examined for the blocks inside Shark Bay (24° to 26°S, 113° to 114°E).

Results and Discussion

The correlation of the recruitment index with the Fremantle sea level during the period March to August indicates that this correlation was significant during the April - May period, having a correlation of 0.60 ($p=0.001$) (Figure 4.1). Because of the lag in the sea level height between Fremantle and Carnarvon in Shark Bay of about a month (Figure 1.9), the April - May period for sea level at Fremantle corresponds to the March - April period in Shark Bay. This period coincides with the time of the Leeuwin Current strengthening and the start of the recruitment period of the king prawn fishery in Shark Bay.

Examination of the effects of SST from the Reynolds dataset indicates no significant correlation with prawn recruitment. However, the use of satellite SST information may be unreliable in a confined area close to the land like Shark Bay. The effect of water temperature may need to be further tested with *in situ* measures such as temperature loggers.

The influence of the Leeuwin Current occurs at the time of migration of the prawns to the fishery from the nursery area and hence may affect the catchability, growth and/or survival of the migrating prawns. Computer simulations of the effect of the annual temperature cycle on catchability indicate catch variations of about 20% can result from the timing of the temperature decline starting in May/June (N Hall pers. comm.).

The influence of the current on the recruitment phase of the life cycle is in contrast to its effect on other fisheries where the major influence of the current is during the larval life.

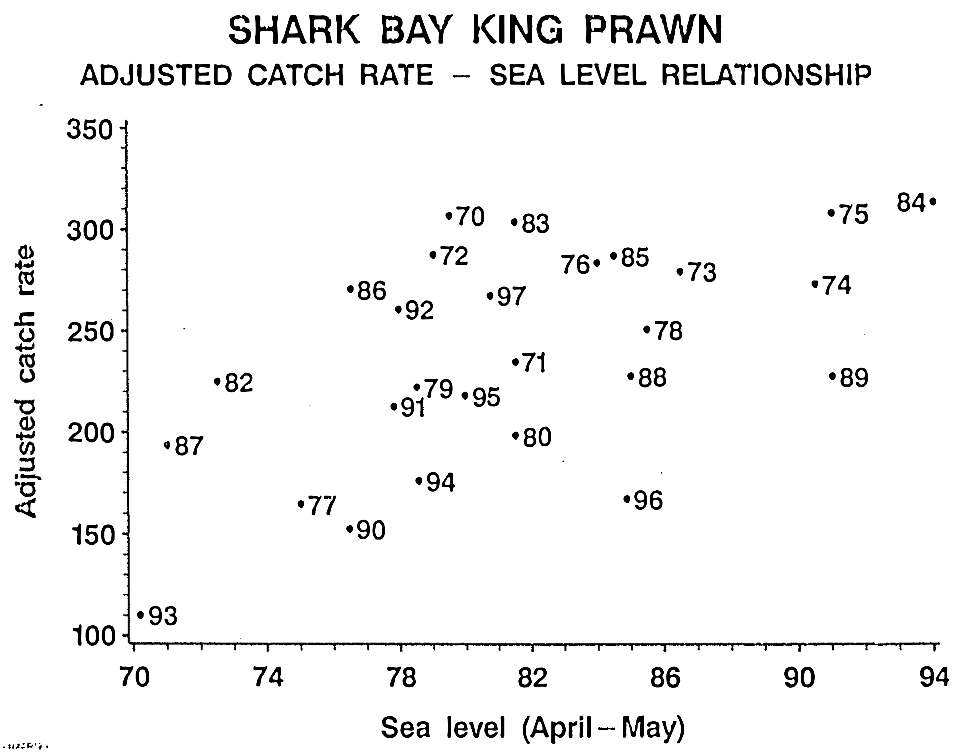


Figure 4.1: Relationship between the adjusted catch rate of king prawns in Shark Bay and Fremantle sea level in April - May. The year is indicated.

5. Banana Prawns (R. Watson, J. Penn, N. Caputi)

Introduction

Banana prawns (*Penaeus merguiensis*) are the main species caught in the Nickol Bay prawn fishery. This is the third largest prawn fishery in Western Australia with catches generally ranging from about 50 to 250 t since the fishery commenced in 1966, with a maximum catch of about 450 t in 1967 and 1976. This large annual variation in catch is similar to other banana prawn fisheries in Australia. Work undertaken on the banana prawn fishery in the Gulf of Carpentaria showed that rainfall during the wet season (January to March) at the time of juvenile migration from the estuaries into the fishery was the key environmental factor affecting recruitment (Rothlisberg *et al.* 1985). The impact of summer rainfall generally associated with cyclones has also been observed to affect the banana recruitment in Nickol Bay and this relationship is examined in this section.

Methods

The catch data from this fishery are obtained from monthly returns and are available for the period that the fishery has been operating, 1966 to 1997. However in the first year of the fishery there was only one boat operating and hence results shown are based on catches from 1967 onwards. The catch was logarithmically transformed to take into account its skewed distribution when assessing the affect of the rainfall data.

The rainfall data was obtained from Roebourne for the cyclone wet season period, December to March, as this is the period of emigration of juvenile prawns from estuaries into the offshore fishery. As the cyclonic rainfall may be influenced by ENSO events, the relationship between the southern ocscillation index (SOI), rainfall and catch are also examined.

Results and Discussion

The relationship between catch (log transformed) and rainfall showed a significant positive correlation of 0.75 ($p<0.001$) (Figure 5.1). The two best catches of about 450 t in 1967 and 1976 were associated with rainfall of about 350 mm over the four months, while rainfalls of less than 100 mm resulted in catches between 20 and 70 t. Thus the 1997/98 rainfall of 45 mm would predict a below average catch about the 20-70 t range in 1998.

The SOI over the December to March period was significantly correlated with the rainfall over this period ($r=0.46$, $p<0.01$, $n=31$) and it had a lower correlation with log transformed catch of 0.34 ($p=0.06$). The low rainfall for the 1997/98 summer period would have been influenced by the ENSO event in 1997/98. This indicates that ENSO events are usually associated with a reduced number of cyclones, and hence lower summer rainfall. However the rainfall over this period is clearly a better direct indicator of likely catch, having a correlation of 0.75.

This relationship between catch and rainfall is thus similar to that obtained in the Gulf of Carpentaria banana prawn fishery. The causal factor responsible for the relationship is probably the enhanced survival of the juvenile prawns from their predators as they migrate from the estuaries. It may also be due to the increased number of juveniles which are flushed out of the estuary to the area that the fishery operates. This relationship has been useful to the fishermen and the managers of this fishery in providing an understanding of the catch fluctuations and a forecast of the catch.

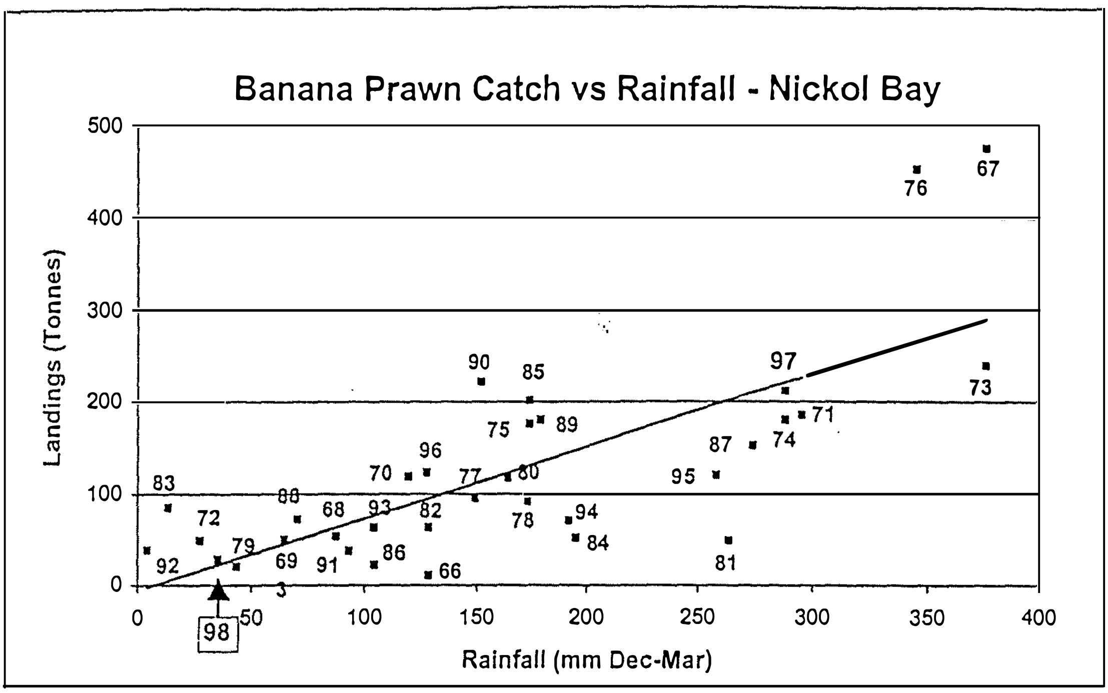


Figure 5.1: The relationship between the Nickol Bay banana prawn catch and rainfall between December and March for the years 1967 to 1997. The catch year is indicated.

6. Pilchards (N. Caputi, D. Gaughan and A. Pearce)

Introduction

Pilchards (sardines), *Sardinops sagax neopilchardus,* are caught in relatively large numbers in Western Australia, particularly in the south coast region near Albany (Fletcher 1991). The same species is caught in South Africa, Peru/Chile, Japan and California and can make up to 12% of the total world catch of fish (Whitehead 1985). *Sardinops* is well known for large scale variations in recruit abundance with major declines in abundance recorded during this century which have often been associated with heavy fishing mortalities (*e.g.* MacCall 1979). There is, however, evidence that these stocks have fluctuated greatly through time even before fishing began (Baumgartner *et al.* 1991). These variations in relative recruitment success (not stock size), at least over the last century, have been linked to changes in the prevailing environmental conditions (Lluch-Belda *et al.* 1989, 1992; Crawford *et al.* 1991).

This study examines the influence of the Leeuwin Current on the recruitment of pilchards as the current is flowing strongly at the time of winter spawning and hence would be expected to affect egg and larval movement and survival. Interannual variations in the strength and position of the current may also affect breeding success through changes in reproductive output (*e.g.* fecundity).

Methods

The recruitment index for the Albany pilchard fishery is based upon the relative abundance of 2 year old recruits as they enter the fishery (Fletcher 1995).

The Leeuwin Current strength during June and July was examined as this appeared to be the main period of spawning. The sea level at Fremantle during these months was used as an index of the strength of the current as the data were consistently available for Fremantle and the Fremantle sea level was strongly correlated with the Albany sea level (Section 1 Figures 1.6 and 1.8). Alternative satellite-derived indices of the annual strength of the Leeuwin Current (described in Section 1) are also examined.

As the influence of the Leeuwin Current on the larval life may be due to the impact of the current on the SST, the Reynolds SST data was examined for the blocks adjacent to Albany.

Results and Discussion

A significant negative relationship (r=-0.93) was found between the relative strength of the cohort of 2 year old recruits entering the fishery during the period 1987 to 1994 and the strength of the Leeuwin Current measured two years previously during the June spawning period (Caputi *et al.* 1996b). This relationship predicted two good years of recruitment for 1995 and 1996 following the weak Leeuwin Currents in 1993 and 1994. However these good recruitments did not eventuate in 1995 and 1996 with the recruitment in these years being well below that expected from the sea level data (Figure 6.1). The recruitment for 1997 was within the range expected based on the sea level in 1995. The recruitment for 1998 is expected to be low based on this relationship as the sea level in June 1996 was the highest for the month of June in over 30 years; the 1999 recruitment is expected to return to average as result of average sea level in June 1997. The four satellite-derived indices of the Leeuwin Current were not found to be significantly related to the recruitment of pilchards.

There are a number of hypotheses why the predicted good recruitments in 1995 and 1996 did not occur and these include: (a) other environmental factors may have influenced recruitment during those periods; these as yet unknown environmental factors could influence recruitment in addition to or instead of the strength of the Leeuwin Current. (b) The breeding stock may have been low and hence influenced the recruitment for that period. (c) The mass mortality of pilchards in autumn 1995 (Fletcher *et al.* 1997) may have affected the 1 and 2 year olds in 1995 which form the basis for the 2 year old recruitment index in 1995 and 1996.

The breeding stock for 1993 and 1994 was above average for the period examined, 1985 to 1996, indicating that this should not have been a major factor for the decline in recruitment. Examination of other environmental variables such as Reynolds SST do not explain the low recruitment in 1995 and 1996.

The mass mortality of pilchards was first reported in March 1995 in South Australia and reached Albany by May 1995 (Fletcher *et al.* 1997). While only adult pilchards were found dead (pilchards are generally adults at 2 years old), its effect on juveniles is unknown as the distribution of juveniles is not well understood. If the 1 and 2 year olds were affected in 1995, this would have resulted in the observed lower than expected number of 2 year olds in 1995 and 1996. The 1997 recruitment index has since fitted the relationship well and the relationship will be further tested in the next few years with low recruitment expected in 1998 as result of a record high June sea level in 1996, followed by an average recruitment in 1999 (Figure 6.1).

A possible basis for the relationship between the Leeuwin Current and pilchard recruitment could be the advection of pilchard eggs and larvae by the Leeuwin Current (Fletcher *et al.* 1994). For example, in 1991 when there was a strong Leeuwin Current on the south coast, eastward advection of eggs and larval stages of pilchards was very evident (Figure 6.2a). Most of the day one eggs (*i.e.* those spawned the night before) were immediately offshore of Albany. Day 2 eggs were 40 km to the east of Albany, while yolk sac larvae were further east and post larvae were mostly located near Bremer Bay. These stages moved a total distance of 140 km in about a week. This corresponds to about 0.23 m/s for the inshore waters where these stages occur, with the current being stronger offshore. By contrast, in 1993, when the Leeuwin Current was weaker, there was little advection occurring, with most stages remaining in about the same 2 to 3 sampling transects with the net transport being only 20 km (Figure 6.2b). Thus, for the four years of data during the July spawning period there is a positive relationship between the strength of the Leeuwin Current and the transport of pilchard plankton stages out of the Albany region (Figure 6.3).

By contrast, in the Japanese sardine fishery the advection of eggs and larvae has a positive influence on recruitment (Kobayashi and Kuroda 1991). Depending upon the path of the Kuroshio current, eggs and larvae will either remain in a small number of coastal locations, which is associated with a small biomass. However if larvae are distributed widely to a large number of nurseries, this pattern is associated with an increase in biomass.

This relationship between the Leeuwin Current and recruitment will be monitored closely over the next few years to see if it remains consistent and possibly predictive. If the recruitment in the next few years can be explained by the strength of the Leeuwin Current then we can conclude that the unexpected low recruitment in 1995 and 1996 may have been due to the pilchard mortality event in 1995. The advection theory, as a process in this relationship, may be examined more carefully once we establish the major nursery areas of pilchards for the south coast.

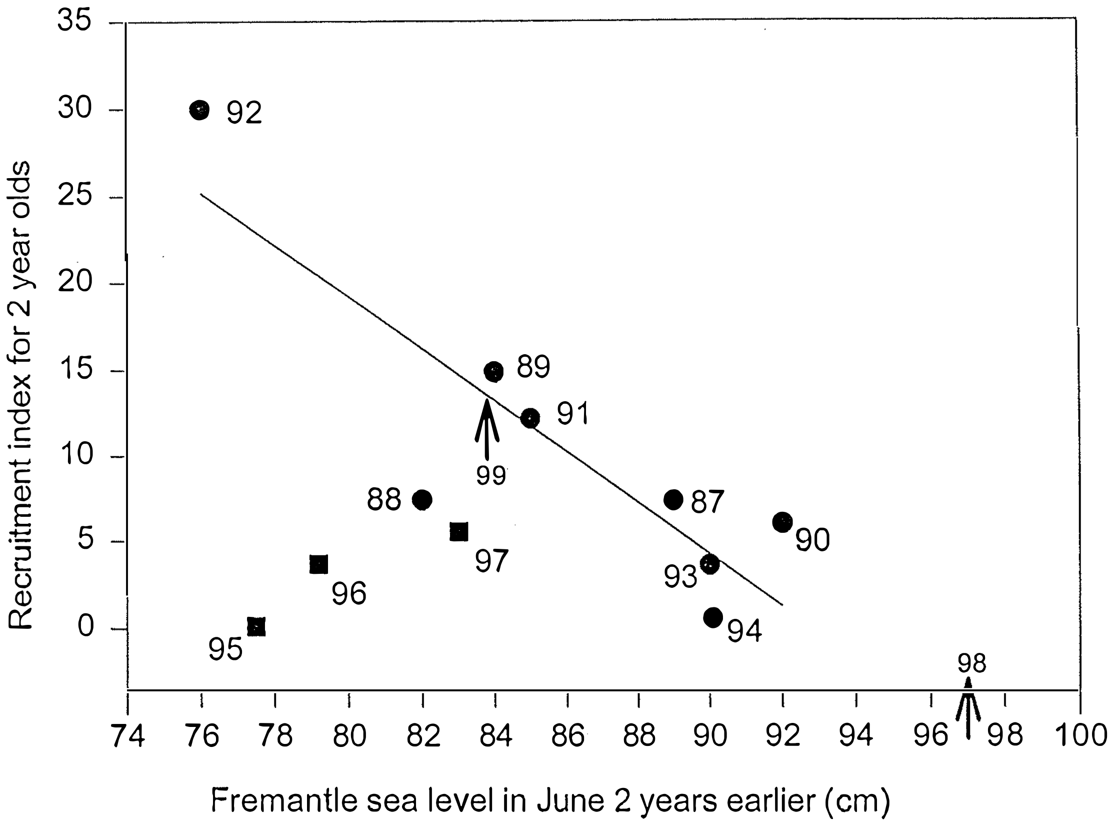


Figure 6.1: Relationship between the recruitment (2+) in the pilchard fishery and the strength of the Leeuwin Current during June two years previously (measured by the Fremantle sea level). The year of the recruitment is indicated including the values for 1998 and 1999 as predicted by the sea level for 1996 and 1997. The relationship shown is based on recruitment years 1987-1994 (circles). Recruitment subsequent to 1994 (squares) have not been used in the regression (see text).

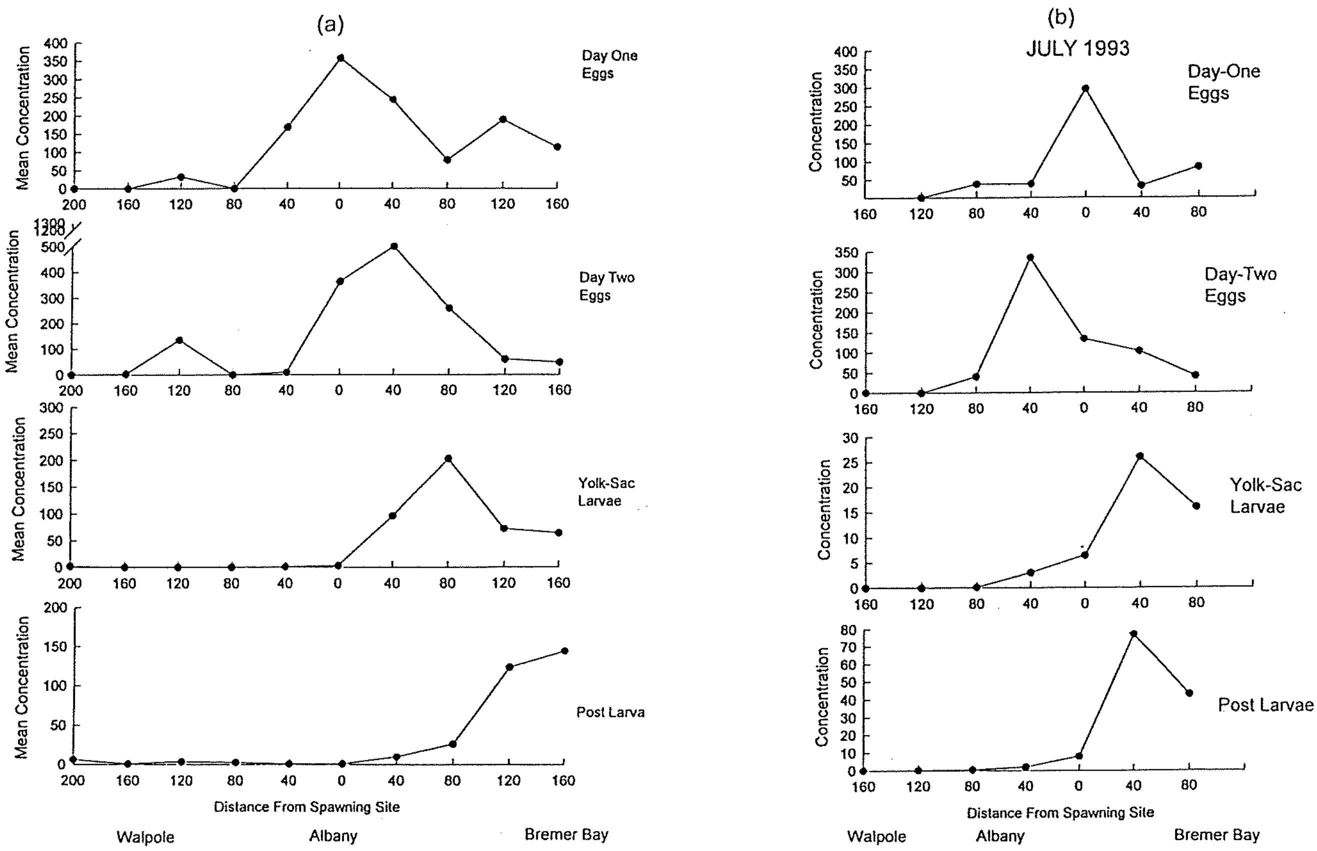


Figure 6.2: The mean abundance (number per 200 m^3) of pilchard eggs and larvae from 40 km transects between Walpole and Bremer Bay in July of (a, left panel) 1991 (Modified from Fletcher *et al.* 1994) and (b, right panel) 1993.

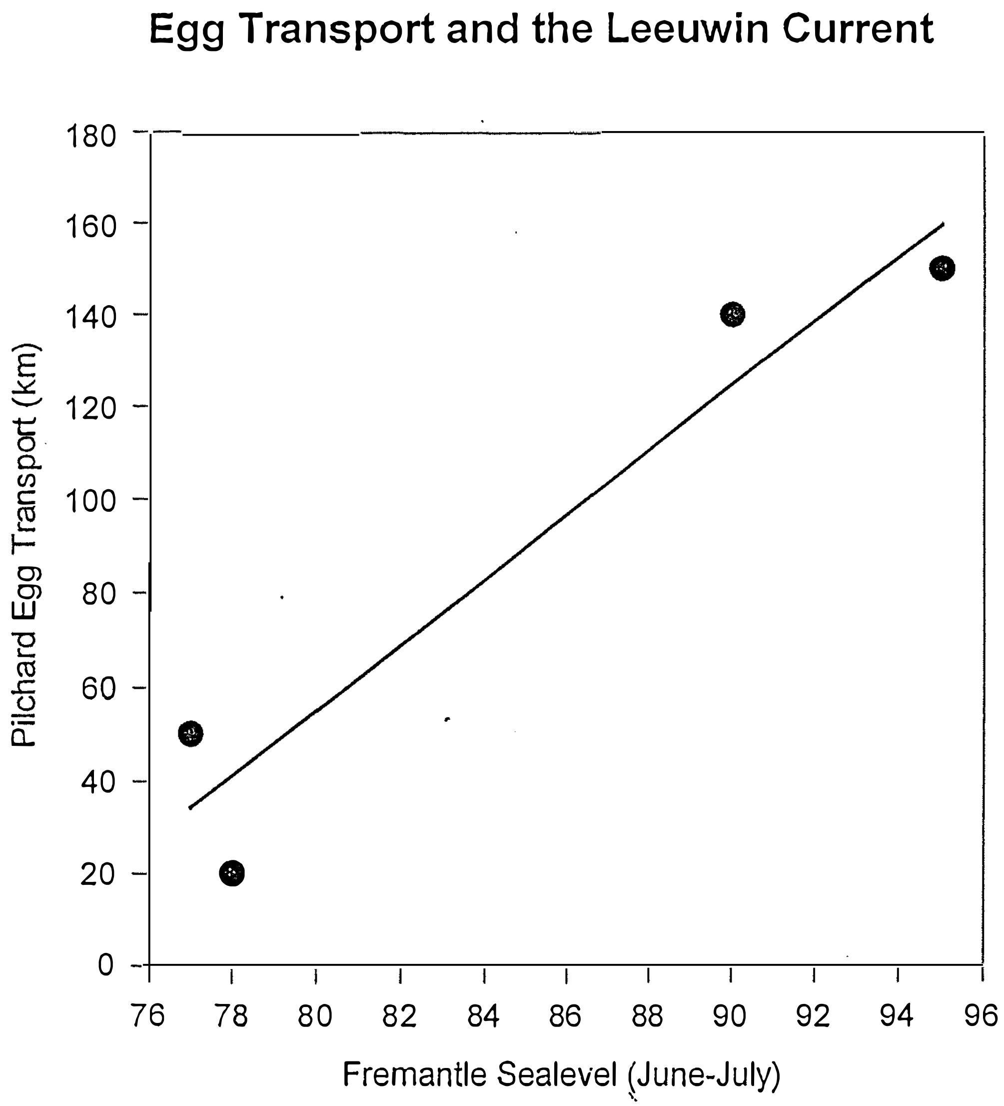


Figure 6.3: Relationship between pilchard egg transportation and the strength of the Leeuwin Current in June-July (measured by Fremantle sea level).

7. Whitebait (N. Caputi, D. Gaughan and A. Pearce)

Introduction

The inshore schooling species whitebait, *Hyperlophus vittatus*, has been the basis for a small beach seine fishery in the southwest region of Western Australia for over 20 years with catch undergoing a gradual increase then a decline in more recent years (Figure 7.1a) due to changes in fishing effort. The species is short-lived with most of the catch being less than 2 years old (Gaughan *et al.* 1996). Spawning generally occurs close to the coast during May to August (ie winter) once the fish reach about 1 year old.

This small pelagic fish species appears to be positively affected by variations in the Leeuwin Current. This may be due to the current affecting movements or retention of larvae, or the higher water temperatures which are associated with the Leeuwin Current. The contrast in the strength of the current in the last 3 years as a result of the strong Leeuwin Current in 1996 provides an opportunity to test the relationship first reported by Caputi *et al.* (1996b).

Methods

A 3 year moving average model was applied to the annual catch since 1977 to determine the long term trend as a result of changes in fishing effort. The residuals between the annual catch taken and the smoothed estimates should better reflect the annual variation in recruitment (Figure 7.1b) and this will be used to assess the environmental effects.

The Fremantle sea level, which is an index of the strength of Leeuwin Current, is examined for the two years prior to the catch as the age of most of the catch is less than two years. The Reynolds SST (which is only available from 1982) for the 1 degree block near Bunbury, where most of the catch is taken, is also used to examine its effect on recruitment.

Results and Discussion

A strong correlation ($r=0.88$, $p<0.001$) was found between the catch residuals for the 21 years between 1977 and 1997 and the strength of the Leeuwin Current during the previous year (Figure 7.1b). The correlation for the sea level 2 years previously was 0.35 ($p>0.05$) and with the current year of fishing -0.08 ($p>0.05$). This highlights the importance of the Leeuwin Current in the year before the catch is taken relative to the other years. Examination of the correlation between the residual catch and the individual monthly sea levels lagged for 1 and 2 years indicate that the correlation is generally significant for the period August 2 years before the catch season through to December the previous year (Figure 7.2). The correlation using the mean sea level over this extended period of 17 months prior to the catch year results in an improved correlation of 0.90 (Figure 7.3). Thus, in general, the stronger the Leeuwin Current in the previous year or two, the greater was the relative catch of whitebait.

The relationship was first established with catch data up to 1994 (Caputi *et al.* 1996b) and hence the 1995 to 1997 catch years provide an independent check of the relationship. The catch has improved over these three years and this has been associated with the strengthening of the Leeuwin Current from 1994 to 1996 after the extended ENSO event of the early 1990s. The 1997 catch which was predicted to be very good based on one of the highest sea levels for over 40 years in 1996 resulted in the second highest catch in the fishery. As a result of the ENSO event which started in 1997 the Leeuwin Current was weaker in 1997 which should result in an average to below average catch in 1998.

The relationship between the residual catch for the period 1984 and 1997 and Reynolds SST lagged 1 and 2 years showed a correlation of 0.78 and 0.62, respectively. Examination of the correlation between the residual catch and the individual monthly Reynolds SST lagged for 1 and 2 years indicates that the correlation is highest for the months lagged 7 to 18 months *i.e.* the period July lagged 2 years to June lagged 1 year (Figure 7.4). The relationship for residual catch and the mean Reynolds SST for the period July lagged 2 years to June lagged 1 year resulted in a correlation of 0.85 (Figure 7.5). Over the same years the correlation of the residual catch with the sea level the previous 12 months was slightly better at 0.90 and even better using the sea level the previous 17 months at 0.94.

Combining the relationship between the residual catch and the Leeuwin Current (Figure 7.1a) and the moving average trend (Figure 7.1b) enables a preliminary catch forecast to be undertaken (Figure 7.6). This relationship has been invaluable to the management of this fishery, particularly as in the early 1990s the catch declined from 321 t in 1990 to 125 t in 1994 as a result of the extended ENSO event and subsequent weaker Leeuwin Current. We are examining the data further to determine whether the effect of the Leeuwin Current is more likely to be on the survival and advection of eggs and larvae or on temperature-induced variation in growth and survival of juveniles.

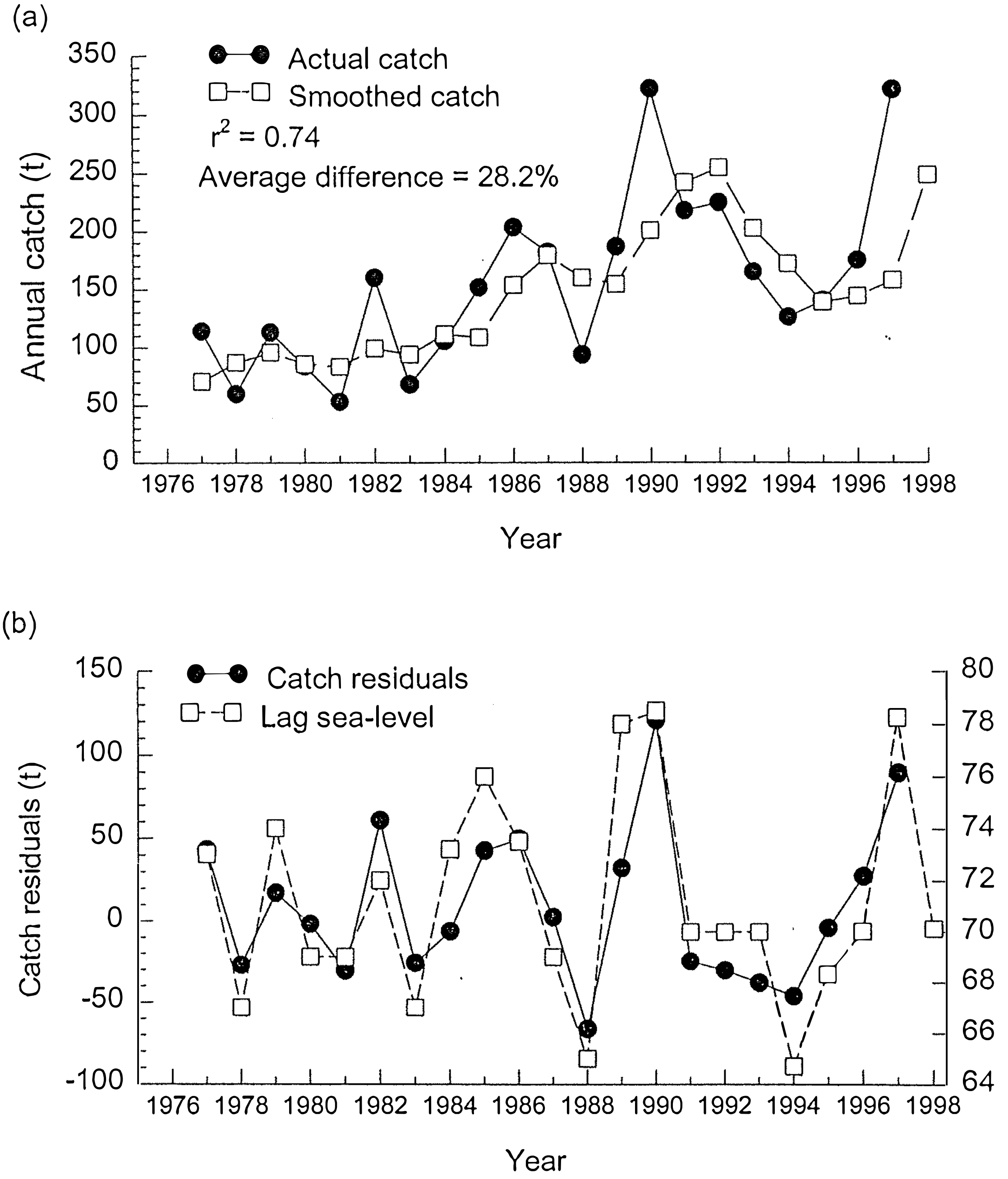
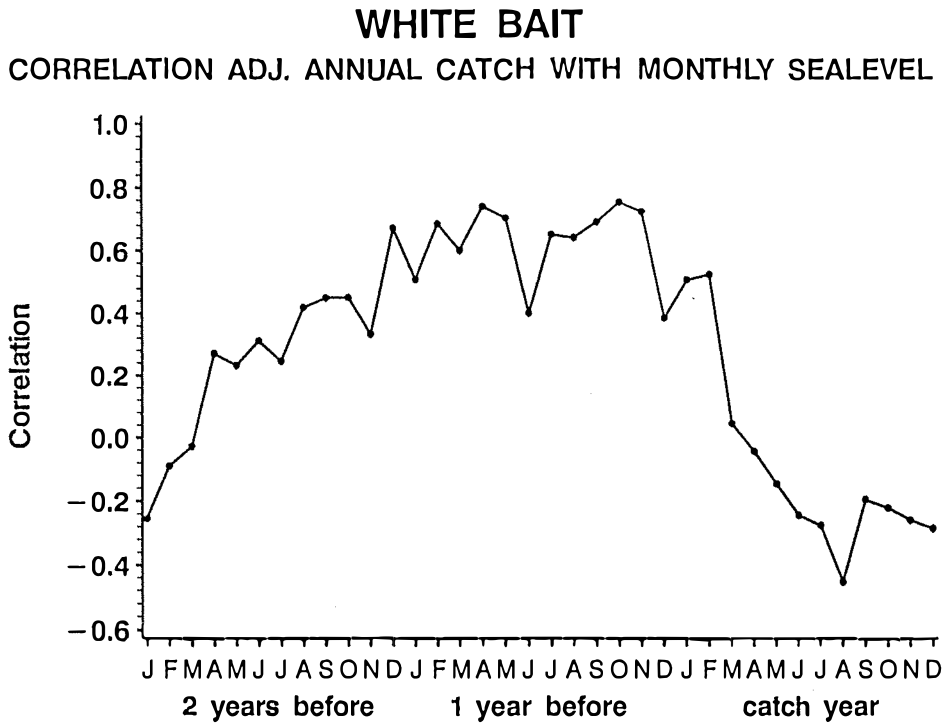


Figure 7.1: The time series of (a) white bait catches (solid circles) with the expected values using a 3-year moving average (open squares) to identify the trends and (b) the residual of the white bait catches (solid circles) which takes into account the trend in the time series and sea level time series lagged 1 year (open squares).



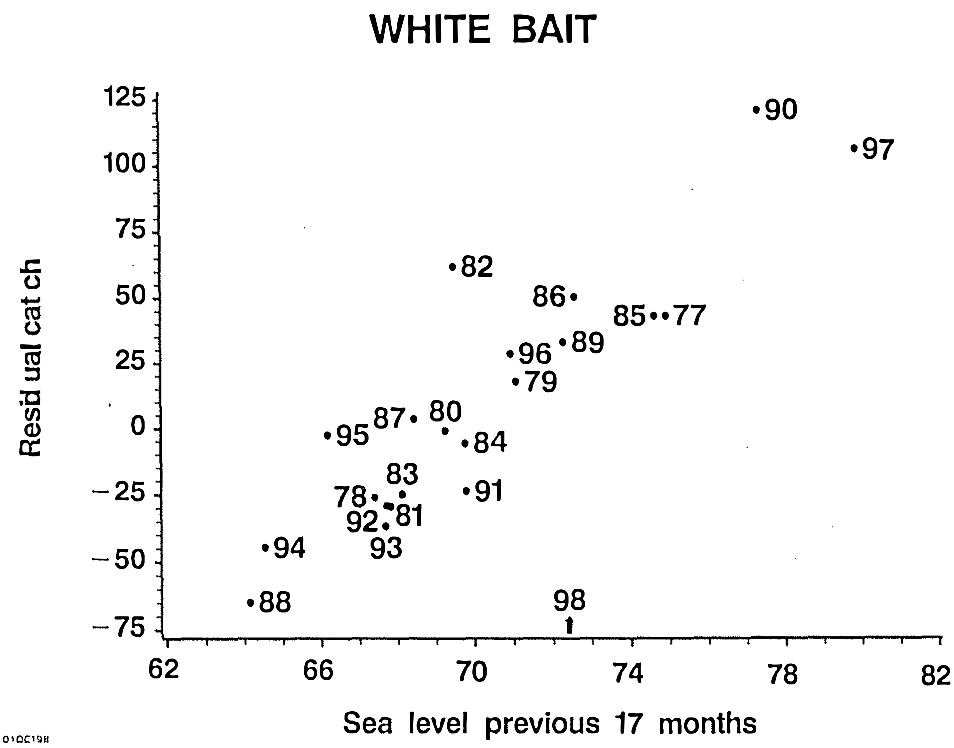
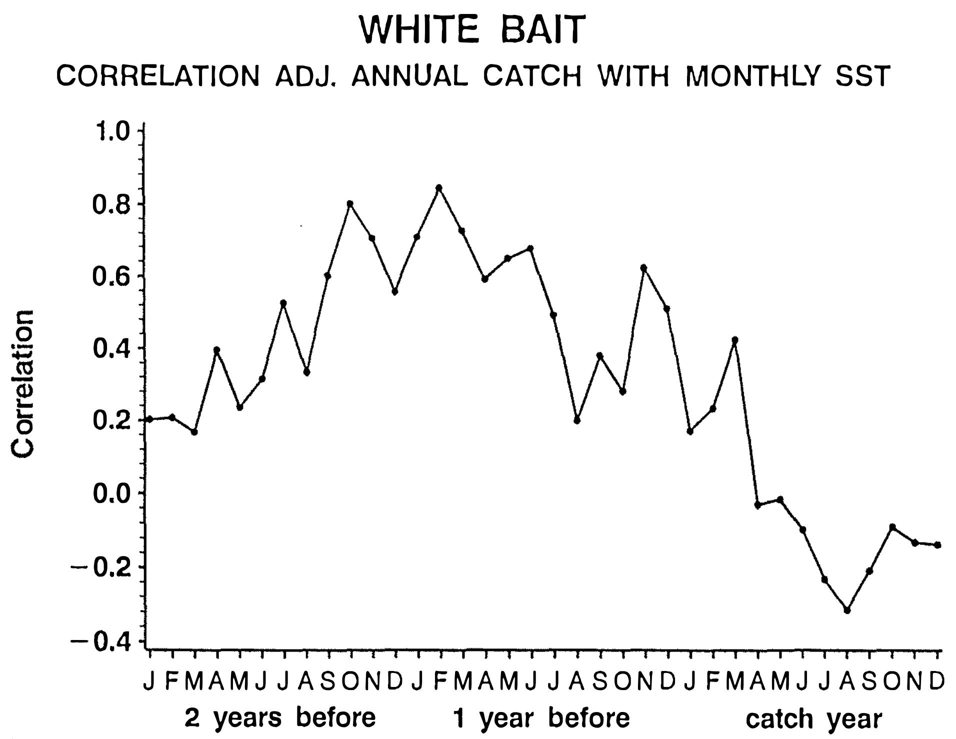


Figure 7.2 (top): The correlation between the annual residual white bait catch in Western Australia and monthly Fremantle sea level in the previous two years.

Figure 7.3 (bottom): The relationship between the residual white bait catch in Western Australia for 1977 to 1997 and Fremantle sea level in the period August, 2 years before the catch season, through to December the previous year. The year is indicated.



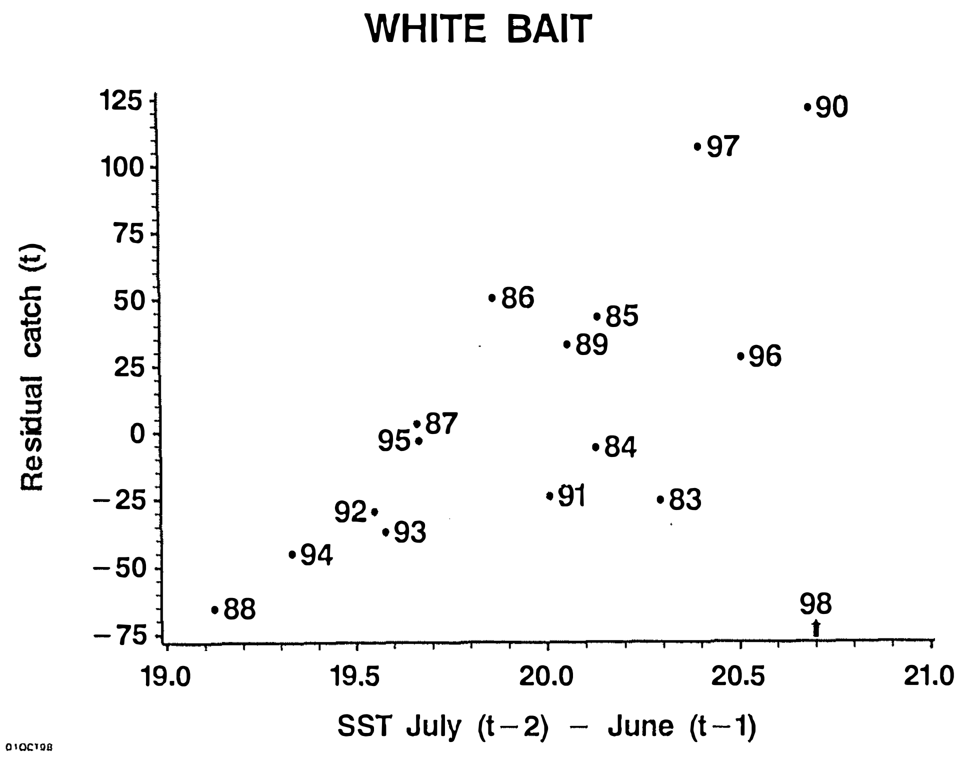


Figure 7.4 (top): The correlation between the annual residual white bait catch in Western Australia and the monthly Reynolds sea-surface temperature near Bunbury in the previous two years.

Figure 7.5 (bottom): The relationship for residual white bait catch and the mean Reynolds SST near Bunbury for the period July, 2 years before the catch year, to June the previous year. The year is indicated.

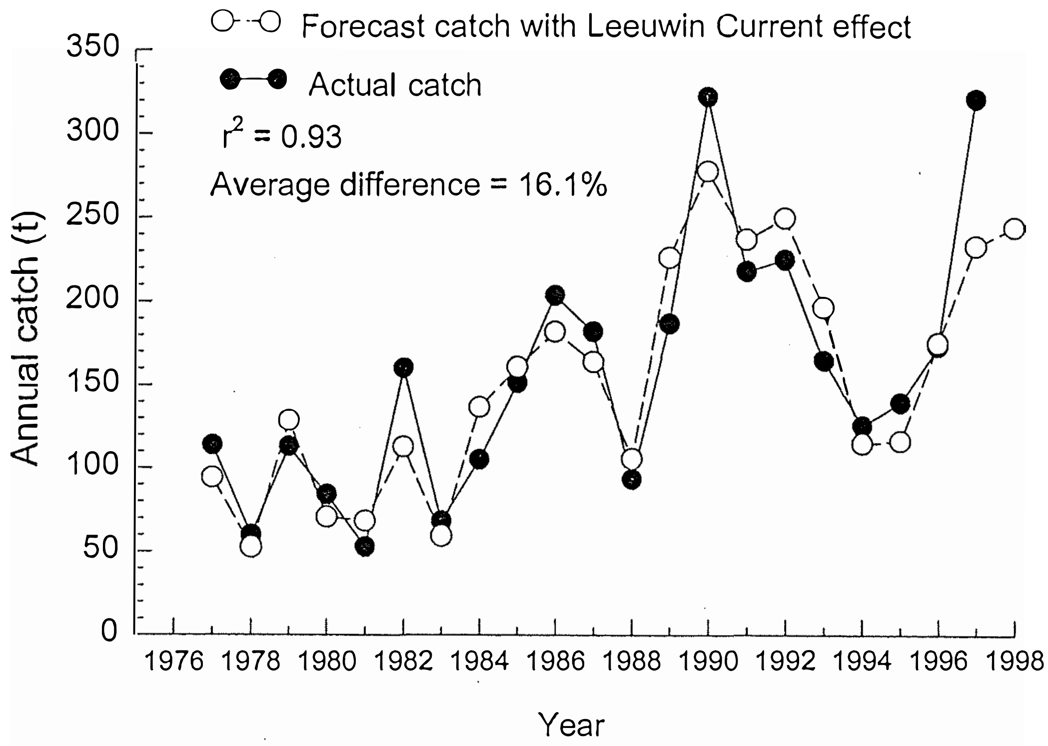


Figure 7.6: The relationship between catch (solid circles) and the expected catch (open circles) based on the 3 year moving average and the Leeuwin Current in the previous year.

8. Western Australian Salmon and Australian Herring (N. Caputi, S. Ayvazian and R. Lenanton)

Introduction

Western Australian salmon (*Arripis truttaceus*) and Australian herring (*Arripis georgianus*) are distributed predominantly from the lower west coast of Western Australia to South Australia and Victoria. They are also similar in that all mature fish are found only in Western Australia with spawning occurring in autumn which is the time that the Leeuwin Current is flowing strongly south along the west coast and east along the south coast of Western Australia and sometimes evident along South Australia.

A significant positive correlation between the recruitment of 0+ salmon in South Australia and the strength of the Leeuwin Current during the same year has been noted (Lenanton *et al.* 1991). This study follows up this result and the impact of the current on the 0+ herring in South Australia. It also examines the impact of the current strength and water temperatures on the commercial catches of salmon and herring in Western Australia.

Methods

The annual commercial catch of herring in Western Australia since 1976 was separated into south, south-west and west coast to enable an assessment of the environmental effects for each of the catches separately. The commercial salmon catch in Western Australia since 1976 was separated into south and west coast.

The Fremantle sea level, which is an index of the strength of Leeuwin Current, is examined for up to 3 years prior to the catch as the age of most of the herring catch is between 2-3 years and the salmon catch is mostly 3 and 4 year old fish. The Reynolds SST near Bunbury and Albany up to three years prior to the catch year is also examined for its effect on recruitment. The SST data are only available from 1982.

Results and Discussion

The south-west catch of herring showed a significant correlation of -0.56 ($p<0.01$, $n=21$) with the sea level two years previously. The Reynolds SST two years previously also showed a negative correlation of -0.70 ($p<0.01$, $n=14$) with the herring catch for the catch years 1984 to 1997. The very high SST in 1996 of 20.8°C would then indicate a low catch in 1998 based on this relationship. The correlation of the catch with these two environmental variables lagged one year also showed a negative correlation of -0.32 and -0.37, but not significant. The catch on the west coast also showed a negative correlation with the two environmental variables lagged 1 and 2 years of between -0.26 to -0.44, although not significant at the 0.05 level. A similar analysis of the south coast catch did not reveal any significant relationships with the environmental variables, despite the region having the highest commercial catch using trap nets, ranging from 400 to 1400 t. The commercial catch on the west coast based on beach seines ranges from 20 to 65 t and is generally lower than that on the south-west region of 40 to 160 t. and probably consists of mainly Western Australia recruited fish.

The relationships above indicate that the strength of the Leeuwin Current at the time of the larval or juvenile stage may have a negative impact on the recruitment of herring to the fishery on the south-west region, in particular, and possibly the west coast of Western Australia. The catch on the south coast probably consists of a combination of fish recruiting from South Australia as well as local recruits and these catches are of multiple year-classes; this situation makes it difficult to identify environmental factors affecting recruitment.

Examination of the environmental factors affecting the salmon catch in Western Australia, like the south coast herring catch, did not reveal any significant correlations. One of the problems in the examination of environmental effects on recruitment using catch data is that catches consist of multiple year-classes and in this case from multiple sources, Western Australia and South Australia. These analyses will only provide useful indicators if the data are dominated by 1 or 2 year-classes as in the herring fishery. An estimate of the proportion of the key age classes in the salmon fishery, in particular, would enable a better assessment of the relationships as this would enable an assessment of the strength of an age class to be related back to the appropriate environmental factors. In addition, monitoring the abundance index of the post-settled juvenile herring (and other species such as salmon) between Western Australia and South Australia being undertaken as part of the FRDC project on "Stock Assessment of A. herring", will enable a more precise understanding of the environmental factors affecting the larval stages. A similar study in South Australia over the past 15 years has enabled an assessment of the impact of the Leeuwin Current on the larval movement to South Australia (Jones and Dimmlich in prep.).

The significant positive correlation between 0+ salmon in South Australia and the Leeuwin Current reported previously (Lenanton *et al.* 1991) has been maintained with the addition of data from more recent years resulting in a correlation of 0.63 with the sea level at Albany in April during the early larval phases and 0.64 at the Outer Harbour in South Australia in August prior to entering the nursery area (Jones and Dimmlich in prep.).

For Australian herring, a similar pattern to salmon was observed except delayed by 1-2 months, with a significant correlation of the 0+ herring with the sea level in Albany in June of 0.61 and at the Outer Harbour in September of 0.61 (Jones and Dimmlich in prep.). Hence recruitment in South Australia is dependent on the spawning which occurs in south-western Australia waters during March-May when the Leeuwin Current is strengthening in its eastward flow across southern Australia.

The salmon and herring fishery in South Australia appear to be affected in a similar way with recruitment being dependent on spawning occurring in the south-west of Western Australia in late autumn and the Leeuwin Current transporting recruits to South Australia in late winter. Petrusevics and Bye (1996) indicated that the Great Australian Bight current and duration of westerly winds may also influence the transportation of salmon larvae from the spawning area to the nursery area in South Australia. The sea level heights and the Leeuwin Current strength are affected by ENSO events (Pearce and Philips 1988) and hence the years of low recruitment in South Australia generally coincide with ENSO events.

Benefits

Longterm sustainable management of all the fisheries involved will benefit from this information and potential for catch forecasting. The fisheries involved have a combined value of approximately $300M annually (mostly due to the value of rock lobsters). In the finfish area, the fisheries involved represent the major volume production for Western Australia and employ significant numbers of fishermen, although the value of the production is limited. This study should also benefit South Australia with respect to salmon (complementing FRDC project 93/50) and CSIRO Marine Research in their southern bluefin research.

State	%	Fishery(ies)/Other beneficiaries	%
WA	80%		
Other states and Commonwealth	20%	Mostly useful to SA and other states in terms of techniques for environmental monitors and the development of catch prediction techniques.	
Total	100%		

Further development

Satellite altimeters such as TOPEX measure variations in sea-surface topography (or heights) to a precision of about 3 cm, allowing direct estimates to be made of the surface currents across the satellite track. Altimeter data from TOPEX dating back to December 1992 are available from CSIRO Marine Research in Hobart. Analysis of the altimeter data in conjunction with any available oceanographic data as well as numerical models will enable monthly maps to be derived of the ocean circulation (Craig 1995). This would plug a crucial gap in the study of environmental influences on larval migration and recruitment to the commercial fisheries of Western Australia, and is the subject of a new FRDC grant (project 97/139, from July 1997 to June 2000).

Ocean colour satellite data, which is an indicator of chlorophyll concentrations (and hence phytoplankton distribution and abundance) in the ocean, became available towards the end of 1997 with the successful launch of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on the SeaStar satellite. This complements the thermal SST imagery by showing seasonal and interannual variations in planktonic production along the Western Australian continental shelf and their relation to mesoscale features of the Leeuwin Current. SeaWiFS imagery is being received in Perth, and a local research team is involved in calibration and validation procedures by both fieldwork and atmospheric/oceanic modelling. By the year 2000, the data processing methods will have become established and the calibration/validation techniques refined, and with an archive of 3 years of data a new FRDC proposal may be appropriate to map spatial and temporal variability of ocean productivity along the Western Australian coast.

With the ready availability of the newer datasets, some of the research questions which have not been dealt with in detail in this report can be addressed into the future. Refinement of the numerical indices of thermal structure from the satellite-derived SSTs (both the global Reynolds 1-degree data and the local full-resolution imagery) will be pursued as more adequate cloud-detection techniques become available.

Conclusions

The principal objectives of this project have been met:

1) We now have a 15-year archive 1983-1997 of locally-received AVHRR imagery in mNOAA format, and this will be continuing into at least the near future. Despite problems with cloud-screening, this invaluable dataset will enable us to examine current patterns and SSTs for the Western Australian coastline at full (1 km) spatial resolution. Methods have been established for addressing navigational (positioning) problems, and the accuracy of the derived SSTs can be improved as updated algorithms become available because all the relevant radiometric information has been stored. The advent of the Reynolds 1-degree monthly SSTs have enabled us to overcome some of the mNOAA difficulties for large-scale analysis.

2) The environmental databases have been successfully compiled. These are:

* weekly/daily AVHRR imagery	1983 to present
* monthly Southern Oscillation Index	1897 to present
* monthly Fremantle sea level	1987 to present
* monthly sea levels at 8 other ports	1966 to present (many gaps)
* monthly Reynolds SST (1-degree squares)	1982 to present
* monthly COADS SST (2-degree squares)	1854 to 1989
* monthly COADS SST (1-degree squares)	1945 to 1989
* monthly CSIRO Albany station	1952 to 1956; 1977 to 1983
* monthly CSIRO Augusta station	1978 to 1981
* monthly CSIRO Barrow Island station	1977 to 1979
* monthly CSIRO Esperance station	1979 to 1981
* monthly CSIRO Geraldton station	1978 to 1986
* monthly CSIRO Rottnest station	1951 to 1956; 1969 to present
* monthly temperature/salinity (15 puerulus sites)	1969 to present (many gaps)
* hourly coastal temperature loggers	1990 to 1994
* monthly COADS winds (2-degree squares)	1845 to 1989
* monthly COADS winds (1-degree squares)	1945 to 1989
* hourly winds at Fremantle Port Authority	1971 to 1982
* hourly meteorological Seaframe data at 3 sites	1992 to present

Data quality varies with the data source, but most of the above contribute usefully to the overall environmental picture.

3) As the Leeuwin Current is the dominant feature of the oceanography of Western Australia, it is not surprising that variations in its strength and path will influence the recruitment of species within these waters. The effect of the current occurs mainly during the larval phase of the species but not always with the same result. The strength of the Leeuwin Current has a significant positive influence during the 9-11 month larval life of the western rock lobster (*Panulirus cygnus*) as reflected by the level of

puerulus settlement. The puerulus settlement is also influenced by the strength of westerly winds and possibly water temperature. The current strength has a negative influence during the larval life of the scallop (*Amusium balloti*) in Shark Bay.

Similarly for the pelagic finfish species pilchards (*Sardinops sagax neopilchardus*) and whitebait (*Hyperlophus vittatus*), the current strength has a negative effect on larval survival of pilchards but a positive impact for whitebait. Further examination of these relationships should be aided by extending the plankton sampling programme to look at the processes involved in these variations and not just the patterns.

The salmon and herring fisheries in South Australia appear to be affected in a similar way with recruitment being dependent on spawning occurring in the south-west of Western Australia in late autumn and the Leeuwin Current transporting recruits to South Australia in late winter. The factors affecting the salmon and herring catches in Western Australia are not as clear as a result of the multiple year classes in the catch and fish recruiting from Western Australia and South Australia being part of the catch. However there is an indication of a negative relationship between the herring catch in the south-west of Western Australia and the Leeuwin Current.

The current may also affect the growth and catchability of later life history stages for some species, *e.g.* western king prawns and western rock lobster (Morgan 1974), though its effect for these stages is not as marked as during the larval phase. For the banana prawn fishery, the survival during the juvenile phase when the prawns migrate from the estuary to the ocean appears to be the key life history stage.

The environmental assessments on recruitment have used Fremantle sea level as the measure of the strength of the Leeuwin Current, as well as satellite-derived sea surface temperature measurements around the Western Australian coast (the Reynolds dataset) and wind and rain data from the Bureau of Meteorology.

Understanding the influence of environmental effects on recruitment is an important aspect of fisheries stock assessment to help interpret whether fluctuations in recruitment are due to environmental effects or the impact of fishing on the spawning stock. Recognising the effect of the Leeuwin Current on recruitment has played a vital role in management decisions for the rock lobster, scallop, pilchard and white bait fisheries in recent years.

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Appendix 1: Intellectual property

Not applicable

Appendix 2: Staff

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Appendix 3: Glossary of abbreviations/acronyms used in this report

AVHRR	Advanced Very High Resolution Radiometer
COADS	Comprehensive Ocean-Atmosphere DataSet
COSSA	CSIRO Office of Space Science and Applications
DOLA	WA Department of Land Administration
DTDS	Darwin Tropical Diagnostic Statement
ENSO	El Nino/Southern Oscillation
FIRTA	Fishing Industry Research Trust Account
FMSL	Fremantle sea level
FPA	Fremantle Port Authority
FRDC	Fisheries Research and Development Corporation
NOAA	National Oceanic and Atmospheric Administration
NTF	National Tidal Facility
SOI	Southern Oscillation Index
SST	Sea-surface temperature
WAFIC	Western Australia Fishing Industry Council
WASTAC	Western Australian Satellite Technology and Applications Consortium

Appendix 4: PROJECT BUDGET SUMMARY

	1993-94	**1994-95**	**1995-96**	**TOTAL**
Salaries and on-costs	$53 980	$55 610	$57 280	$166 870
Travel	$500	$550	$600	$1 650
Operating	$21 700	$22 350	$23 030	$67 080
Total	**$81 180**	**$78 510**	**$80 910**	**$240 600**

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