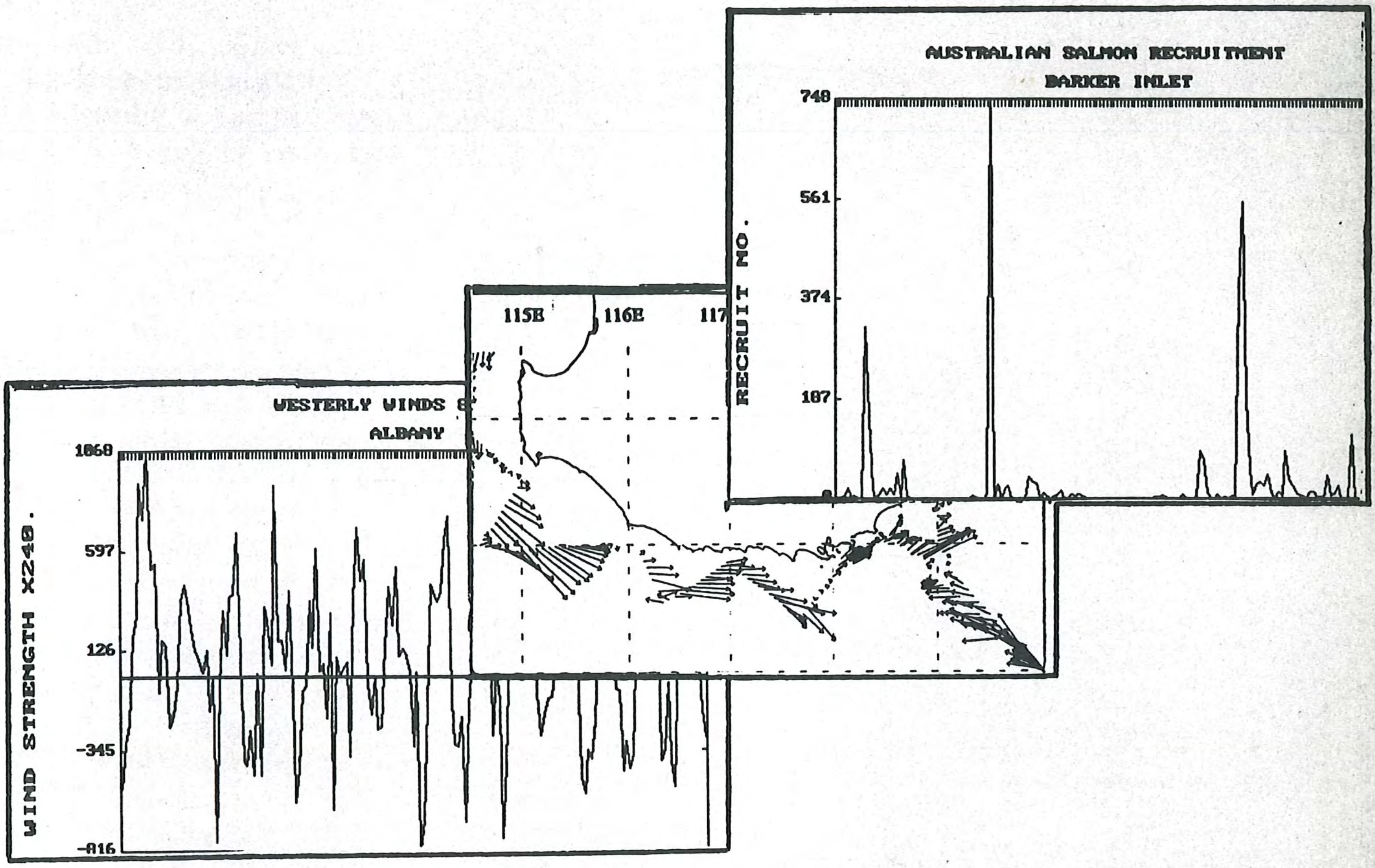
LEEUWIN ENVIRONMENT INDEX-PELAGIC RECRUITMENT STRENGTH RELATIONSHIP

FINAL REPORT TO FRDC COMMITTEE ON PROJECT 93/050



P.PETRUSEVICS
FLINDERS INSTITUTE OF ATMOSPHERIC AND MARINE SCIENCES
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SUMMARY

This study investigated the relationships between recruitment of Australian salmon (western species *Arripis truttaceus*) in Barker Inlet, South Australia for the period 1981-1994 and environmental factors such as wind, mean sea level, Southern Oscillation Index (SOI) in spawning grounds Western Australia.

Recruitment of salmon in Barker Inlet peaked in 1981, 1984 and 1990. Correlations between recruitment numbers in Barker Inlet and mean sea level in Albany, near the spawning grounds, for March, April, May and June for the period 1981-1993 were carried out. This ensured that the periods leading up to, during and after spawning were considered. The regressions were non-significant for mean sea level for all months except May. The correlation for May was significant (r^2 = .188). Peak spawning is believed to occur between April-May. Correlation between the SOI and mean sea level for May in Albany was significant (r^2 =.51), but correlation between the SOI and salmon recruitment numbers in Barker Inlet was not significant

Three hourly wind data for Albany, Western Australia for the period 1981-1995 were resolved into northerly, southerly, easterly and westerly components. A consistent feature of these results was the presence of westerly winds which followed the time of spawning of the salmon (April-May). This suggested that a favourable mechanism was provided for the salmon larvae by the westerly winds in all years during the period 1981-1995. The northerly and southerly components did not exhibit a sense of coherence for the period 1981-1994 which may be linked to favourable conditions for recruitment in Barker Inlet, South Australia. A regular feature of the westerly winds was their consistency of onset. Onset occurred between April and May for the majority (80 % of the time) of the years in the period 1981-1994. The only exception was during 1985-1986. Duration of continuous westerly component winds ranged between 3 to 7 months during the period 1981-1994. Peaks in duration of westerly winds occurred in 1981-1982, 1984, 1987 and 1990 which except for 1987, corresponded to the peaks in recruitment of salmon larvae in 1981, 1984 and 1990 in Barker Inlet. Correlation between westerly wind duration and recruitment numbers was significant (r^2 =.245)

NOAA/AVHRR sea surface temperature (SST) data of cross-shelf gradients in spawning grounds near Albany, Western Australia were examined. SST data corresponding to approximate times of spawning for the years 1985-1994 were analysed to determine if years of high recruitment in Barker Inlet were related to cross-shelf sea surface temperature features near Albany. No positive relationship was found. Published SST data of the Great Australian Bight (GAB) were examined and used to delineate major current systems of the region.

During July 1994 a joint oceanographic and larval sampling cruise of the GAB and off the continental shelf was carried out in the ORV Franklin. Conductivity-temperature- depth

(CTD) surveys were conducted which allowed differentiation of the various water masses present on and off the southern continental shelf. The easterly extent of the Leeuwin Current during this period was found to coincide with the eastern end of Recherche Archipelago, approximately longitude 124°E. A previously unreported bottom outflow from the head of the GAB was observed. Also GAB winter surface waters were distinguished from those of the Leeuwin Current. With the limit of the Leeuwin Current being confined to about 124°E during the winter, the mechanism(s) which transported salmon larvae to South Australian Gulfs appeared to be the west wind drift in combination with the surface outflow from the north-west portion of the GAB.

Acoustic Doppler Current Profile (ADCP) measurements along route confirmed the CTD survey results that the easterly limit of the Leeuwin Current was approximately 124°E and confirmed presence of increased shelf edge flow in the eastern portion of the GAB. ADCP results indicated that currents on the shelf were generally weaker than currents on the shelf edge but retained an easterly set. Off the shelf there were indications of westerly currents. The observed reversal of ADCP currents off-shore may be due to presence of a permanent westerly geostrophic flow or anti-clockwise rotating eddies which may be off-shoots from the main shelf edge flow. Off-shoots from the main shelf edge current were readily identifiable from satellite infra-red imagery during the ORV Franklin cruise in July 1994 The presence of offshoots provided an additional unquantifiable parameter which complicated the development of a Leeuwin Current strength index to link with recruitment of Australian salmon larvae in Barker Inlet. The presence of westerly currents off the shelf provided a counter-productive mechanism for recruitment of Australian salmon to South Australian nurseries but may have enhanced recruitment to Western Australian nurseries.

Otolith ageing was carried out on Australian salmon larvae samples obtained during the ORV Franklin cruise in July 1994. Back-dating indicated that spawning occurred between March and June 1994. ADCP data was used to calculate transit times prior to capture which indicated that regions of spawning ranged between Bunbury and Esperance, Western Australia.

Uncertainty in the spawning time and spatial distribution of the eggs prevented a concise model for advection to be formulated, however the results obtained were encouraging and allowed a conceptual impression for advection of Australian salmon larvae to be advanced. The temperature of the Leeuwin Current appears as one of several factors which induce spawning. Afterwards the salmon eggs need to be favourably positioned within the mainstream of the Leeuwin Current to be advected to the east. This is effected by favourable winds which transport the larvae into the main stream of the Leeuwin Current. When the influence of the Leeuwin Current is diminished near Rehearche Archipelago continuity of larval advection eastwards is maintained by westerly winds, and further in the eastern portion of the GAB, by the south-easterly surface outflow from the GAB. Larval advection may be adversely affected by offshoots or cold water intrusions which may transport salmon larvae well off the shelf. The larvae navigate Investigator Strait and a large portion of Gulf St Vincent before settlement occurs in Barker Inlet. This part of the advection process remains largely unknown although drift card investigations in the GAB indicated that the local wind regime is important in advection of surface borne material from the continental shelf into Gulf St Vincent.

1.0 BACKGROUND

The intent of the study was to examine links between recruitment of Australian salmon (western species *Arripis truttaceus*) in Barker Inlet ,South Australia and environmental factors in Western Australia at the time spawning of salmon. Figure 1.

The "strength" of the Leeuwin Current was considered to be a major factor in formulating a forecast of recruitment strength in South Australian nurseries such as Barker Inlet. However part way through the study it became obvious that factors other than the Leeuwin Current had a greater influence on recruitment of salmon in Barker Inlet. Consequently far greater attention was devoted to other factors than originally planned.

The factors considered included

1) Analysis of wind data from Albany, Western Australia, a location close to the region of spawning of the Australian salmon, indicated that the local wind regime had a potentially greater influence on the advection of eggs and larvae than originally thought. The Leeuwin Current in unison with westerly winds has an important role in the initial stages of advection. However, the Leeuwin Current does not maintain a dominating influence in advection of larvae to South Australian nurseries along the entire advection route.

2) A joint oceanographic and larval sampling survey of the Great Australian Bight (GAB) on ORV Franklin in July 1994 produced a large amount of unexpected data which required analysis. During this survey continuous under way measurements between Kangaroo Island and Fremantle were made using an Acoustic Doppler Current Profiler (ADCP). Preliminary on-board analysis of the ADCP data revealed detailed structure of currents on the shelf and an apparent reversal of currents in some regions off the shelf. The nature of the offshore regime remains unexplained at this stage but may be due to sporadic intrusions by cold water anti-clockwise eddies or a more permanent current set associated with a westerly geostrophic current.

3) The highly successful larval sampling program conducted by the Western Australian Marine Laboratories, co-investigators of the ORV Franklin survey July 1994, provided many valuable surface net samples which included Australian salmon larvae. The larvae samples were analysed at the Flinders University of South Australia and the South Australian Research and Development Institute. Analysis included otolith ageing which provided spawning dates and locations in Western Australia.

The varied and large quantity of results obtained during the ORV Franklin survey were beyond the time scale and personnel resources of this project at the time. Further, the ADCP and CTD data had to undergo instrument calibration and quality assurance procedures before being released by the CSIRO Division of Oceanography, Hobart. The ADCP and CTD data were received in January 1995. Bearing in mind the high cost of use of a sophisticated national resource such as the ORV Franklin and the highly competitive selection procedure to access this resource it was essential that a rigorous analysis of these data were carried out. To ensure that such objectives were met a data analysis co-ordinating group comprising of personnel from School of Earth Sciences, School of Biological Sciences, Flinders University of South Australia and the South Australian Research and Development Institute (SARDI-Aquatic Sciences) was formed.

Summary reports from the School of Earth Sciences and School of Biological Sciences which relate to analysis of ADCP and salmon larvae samples are included with this report. This project was also greatly assisted by the CSIRO Division of Oceanography, Perth who provided archived NOAA/AVHRR SST data to examine features of the Leeuwin Current at the time spawning. Due to technical and resource problems it was not possible to maintain a continuity of SST data from an originally planned source.

The change in emphasis of research provided an opportunity to form closer links with groups in Western Australia such as the CSIRO Division of Oceanography and the WA Marine Research Laboratories whose current interests include effects of oceanic environment on recruitment to the fisheries in Western Australia and the work conducted by SARDI on recruitment of salmon in South Australia.

1.1 Introductory Considerations

Knowledge of recruitment/environment relationship for Australian salmon can provide a forecast to the South Australian fishery on the likely recruitment strength in South Australian nurseries several months before larvae and juvenile fish arrive in South Australian nurseries. Statistically significant correlations between recruitment and environmental variables have been reported in other fisheries. Pearce and Philips (1988) found that high annual mean sea levels at Fremantle were associated with high rock lobster puerelus settlement levels in Western Australia. In Western Australia stock abundance of the Australian salmon has been shown to be related to the magnitude of annual recruitment and environmental effects caused by the Leeuwin Current, Lenanton et al (1991). In South Australia, (Jones pers com ,1991) showed a significant correlation between annual recruitment index of salmon and sea levels at Outer Harbor in August when salmon enter South Australian nurseries.

These investigations provided a useful model and guidelines of approach to the investigations reported here.

At the end of January/ early February mature salmon fish migrate to spawn off the lower west and south coasts of Western Australia (Malcolm 1960, Stanley 1980a). Malcolm (1960), Nicholls (1973) suggested that spawning occured during March and reached a peak in about April. Recent investigations (Lenanton, pers. com, 1995) indicated that spawning may be extended over a period March to April. Analysis of gonad weights showed maximum gonad weights were reached in late March-early April during 1984 and 1985 and early May during 1987. This suggested that local environmental conditions such as photoperiod plus attainment of critical threshold temperature may be responsible for triggering spawning. The latter condition may be associated with the annual warming of waters in south-west Western Australia by the Leeuwin Current.

It has been suggested that the larvae are transported eastwards by the Leeuwin Current to nursery ground located between the western part of the Great Australian Bight and Victoria. (Cresswell 1986, Malcolm 1960, Robertson 1982).

Calculation of expected transit time of larvae across the GAB provides support to this general hypothesis as far as recruitment of salmon to Barker inlet, South australia is concerned. For example, assuming a distance of about 2000 km between Albany and the South Australian Gulfs and a mean current speed of 15-20 cms^{-1} the mean transit time is about 4-5 months. This is in agreement with observations that new year recruits begin to arrive in Barker Inlet in about August-September. This also suggested that new year recruits in Barker Inlet are as a result of spawning which occurred in Western Australia the same year and not from localised spawning in South Australia. It suggested that the strength of the recruitment in South Australia is governed by environmental factors present in spawning grounds in Western Australia and the subsequent strength and directional characteristics of the currents en route to South Australian nurseries.

The success of recruitment/environment link type investigations reported elsewhere were greatly aided by long data sets of 15-20 years at least. This project has the advantage that already 13 years of high quality juvenile recruitment data from Barker Inlet, South Australia was available.

2.0 NEED

The original need expressed in the submission **was to provide fisheries managers specifically in South Australia but generally elsewhere a predictive mechanism by which the recruitment strength and hence subsequent adult populations of Australian salmon could be made in advance. Because fishery managers and industry need to regulate and make investment decisions in a world of imperfect knowledge considerable advantage may be gained if an estimate of recruitment and subsequent adult population strength can be made in advance. This work may provide benefits for other fisheries by providing generic principles for forecasting recruitment in fisheries where spawning and recruitment grounds are significantly removed from each other.**

Whilst the above comments constitute the principal need for the investigation much greater momentum and significance has been added to the study by the recent decision by the United Nations (UN) to grant Australia in November 1994 the sovereign right to explore, exploit, conserve and manage the living and non-living resources surrounding its territories out to 200 nautical miles. This was effected under the United Nations Law of the Sea (UNCLOS). Whilst the Commonwealth, through the Australian Fisheries Management Authority (AFMA) assumed responsibility out to 200 nautical miles upon establishment of the Australian Fishing Zone in 1979 the recent UN decision has wider implications. The declaration of the 200 nautical mile Exclusive Economic Zone whilst offering Australia the opportunity to manage all resources within the zone will also require a commitment by the Australian government to ensure conservation of the resources consistent with long term economic benefits. From a fisheries management perspective this will require a better understanding of the relationships between oceanographic processes and fish recruitment and abundance along the southern shelf and offshelf waters for optimal use to be made of the new resource. Research in oceanographic/recruitment coupling in southern shelf waters will need to be increased to assist fisheries management of the region in a broader sense. The results of this project can provide a contribution to that requirement.

Recent (March 1995) widespread mortalities in the pilchard fishery due to uncertain causes highlighted the importance of having knowledge of the coupling between oceanographic and biological processes. This study concentrated on a substantial portion of the southern Australian continental shelf and can provide a significant input to examining and collating oceanographic, meteorologic and fish kill history events.

3.0 OBJECTIVES

3.1 Original objectives of the study were to

1. To develop a method to systematically measure key environmental and oceanographic variables in the Cape Leeuwin region.

2. To develop a Leeuwin Current Environment Index (LEI) to predict Australian salmon levels along the southern ocean continental shelf, including Barker Inlet.

3. To establish an effective information transfer system where monthly LEI information is conveyed to fisheries managers and industry

4. To provide a framework to develop a LEI type system for pelagic species such as southern bluefin tuna, crustaceans and freshwater species.

3.2 Change in Objectives

During the course of the investigation a number of issues arose which altered the original objectives. These included

1.Regular acquisition of satellite sea surface temperature time series. Although some images were obtained it was not possible to establish a time series of images of the Leeuwin Current. In hindsight, limited value would have been gained by acquisition of SST images over the duration of this project. Far greater value was obtained from analysis of archived data corresponding to approximate period of spawning. These data, which spanned 9 years, were obtained from the CSIRO Division of Oceanography, Perth.

2. The ORV Franklin survey in July 1995 provided an unexpectedly high return of results from an oceanographic and fisheries research point of view. The ADCP, CTD and Australian salmon larval survey data has provided an opportunity to pursue the investigation with far more purpose and substance.

3. The wind regime of south-western Australia emerged as an important factor which required extended examination. Indications are that it is strongly influential in controlling dispersion of larvae away from spawning grounds in Western Australia and hence recruitment in South Australia waters.

The changed objectives of the investigation were as follows

1. Conduct, as originally planned, examination of historical data sets for the period of recruitment data (1980-1993) in Barker Inlet, and examine the link between recruitment numbers in Barker Inlet, South Australia and

. wind strength and direction data from Albany
. mean sea level data from Albany
. Southern Oscillation Index.

2. Analysis of the ORV Franklin cruise data to identify major advection pathways by which the Australian salmon larvae are transported from spawning grounds in Western Australia to nursery grounds in South Australia.

3. Acquisition and analysis of satellite sea surface temperature data from south-west Western Australia for the period (1980-1993).

4.0 METHODS

The methodology employed for this investigation involved consideration of the following aspects.

4.1 The choice of the species

The choice of the species (Australian salmon) had several positive attributes.

a) Australian salmon (western species) spawn only in the south-western waters of Western Australia commencing about March and peaking in April (Malcolm, 1960). Juvenile fish commence to arrive in South Australian waters by about August of the same year (Jones pers.com, 1991). By identification of critical environmental factors a lead time of about 4-5 months may be provided to fisheries managers in South Australia. This will allow recruitment strength to be made in advance, initially, in terms of broad predictors such as poor, average and good years. This will lead to industry being able to optimise effort for expected adult populations of Australian salmon in subsequent years.

b) A relatively long (13 year) time series of recruitment data for this species was available between 1980 and 1993 for Barker Inlet, South Australia which could be tested with environmental factors present at the time of spawning in waters of south-western Australia. The advantage of using the historical recruitment data set was that the data were obtained using a standard beach seine sampling method and thus were not affected by changes in effort in recruitment sampling.

4.2 Time series analysis

Analysis and correlation of time series of salmon recruitment data from Barker Inlet, South Australia between 1980 and 1993 and the following attributes were carried out. These included

<u>The Southern Oscillation Index (SOI)</u> The relationship between the SOI and salmon recruitment in Barker Inlet was examined. Annual mean values of the SOI are those computed from Darwin and Tahiti mean sea levels (Troup, 1965).

<u>Mean sea level</u> data from Albany Western Australia was tested against salmon recruitment data for Barker Inlet. The mean sea level data for Albany was used because this station is the closest to the assumed spawning area of the Australian salmon and has a long time series of quality assurance tested mean sea level data.

<u>Wind data</u> from Albany for the period corresponding to the duration of recruitment data from Barker Inlet (1980-1993) was acquired and analysed to determine the seasonal characteristics of the wind regime, particularly to observe any significant features which may occur at the time of assumed spawning.

4.3 Satellite Sea Surface Temperature Data

The least cloudy NOAA/AVHRR imagery for March and April for the period 1985-1994 was selected from the CSIRO Division of Oceanography, Perth, archives.

The following images were chosen for analysis

24 March 1985
24 March 1986
17 March 1988
28 March 1989
29 March 1990
4 April 1991
28 March 1992
29 March 1993
1 April 1994

Each image was re-mapped to a Standard Transverse Mercator projection and the sea surface temperature (SST) computed using the McMillan and Crosby algorithm.
Digital transects were extracted between the coast and 38°S along meridian 117°E. The extracted data comprised data in the AVHRR visible band 1, near IR band 2, the brightness temperature in bands 4 and 5 and the derived SST. Cloud were screened by inspection of 1) the visible and near IR data 2) spatial coherence in band 2.

4.4 ORV Franklin Cruise July 1994

During the period 6-27 July 1994 a 22 day joint oceanography/larval sampling survey between Adelaide and Fremantle on the ORV Franklin was conducted by Flinders University of South Australia (Drs Petrusevics and Bye) and Western Australian Marine Research Laboratories (Dr Fletcher). The objectives of the cruise were to determine detailed knowledge of the Leeuwin Current structure at a time when the Australian salmon were in the process of translocating from Western Australia spawning grounds to eastern Australia. Whilst the objective of the larval sampling program was to determine the distribution and abundance of pilchards, the Flinders group took advantage of the larval sampling program to conduct surveys targeting Australian salmon larvae. Conductivity-temperature-depth (CTD) and acoustic doppler current profiling (ADCP) surveys were conducted on the shelf and off-shelf region. In excess of 120 stations were occupied between South Australian Gulfs and Fremantle. At approximately 15 stations Australian salmon larvae were found.

The oceanography instrumentation aboard the RV Franklin included a WOCE standard Neil Brown MK3 conductivity-temperature-depth recorder (CTD), a thermosalinograph, an acoustic Doppler current profiler supported by a Global Positioning System, a Turner underway fluorometer and a profiling flurometer. Water samples for calibration of the CTD and analysis of water quality were provided by a 12 bottle, 5 litre Niskin rosette.

4.5 Data Sources

Australian salmon recruitment data was provided by Dr K Jones of the South Australian Research and Development Institute (Aquatic Sciences). The recruitment data used in this analysis was obtained from a number of sites in the Port Adelaide River-Barker Inlet region north of Adelaide. The time series of recruitment data used in this analysis spanned the period between 1980 and 1993. The sampling sites are shown in Figure 2.

Mean sea level for Albany for the corresponding period was obtained from National Tidal Facility, Flinders University of South Australia

Southern Oscillation Index data was obtained from the CSIRO Division of Atmospheric Research, Aspendale, Victoria.

NOAA/AVHRR sea surface temperature data of south-western portion of Western Australian waters were obtained from the Flinders Institute of Atmospheric Marine Sciences (FIAMS), Flinders University of South Australia and the CSIRO Division of Oceanography, Perth, Western Australia.

Wind data for Albany was obtained from the Bureau of Meteorology, Melbourne.

5.0 RESULTS

5.1 Time series analysis

Correlation of environmental factors at Albany and Australian salmon time series data from Barker Inlet was carried out and tested for significance at the 0.05 level of confidence for 12 degrees of freedom using the 1-tailed test.

A listing of the monthly mean sea levels for Albany, Western Australia and salmon new year recruit numbers for the period 1981-1993 for Barker Inlet, South Australia is given in Appendix 1.

5.1.1 Distribution of Australian salmon-Barker Inlet

The variation in monthly salmon survey numbers for the period January 1981 and December 1993 in Barker Inlet, South Australia is shown in Figure 3. For this period, a relatively large numbers of salmon recruits were recorded in Barker Inlet in September 1981, September 1984 and September 1990. On these occasions approximately 320, 748 and 556 new year salmon recruits were recorded. The influx of new year recruits can also be clearly seen. These occurred between August and October each year. By comparison, the numbers of recruits per year during years other than 1981, 1984 and 1990 years were relatively low and ranged between 0 and 100.

5.1.2 Monthly mean sea level-Albany

The variation of monthly mean sea levels at Albany is shown in Figure 3. Mean sea levels during the period between May and July are relatively higher than for other months of the year. For example, for the 13 year period between 1981 and 1993 the highest sea levels for the year occurred in May (38 % of time), June (54%) and July (7%).

Mean sea level (MSL) data for Albany were correlated with *annual salmon new year recruitment numbers* from Barker Inlet, South Australia. The analysis consisted of separate cross correlations of mean sea level for March, April, May and June and new year recruitment numbers for the period between 1981 and 1993. This was done to ensure that the period leading up to, during and after the period of spawning was considered.

The analysis showed that the correlation between March, April and June mean sea at Albany and Barker Inlet recruitment data was not significant. However the correlation between mean sea level in May and recruitment was significant (r^2 = .188) at the level of confidence defined above.

The variation in the mean sea level for May in Albany and new year recruitment numbers in Barker Inlet is shown in Figure 4. Salmon recruitment was relatively higher in Barker Inlet for the years 1981, 1984 and 1990. The relatively higher number of recruits in 1984 in Barker Inlet corresponded to a higher mean sea level at Albany in May 1984 however the 1990 peak in recruitment did not correspond to a high 1990 May mean sea level at Albany.

5.1.3 The Southern Oscillation Index

The annual Southern Oscillation Index (SOI) for the period 1980 and 1993 is shown in Figure 5. By comparison with recruitment data in Figure 4 little correspondence between peaks of high salmon new year recruitment numbers in Barker Inlet, South Australia and the SOI, except for 1981, can be noted.

Correlation between the SOI and Albany May mean sea level was significant ($r^2 = .51$). However correlations between the SOI and salmon new year recruitment numbers in Barker Inlet were not significant ($r^2 = .107$).

A summary of the regression analysis is given in Table 1.

Table 1

Regression Analysis

NEW YEAR RECRUIT NUMBERS BARKER INLET (NYRN-BI)	MAY MSL ALBANY	$r^2 = .188$(S)
SOUTHERN OSCILLATION INDEX	MAY MSL ALBANY	$r^2 = .510$(S)
SOUTHERN OSCILLATION INDEX	NYRN-BI	$r^2 = .107$(NS)
NYRN-BI	DURATION EASTWARD WIND ALBANY	$r^2 = .245$(S)

Tests for significance at 0.05 level
N=12
1-tailed test

5.1.4 Wind data-Albany

Wind data for Albany, Western Australia was analysed for the period between January 1981 and December 1994. This corresponded approximately to the period for which salmon recruitment data was available for Barker Inlet.

Three hourly wind data for Albany for the period 1981 to 1994 were resolved into northerly, southerly, easterly and westerly components. The components were summed to produce monthly total wind strength values (ms^{-1}). The mean monthly values are obtained by dividing the total monthly value by 30 (mean number of days per month) and by 8 (the number of observations per day).

Northerly and westerly wind components for the period January 1981 to December 1994 are shown in Figure 6 and 7.

A consistent feature of these results was the presence of westerly winds which occurred during autumn and winter and followed the period of spawning of the salmon (April-May). This hinted that a favourable mechanism for eastward advection of the larvae was provided by the westerly winds in most years during the period between 1981-1995.

Based on the assumption that salmon spawning occurred during April-May the northerly wind component did not exhibit a sense of coherence for the period 1981-1994 which may be linked to favourable conditions for recruitment in Barker Inlet, South Australia. For the early part of the record (1981-1984) southerly winds dominated over the region until about March-April for 1981, 1982, 1983 and 1984. By May for the above years a reversal of direction occurred and winds tended to be northerly.

From 1985 onwards the concurrence of northerly and westerly winds disappeared and any advantage gained from unison of these conditions was diminished. In the period between 1981 and 1994 the time of transition from southerly to northerly winds changed from about April-May in the period 1981-1984 to December-February from about 1985 onwards. The changes in the wind patterns suggested changes in the synoptic wind patterns of south-western Australia. Similar observations were made in South Africa (J. Bye, perse. com). In the period, 1981-1984 the winds during the winter were predominantly north-westerly whereas in the period between 1985-1995 the winds in the winter were predominantly south-westerly.

The possible association between westerly and northerly wind **strength** with new year recruitment numbers in Barker Inlet (Figure 8 and 9) was examined. No significant qualitative association between the time series of wind strength and new year recruitment numbers was observed. Correlations between new year recruit numbers and westerly and northerly wind **strength** were not significant.

A regular feature of the westerly winds was their consistency of occurrence. For example, for the period 1981-1994, the change from an easterly dominated wind regime to a westerly dominated regime, occurred between April and May for the majority (80 % of the time) of the years in the above period. The only exception was between 1985-1986.

Duration of continuous westerly winds ranged between 3 to 7 months. Peaks in duration of westerly winds occurred in 1981-1982, 1984, 1987 and 1990 which except for 1987 corresponded to the peaks in recruitment in 1981, 1984 and 1990 in Barker Inlet. Table 1 below summarises these observations

Table 2

Month of year and duration of westerly winds Albany 1981-1994

Year	**Month at which changeover to westerly wind occurred**	**Duration of westerly wind (months)**
1981	4	6
1982	5	7
1983	5	5
1984	5	7
1985	6	4
1986*	2*	3*
1986*	7*	3*
1987	4	7
1988	5	5
1989	5	5
1990	4	7
1991	5	6
1992	5	4
1993	4	6
1994	4	6

* occurred twice in 1986

The correspondence between new year recruitment numbers in Barker Inlet and duration of westerly winds is shown in Figure 10. Correlation of these data was significant (r^2 =.245)

5.2 Sea surface temperature data

The reason for acquiring these data was two fold.

Firstly, it was intended to acquire a time series which would provide information of the sea surface temperature variation leading up to the time of spawning of the salmon. This information, in conjunction with fishermans observations would have provided some clue to the temperature at which spawning occurred. Due to technical problems it was not possible to acquire a sufficiently long time series of SST images at the appropriate time to identify spawning events. However, through SST data supplied by the CSIRO Division of Oceanography, Perth, it was possible to examine a number of images recorded as close to the spawning time as possible over a span of about 9 years. The SST transects along 117°E are shown in Figures 11 to 13

In those images which were relatively cloud free, the Leeuwin Current along meridian 117° E was identified by a region of warmer water between mainly the coast and the edge of the continental shelf although on occasions it was noted on the shelf edge and off the shelf. On the southern edge of the Leeuwin Current quite often well defined clockwise eddy structures were noted. These observations confirmed the view that the Leeuwin Current generally flowed along the shelf rather than beyond the shelf. There was often a well defined SST front of 3-4°C along the southern boundary. The presence of eddy structure beyond the shelf break confirmed ADCP measurements that westerly currents were often observed in this region during the ORV Franklin cruise in July 1993. Table 3 below provides a summary of the SST data extracted along meridian 117°E for the period 1985-1994.

Table 3

Summary SST cross-shelf data along 117°E

Date	**Maximum SST (°C)**	**Leeuwin Current Position**	**Recruit Nos Barker Inlet**
24 March 1985	20.5	On shelf	98
24 March 1986	20.0	On shelf	19
17 March 1988	cloudy	cloudy	11
28 March 1989	22.5	shelf break	165
29 March 1990	21	shelf	1129
4 April 1991	23	shelf break	130
28 March 1992	cloudy	cloudy	51
29 March 1993	cloudy	cloudy	1
1 April 1994	23	shelf	N/A

Note

1. The position of the Leeuwin Current was defined as the position of the maximum core temperature.

2. Recruit numbers corresponded to total salmon recruited between August and October.

Based on the above data there was no qualitative correlation between the maximum temperature observed along meridian 117°E and the recruitment of salmon in Barker Inlet to suggest that the temperature of the Leeuwin Current has a direct impact on recruitment.

The second portion of the need for SST data was to delineate on a regional scale the nature and interaction of the various water masses of the GAB. In the absence of new SST data reference to a number of existing sources was made. These included Petrusevics (1991) and Herzfeld (pers.comm.).

Based on examination of SST images of the GAB from the above sources, the following impression of general features of the current systems of the Great Australian Bight (GAB) was made.

During the summer, a region of warm water was noted to develop in the north-western part of the GAB. This was likely to be caused by localised heating of the relatively shallower waters adjacent to the coast. Based on satellite sea surface temperature data, the temperature of this water was 2-3°C warmer than the surrounding water. During the same period persistent south-easterly winds blow over a long fetch parallel to the coastline and exert stress on the warm waters in the north-western sector of the GAB. Persistent wind stress due to the south-easterlies during the summer is likely to be the mechanism by which the warm waters of the north-western portion of the GAB are contained in this region. In the winter the effect of the south-easterlies is reduced and north-westerlies and transient south-westerlies are experienced in the region. These winds are favourable for promoting advection of the warm water from the north-western section of the GAB eastwards along the shelf.

Such observations identified the Leeuwin Current as an independent feature whose eastern extent was the Recherche Archipelago. These observations are consistent with those made by Rochford (1986) who reported the eastern limit of the Leeuwin Current to be the western end of the GAB. The winter surface outflow from the GAB was also clearly identified as an independent water mass which flows along the shelf edge south of Kangaroo Island. This current is often wrongly referred to as the Leeuwin Current. The transportation of the salmon larvae therefore appears to be influenced by several separate mechanisms. Initially, near the spawning grounds the salmon larvae are likely to be influenced by the well defined Leeuwin Current and westerly winds. As the influence of the Leeuwin current diminishes the continued eastward advection of the larvae is maintained by westerly winds and winter surface outflow from the GAB.

5.3 ORV Franklin Survey- July 1994

The main objectives of the oceanography component of this survey was to delineate the various water masses in the GAB region. Details of the survey are given in the Cruise Research Summary. (Appendix 2). The cruise track of the survey is shown in Figure 14. The survey concentrated on sampling mainly on the shelf with some deeper stations being occupied off the shelf in depths of up to 5500 metres. Figure 15.

5.3.1 Conductivity-Temperature-Depth (CTD) Results

The purpose of the CTD survey was to differentiate the various water masses which occupy the Australian southern continental shelf. In this way a clear definition of the easterly extent of the Leeuwin Current during winter 1994 was made.

During the survey which lasted 22 days over 130 stations oceanographic stations were occupied on and off the continental shelf by ORV Franklin. These are marked on the cruise track, Figure 14.

During the course of the survey the CTD data was downloaded after each cast and through use of on-board computing facilities it was possible to conduct analysis of the temperature and salinity data.

Temperature-salinity (T-S) characteristics were used to delineate various water masses which occupied the GAB and offshore region. A summary of these findings is presented in Figure 16. In addition to the well defined water masses of the deeper off-shelf region a number of local features were identified. On the shelf three distinct water masses were identified by virtue of their unique T-S signatures. Temperatures are in °C and salinity in practical salinity units

.GAB winter surface waters	$15.0<T<17.0$ $35.50<S<35.75$
.GAB winter bottom waters	$16.0<T<17.5$ $36.0<S<36.75$
.Leeuwin Current	$19.0<T<17.0$ $35.75<S<36.0$

Although there is some overlap of temperature and salinity for the three water masses the distinguishing features were that the GAB winter surface waters are relatively cooler and less saline than both the GAB winter bottom waters and the Leeuwin Current. The temperature of the GAB winter bottom waters and GAB winter surface waters were similar but former was clearly distinguished by the higher salinities. The salinity of the Leeuwin Current was intermediate of the other masses however its distinguishing feature was the relatively higher temperature, Figure 16.

The easterly extent of the Leeuwin Current during this period was the eastern end of Recherche Archipelago, approximately longitude 124°E. This is evident from comparison of Figures 16 and 17. In Figure 16, the onset of the Leeuwin Current T-S signature was evident as a small number of data points in the upper part of the T-S diagram. In Figure 17 the T-S signature was well established. The first evidence of the Leeuwin Current therefore occurred in the vicinity of station 90. Figure 14. Rochford (1986) reported the eastern extent of the Leeuwin Current at about 130°E. The GAB winter surface waters were noted to be a clearly distinguishable water mass from that of the Leeuwin Current.

5.3.2 The Acoustic Doppler Current Profiler (ADCP)

Preliminary results of ADCP measurements were presented in an earlier progress report. Whilst the results of the preliminary findings remain valid the data has been subjected to more thorough analysis which has provided a more detailed outcome. Details of the methodology and results are presented in Appendix 3.

5.3.3 Summary of major findings

During July 1994 the Leeuwin Current up to about 118°E was characterised by an easterly flow with maximum surface current of 68 cms^{-1} at the shelf edge. On the shelf, the current was easterly but speeds were lower, typically 15 cms^{-1}. East of 118°E the surface currents diminished with maximum current strength of about 58 cms^{-1} recorded just beyond the shelf edge.

Strong current shear was detected between the surface and 200 metres. Maximum current shear was 47 cms^{-1}. Beyond 124°E the current strength decreased, this was consistent with the results of the CTD surveys which indicated that the eastern limit of the Leeuwin Current was about 124°E.

Figures 5.6 a,b and 5.7 a,b in Appendix 3 show vector plots of current speeds at various "bin" depths. The persistent easterly nature of the shelf currents at all depths can be observed. Off the shelf there is evidence of westerly currents, particularly in the region of the shelf in south-west Western Australia, where a north-westerly flow was detected. During the course of the survey satellite imagery showed presence of break away features on the southern edge of the Leeuwin Current which could account for the westerly currents.

Vector plots of the currents indicated the variability of the shelf edge currents. The current regime along the southern continental shelf were characterised by strong currents in the western section (up to 124°E), relatively weaker currents in the middle section of the GAB (between 124° and 133°E) and stronger currents in the eastern section of the GAB (east of 134°E).

From continuity considerations the relative stronger current regime beyond 134°E must be due to a source beyond the eastern limit of the Leeuwin Current. One possible source may the outflow from the head of the GAB. CTD data indicated water masses of other than Leeuwin Current origin present at the surface and on the bottom in the central portion of the GAB. Satellite data confirmed the existence of south-easterly advection of water from the north-west portion of the GAB.

5.3.4 Australian salmon larvae survey

As part of the larval sampling program on ORV Franklin during July 1994 sampling for Australian salmon larvae was conducted. Approximately 100 surface tows targeting Australian salmon were carried out during the survey.

Details of the methodology and results are presented in Appendix 4.

5.3.5 Summary of major findings

Sampling for Australian salmon occurred between south of Kangaroo Island and Albany, Western Australia. Within this region the stations where larvae were captured ranged between the Recherche Archipelago and the eastern end of the GAB (Figure 2, Appendix 4). The majority of the stations where larvae were captured were on the shelf and within the strong current regime on the shelf edge.

Otolith ageing was carried out on the samples which indicated that the age of the specimen larvae ranged between 20 and 129 days. Corresponding back-calculated spawning dates ranged between early March 1994 and late June 1994. The majority of the back-calculated spawning dates occurred in May 1994. Table 1, Appendix 4 provides a summary of the dates.

The possible distance travelled by larvae prior to capture was calculated using a mean current speed which was applicable to the capture location. The mean current speeds were obtained using the ADCP data relevant to the capture location. Possible spawning locations were calculated to be between Bunbury and Esperance, Western Australia and nursery sites were estimated to be largely Barker Inlet. (Table 3, Appendix 4).
The calculated spawning regions were consistent with published information. The calculated arrival times in Barker Inlet were in agreement with field observations in Barker Inlet.

6.0 DISCUSSION

6.1 Time series

Linear regressions between recruitment data of Australian salmon in Barker Inlet, South Australia and environmental factors associated with spawning grounds in Western Australia showed variable statistical significance. A significant correlation was found between recruitment data and mean sea level at Albany. SOI and mean sea level at Albany were significantly correlated. However correlation between SOI and recruitment were not significant. Duration of westerly winds at Albany and recruitment in Barker Inlet were significantly correlated.

The regular onset and persistence of westerly winds in the region of spawning and following spawning appears as a major factor in advection, initially in unison with the Leeuwin Current, and subsequently separately, of the salmon larvae away from the spawning grounds and across the western portion of the GAB.

6.2 Sea surface temperature data

Examination of the cross-shelf SST transects along 117°E at a time which corresponded to close to spawning of adult salmon indicated a variation in the characteristics of the Leeuwin Current. Maximum temperature of the current and location of the core of the current varied on a year to year basis. If temperature of the Leeuwin Current is a critical factor in the spawning process then it is likely that the hatched salmon eggs may be distributed over a wide area of the shelf and beyond the shelf from year to year.

Analysis of published data on SST time series of the GAB provided a qualitative overview of the various water masses in the region and provided evidence of south-easterly advection from the head of the GAB along the shelf edge. This outflow is the likely mechanism, which in unison with westerly wind induced currents maintain larval transport after the influence of the Leeuwin Current has waned in the western portion of the GAB.

6.3 CTD data

Differentiation of the various water masses in the GAB was achieved including the eastern extent, by temperature-salinity classification, of the Leeuwin Current in winter 1994. Other water masses, including the winter surface waters were re-identified. However, a bottom salinity dominated water mass which had been reported on the shelf edge by Godfrey et al (1986) was identified for the first time at the head of the GAB.

6.4 ADCP data

The ADCP measurements confirmed the presence of a shelf-edge eastward flowing current. The eastern limit of the Leeuwin Current was determined by a well defined change in the current speed at all depths. The change in current speed occurred in a region which corresponded to definition of the eastern limit of the Leeuwin Current by CTD measurements. Examination of the current speeds along the shelf edge showed an increase of speed near the eastern end of the GAB which corresponded to the region where the outflow from the head of the GAB was postulated.

6.5 Larval data

The major pathway of larval advection by the shelf edge current was demonstrated by the distribution of salmon larval samples. Most larvae were captured at stations located within the main shelf-edge current with a few being found at stations located in the weaker shelf currents.

From otolith analysis it was possible to determine larval ages and hence back-dated spawning dates which ranged between March and June 1994. This suggested that in 1994 the spawning period was protracted over a considerably longer period than indicated from published reports. Regions of spawning were estimated by using average current speeds with respect to capture locations. The use of average speeds was probably an over simplification of the advection rates.

6.6 Possible processes at spawning grounds and enroute

Uncertainty in the spawning time and spatial distribution of the eggs after hatching for the period between 1981 and 1994 pose a problem in the development of the initial processes of advection of salmon larvae from spawning grounds. Ideally, knowing the period and location of spawning, numerical simulations based on wind and density gradient associated with the Leeuwin Current would permit a better understanding of the initial stages of larval transportation to be developed. In the absence of quantitative data it is possible to advance only hypothesis to formulate, in conjunction with field observations, a model of larval transportation.

Schooling of gonad ripe salmon in regions of warmer water advected in by the Leeuwin Current appears as the starting point of the process under investigation. Assuming that spawning commences about April-May each year the hatched salmon eggs need to be favourably positioned in the main stream of the easterly Leeuwin Current to be successfully advected to the east. At this stage a number of scenarios are possible.

Based on the results of the ORV Franklin ADCP measurements the currents close to the shore are relatively weaker than those closer to the shelf edge. If the salmon eggs are hatched close to the shore an offshore wind, that is a northerly, is required to move the eggs and larvae out of regions of weak currents into regions where the currents are stronger. If however the offshore wind is excessive either in terms of strength or duration then there is the possibility that the larvae can be transported off shore. In this case the larvae may become entrained in westerly flows which can favour recruitment to the west of the spawning region at the expense of recruitment to the east.

For the years between 1981 and 1984 inclusive and partially in 1985 northerly and westerly winds showed a high degree of temporal coherence which suggested that if spawning occurred close to the shore then favourable winds were present to aid efficient transport of the larvae eastwards away from the spawning grounds. Peaks in recruitment in Barker Inlet occurred in 1981 and 1984.

From about 1986 onwards the presence of persistent onshore winds, that is southerlies and westerlies at about the time of spawning would have favoured advection of eggs and larvae from offshore regions towards the coast and eastwards.

The extent to which the Leeuwin Current is influential in transportation of the salmon larvae eastwards following spawning appears to be limited to the eastern region of the Rehearche Archipelago. This feature is amply demonstrated by both the CTD and ADCP results. The persistently occurring westerlies promote a surface current which acts in unison with the Leeuwin Current as far as the eastern limit of the latter. The diminished current speeds beyond 124°E are likely to be mainly due to the westerly induced currents.

Whilst the ADCP measurements provide an accurate impression of the nature of the current structure along the track of the cruise, they are undoubtedly limited in their spatial representation of currents along the entire GAB. The apparent reversal of ADCP currents off-shore from the generally easterly nature of currents noted on the shelf and shelf edge may be due to a number of factors.

Considerations (Bye, personal communication) of the ORV Franklin cruise data suggests that in the eastern portion of the GAB a pattern of onshore and offshore geostrophical motions extending down to about 2000 metres can be noted. Further west this structure is replaced by an along-shelf dynamic topography in which the eastward Leeuwin Current occurs in the upper levels, but a westward transport exists at depth. Cresswell and Golding (1980) suggested that the southerly edge of the Leeuwin Current south of Western Australia can be modified by offshoots from the main flow which can be cyclonic eddies and anticyclonic meanders. Offshoots were found to block temporarily the flow of the Leeuwin Current and divert it into unstable baroclinic waves prior to formation of cyclone-anticyclone eddy pairs (Griffiths and Pearce, 1985). More recently Cresswell and Petersen (1993) reported the use of the ADCP instrument to map the Leeuwin Current and one its off-shoots. The occurrence of off-shoots provides an additional unquantifiable parameter which complicates the development of an index of Leeuwin Current strength to link with recruitment of Australian salmon in Barker Inlet.

Whilst the high degree of correlation shown between environmental factors and recruitment in other fisheries (Pearce and Philips, 1988; Thresher, 1994) has not been demonstrated in this study thus far the results are nevertheless encouraging.

Considering the fact that the salmon larvae need to be located in an appropriate position on the shelf to take advantage of the Leeuwin Current requires favourable winds to occur after spawning. Next, after the influence of the Leeuwin Current has diminished in the vicinity of the Rehearche Archipelago continuity of larval movement must be maintained by the westward drift current and later the outflow from the GAB. The shelf edge flow may be influenced by warm water offshoots or cold water intrusions which can transport larvae up to 100 km away from the mainstream of advection. Finally the larvae manage to navigate Investigator Strait and a large portion of Gulf St Vincent before entering Barker Inlet. The nature of the last section of travel from the shelf edge into Gulf St Vincent remains reasonably unknown. Local wind conditions in Investigator Strait may be important in advection of larvae into Gulf St Vincent. This hypothesis is supported by results of drift card experiments reported by Petrusevics (1991). Drift cards were released at a number of stations on the shelf in the GAB. Reports of drift card sightings along beaches in Gulf St Vincent, including Barker Inlet were made. In many respects , drift cards can behave in a similar fashion to salmon larvae which spend portion of their journey in the upper layer of the sea.

6.7 Concluding remarks

Only preliminary conclusions can be drawn from the results to date due to the relatively short time span of the data, particularly that of Australian salmon recruit data (14 years). Work reported by Philips et al (1991) on recruitment to the rock lobster fishery in Western Australia considered that 20 year settlement records are marginally short and thus justify only preliminary conclusions on relationships between settlement and environmental variables. Continuity of salmon surveys in Barker Inlet will improve the value of the recruitment data bank.

It is unlikely that any one variable may be linked with recruitment in Barker Inlet with a high level of statistical significance . To date, the effect of the westerly wind field along the southern continental shelf appears to be significant. Better information on the timing and distribution of spawned salmon eggs is required. Such information in conjunction with knowledge of the Leeuwin Current characteristics (cross shelf temperature gradients) should increase the level of confidence on the disposition of the larvae "patches" in the initial stage of advection.

The relationship between westerly winds and recruitment needs to be further pursued. Detailed analysis of wind records from Albany need to be analysed over the full length of the record (1975-1995) to identify extreme wind events and periodicity characteristics which may influence eastward advection of larvae.

NOAA/AVHRR satellite sea surface temperature data, subject to absence of clouds, remains as one of the most cost effective long term methods to monitor shelf scale effects, such as across shelf gradients of the Leeuwin Current near the spawning grounds. Resulting analysis could be used in association with other variables (wind) to analyse recruitment variability in Barker Inlet. The critical times being before, during and after spawning.

In spite of all un-favourable factors, a statistically significant correlation between recruitment and duration of westerly winds (r^2 =.245) and with mean sea level (r^2 = .188) was demonstrated after the larvae have travelled a distance of approximately 2000 km from spawning grounds in Western Australia to recruitment in Barker Inlet, South Australia.

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Dr John Bye- (Flinders University) oceanography of the GAB/ORV Franklin cruise
Bill Mitchell- (National Tidal Facility) tidal information
Alan Pearce-(CSIRO-Perth) oceanography of the Leeuwin Current
Dr Rick Fletcher-(WA Marine Labs) recruitment data
Dr Rod Lenanton-(WA Marine Labs) recruitment data

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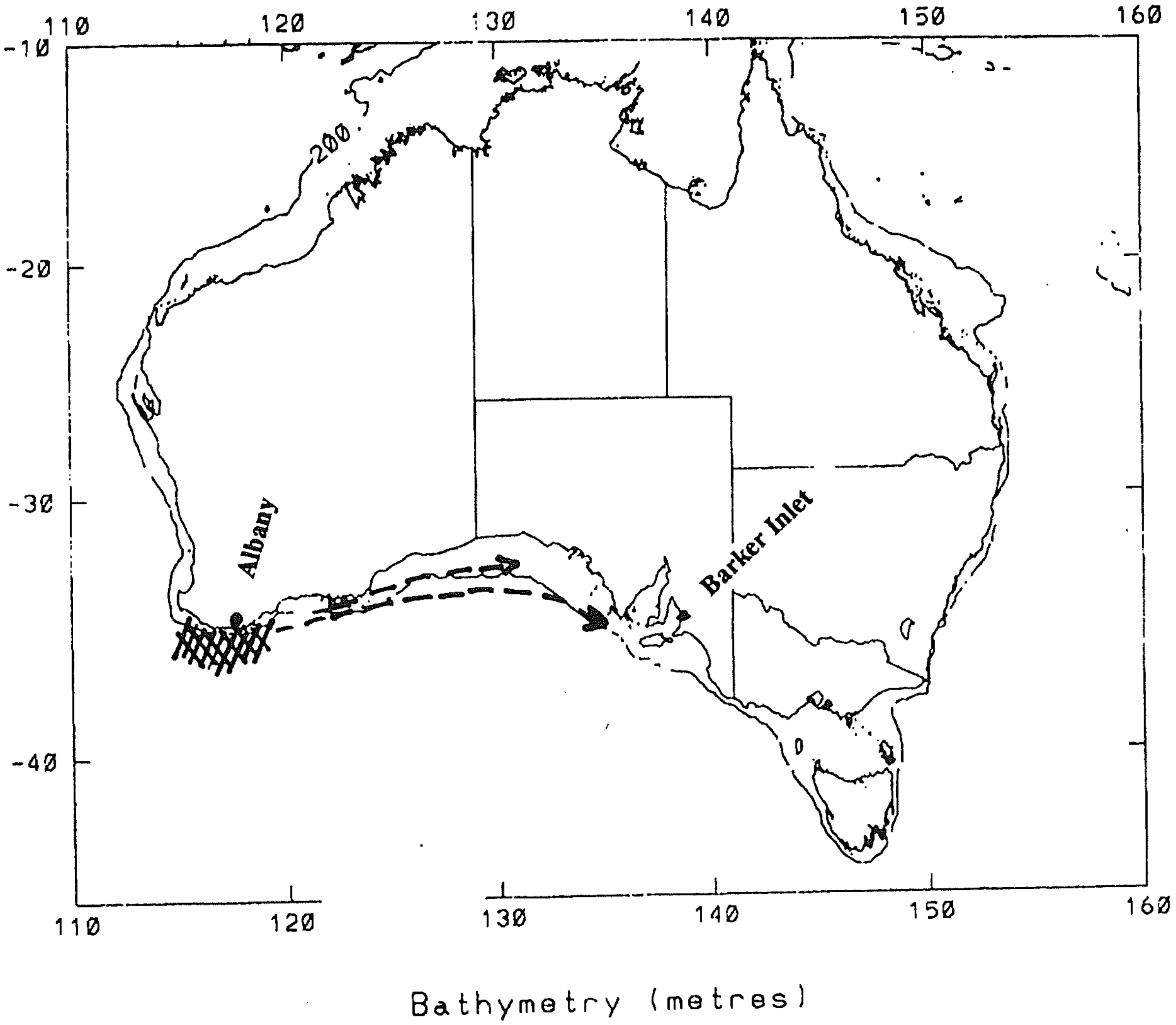


FIGURE 1

The region of the investigation.

.Spawning region (hatched)
.Assumed path of larval advection (dotted)
.Recruitment site Barker Inlet

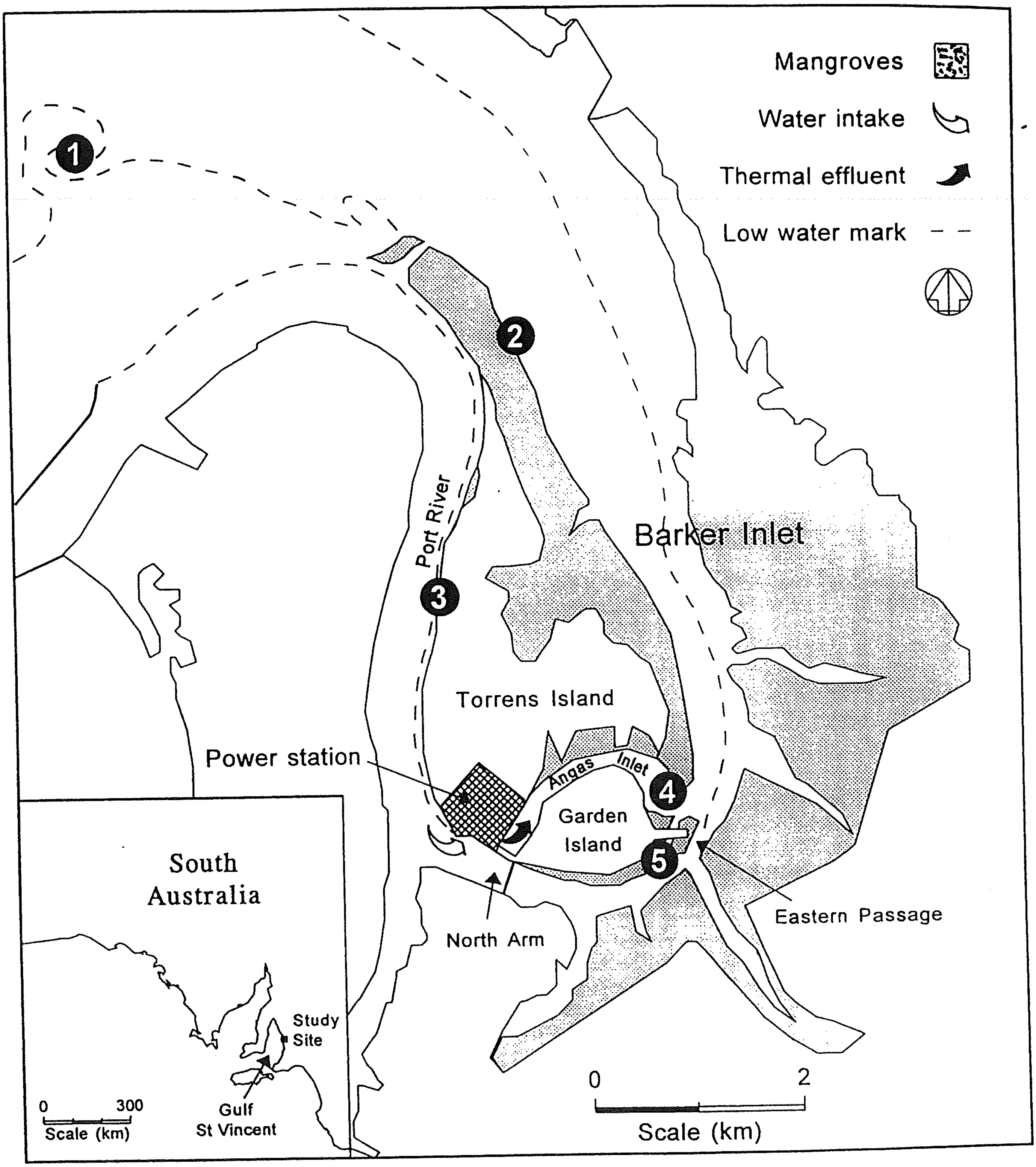


FIGURE 2

Sampling sites in Barker Inlet (After Jones, 1991)

FIGURE 3

Recruitment numbers in Barker Inlet (lower)
Mean sea level Albany (upper)

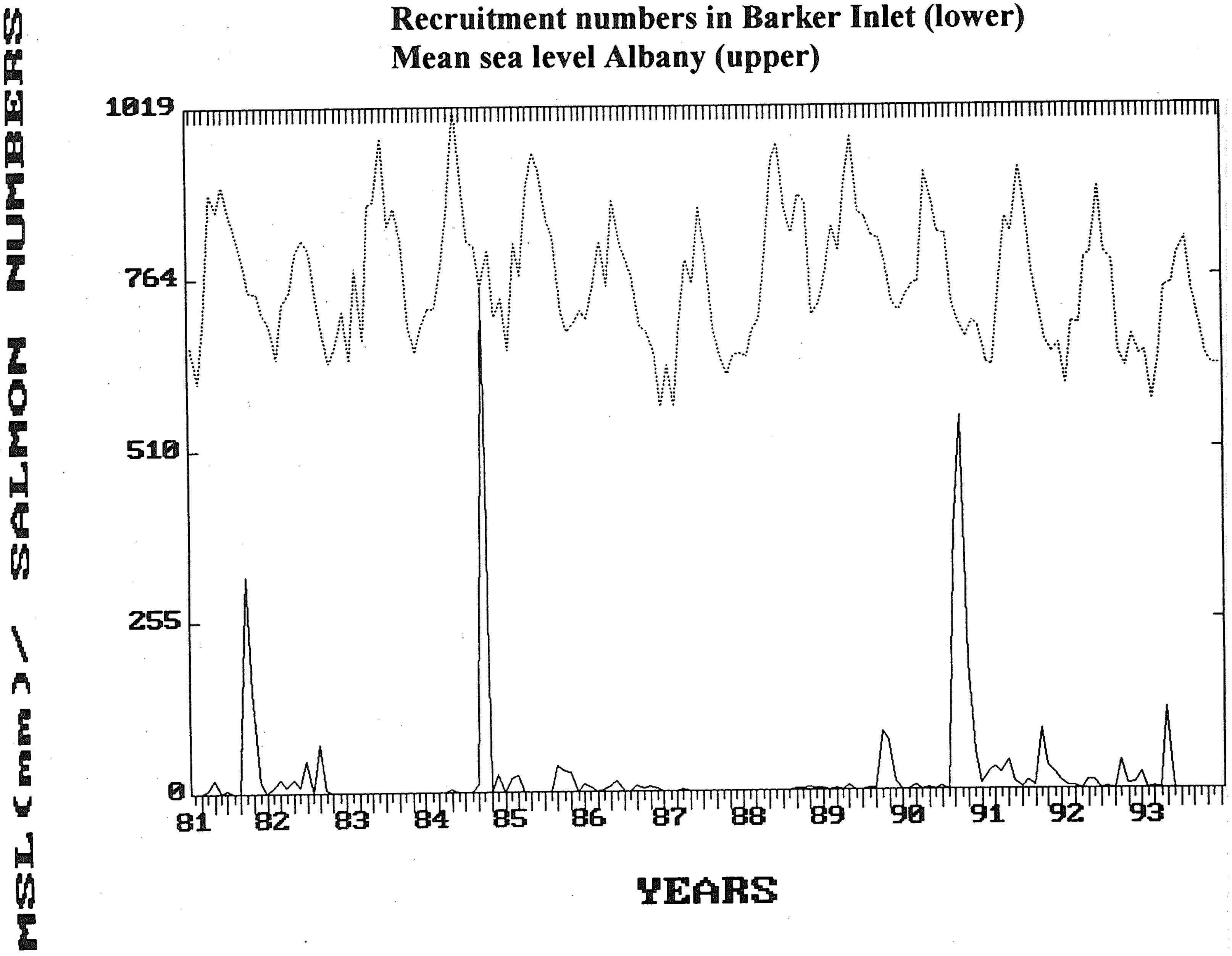


FIGURE 4

Annual May mean sea level Albany (upper)
New Year recruitment numbers in Barker Inlet (lower)

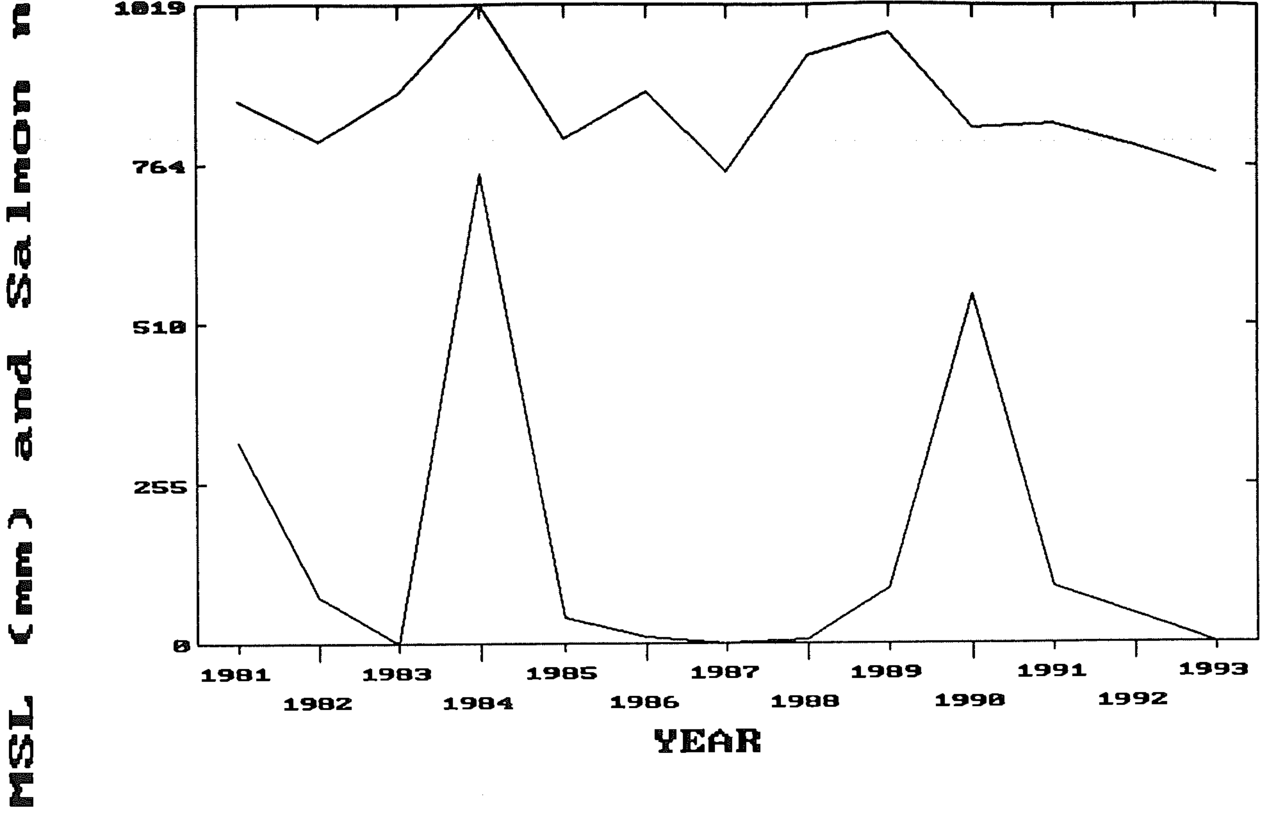


FIGURE 5

Annual Southern Oscillation Index

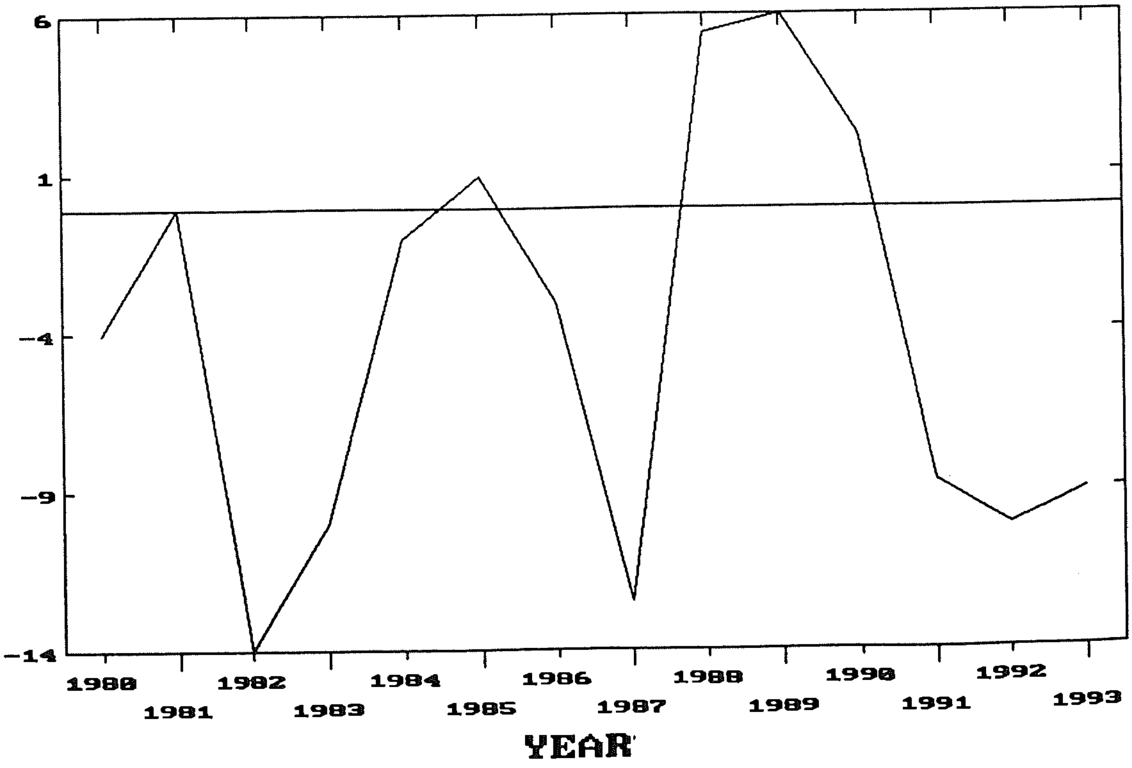


FIGURE 6

Wind strength Albany 1981-1987

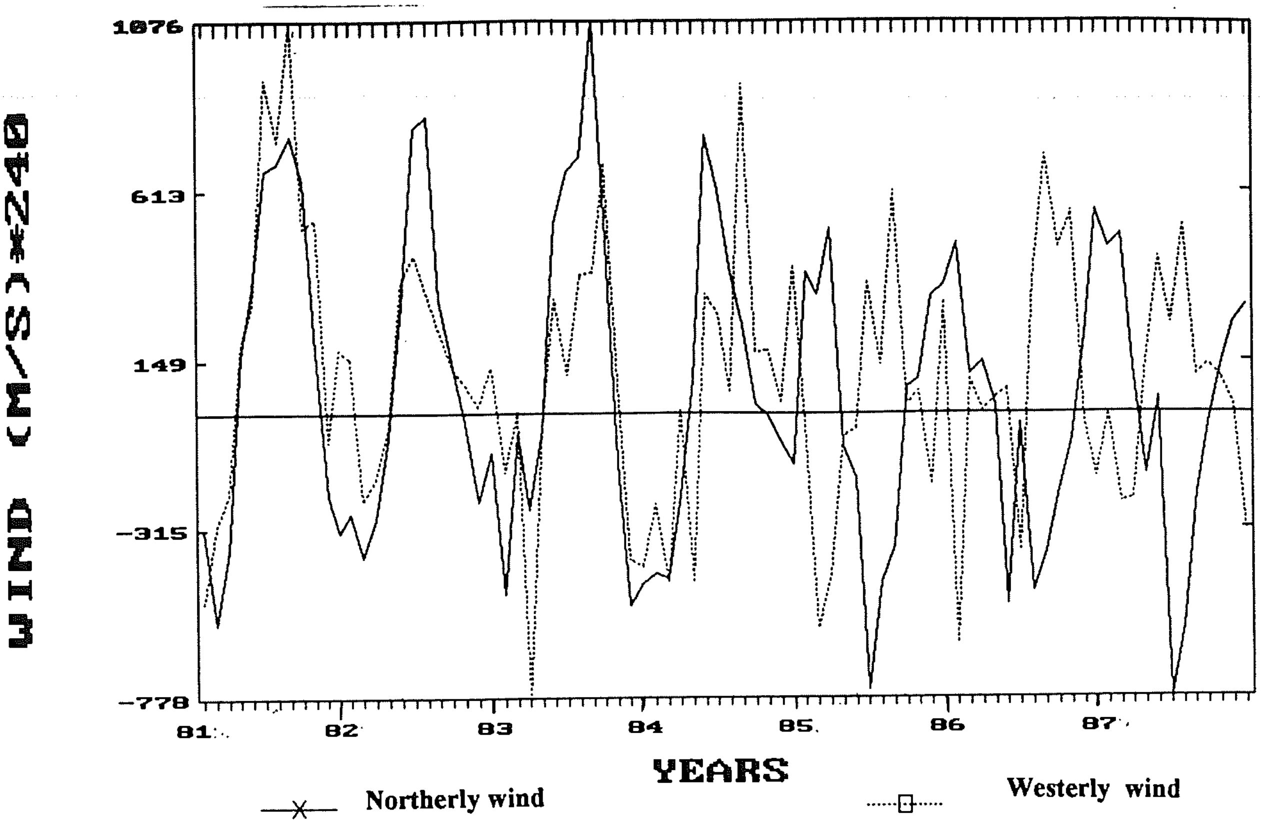


FIGURE 7

Wind strength Albany 1988-1995

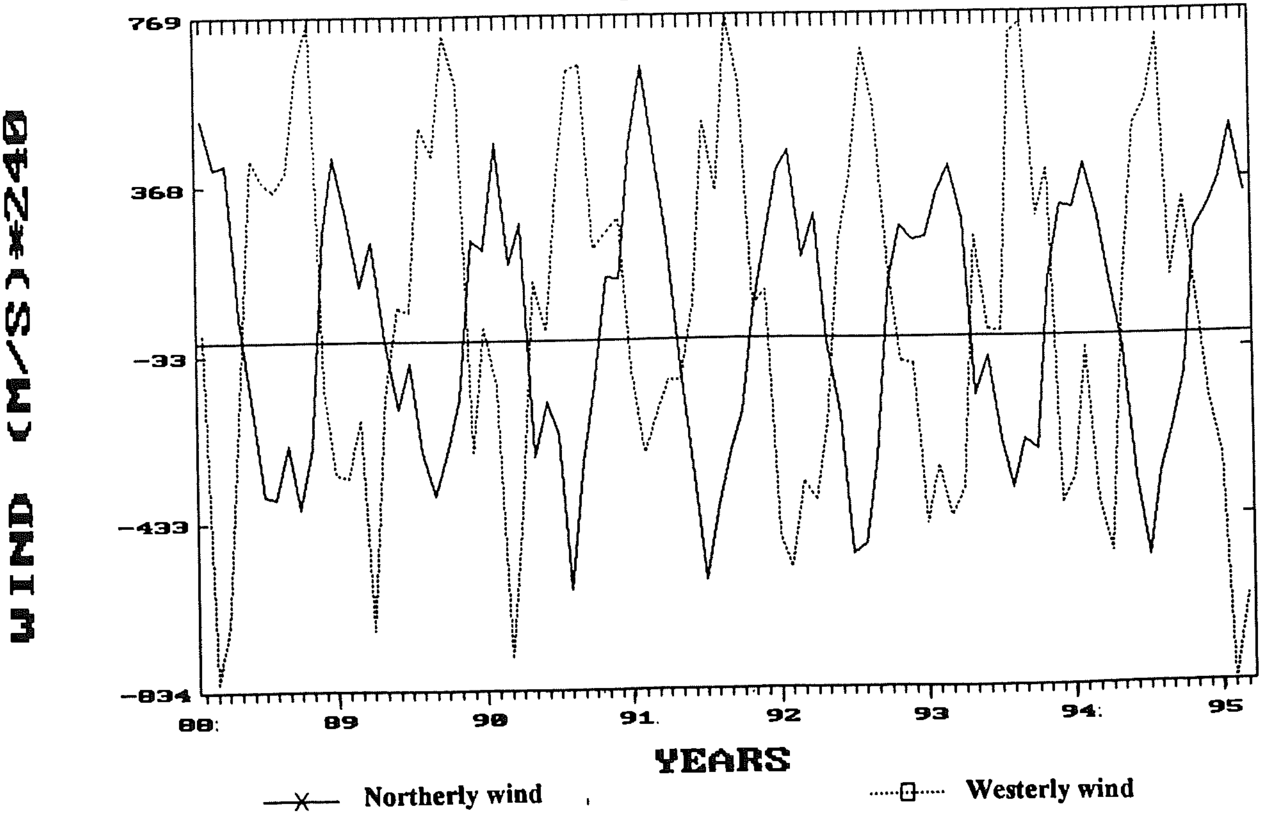


FIGURE 8

Westerly wind-Recruitment Barker Inlet

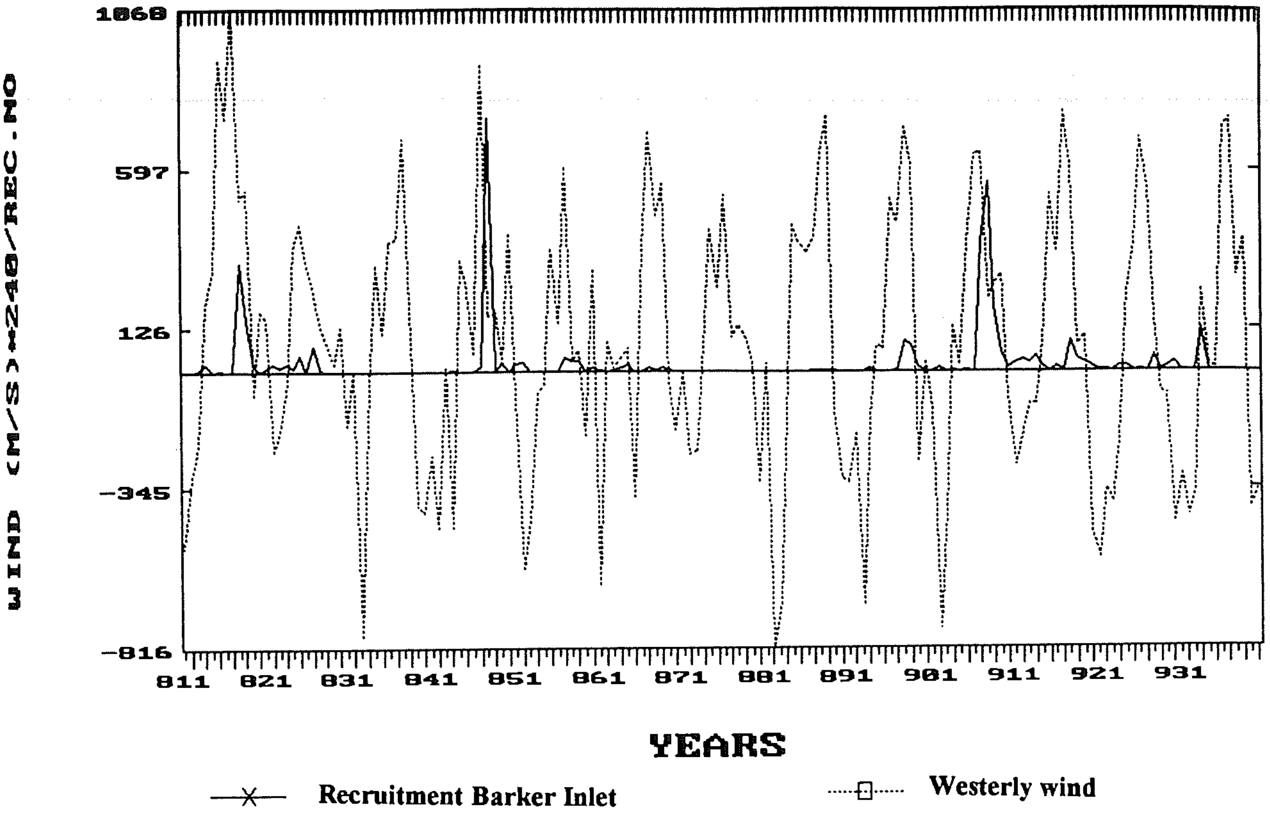


FIGURE 9

Northerly wind-Recruitment Barker Inlet

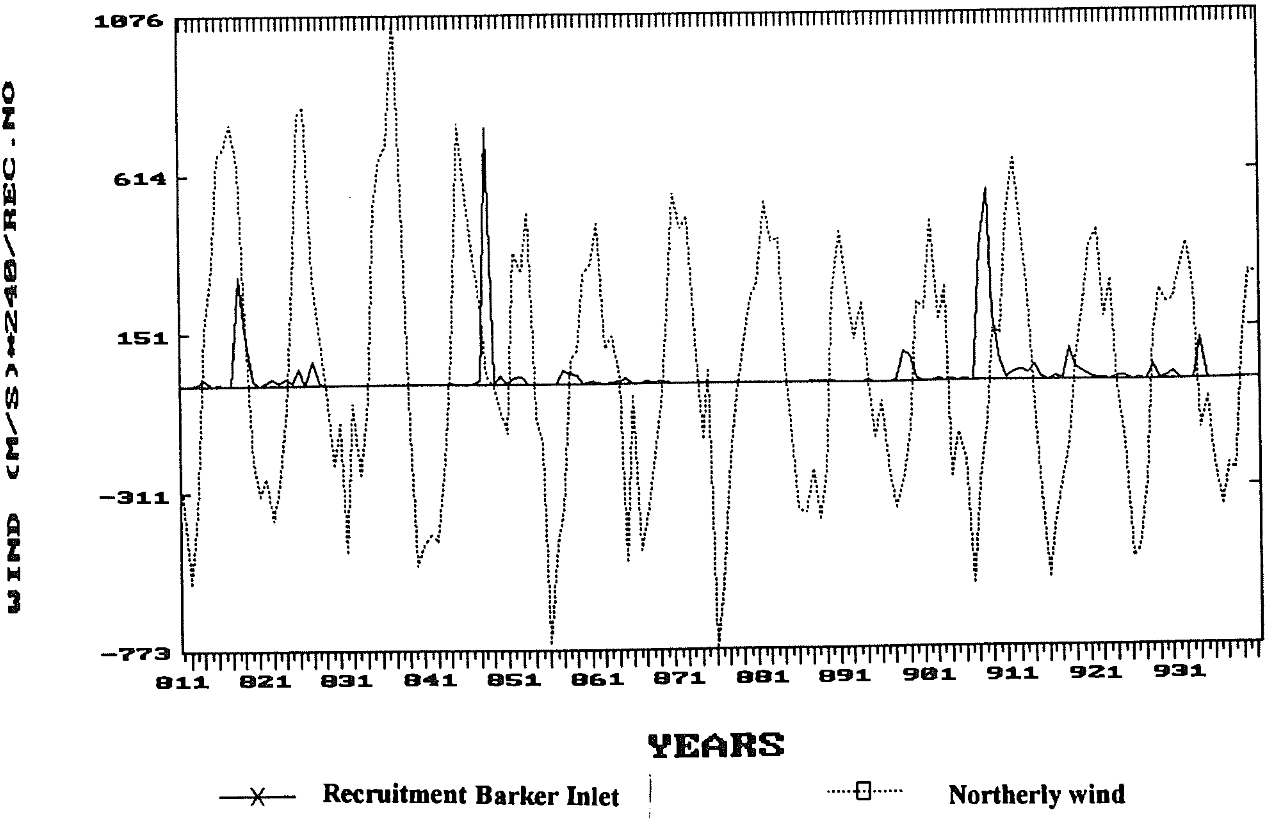
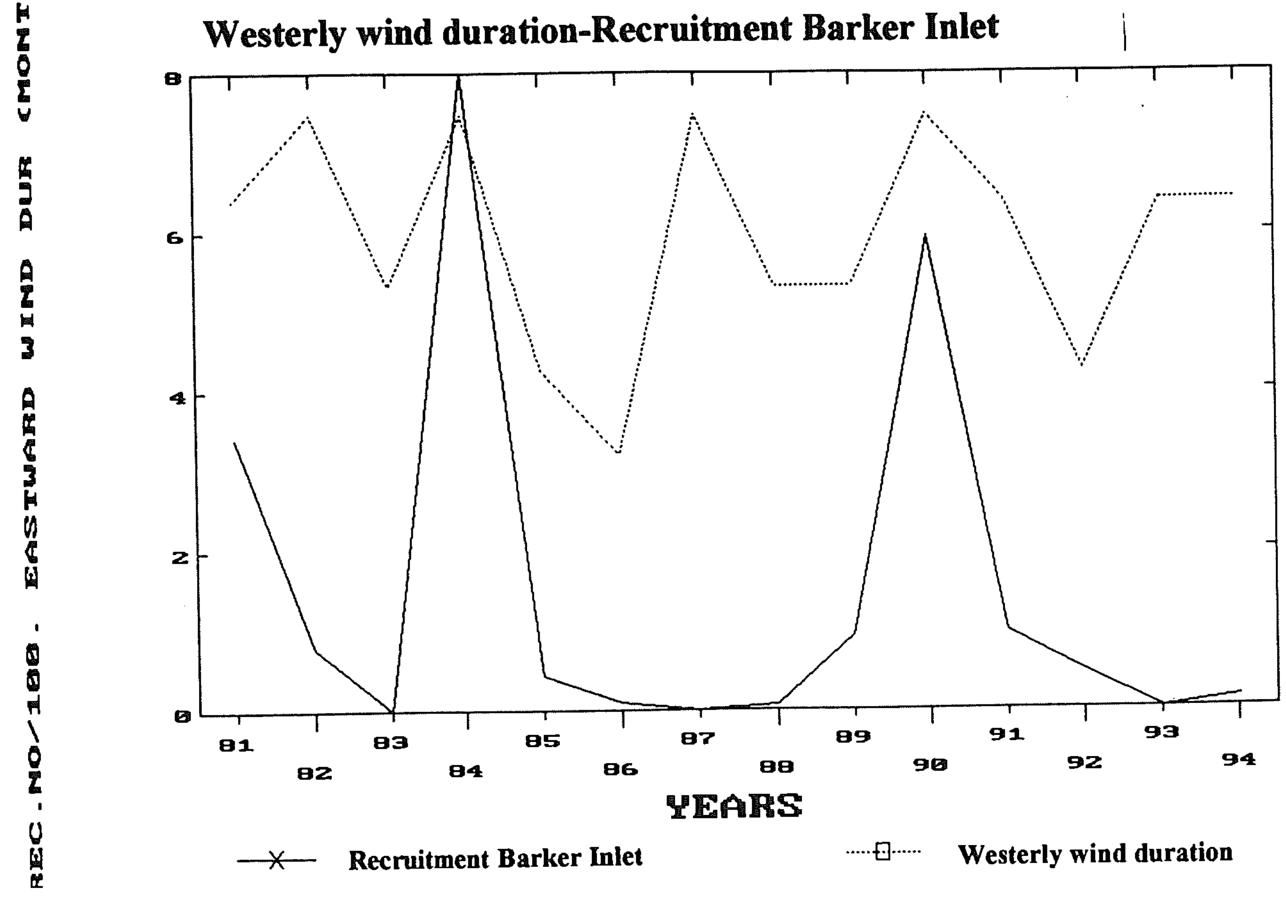


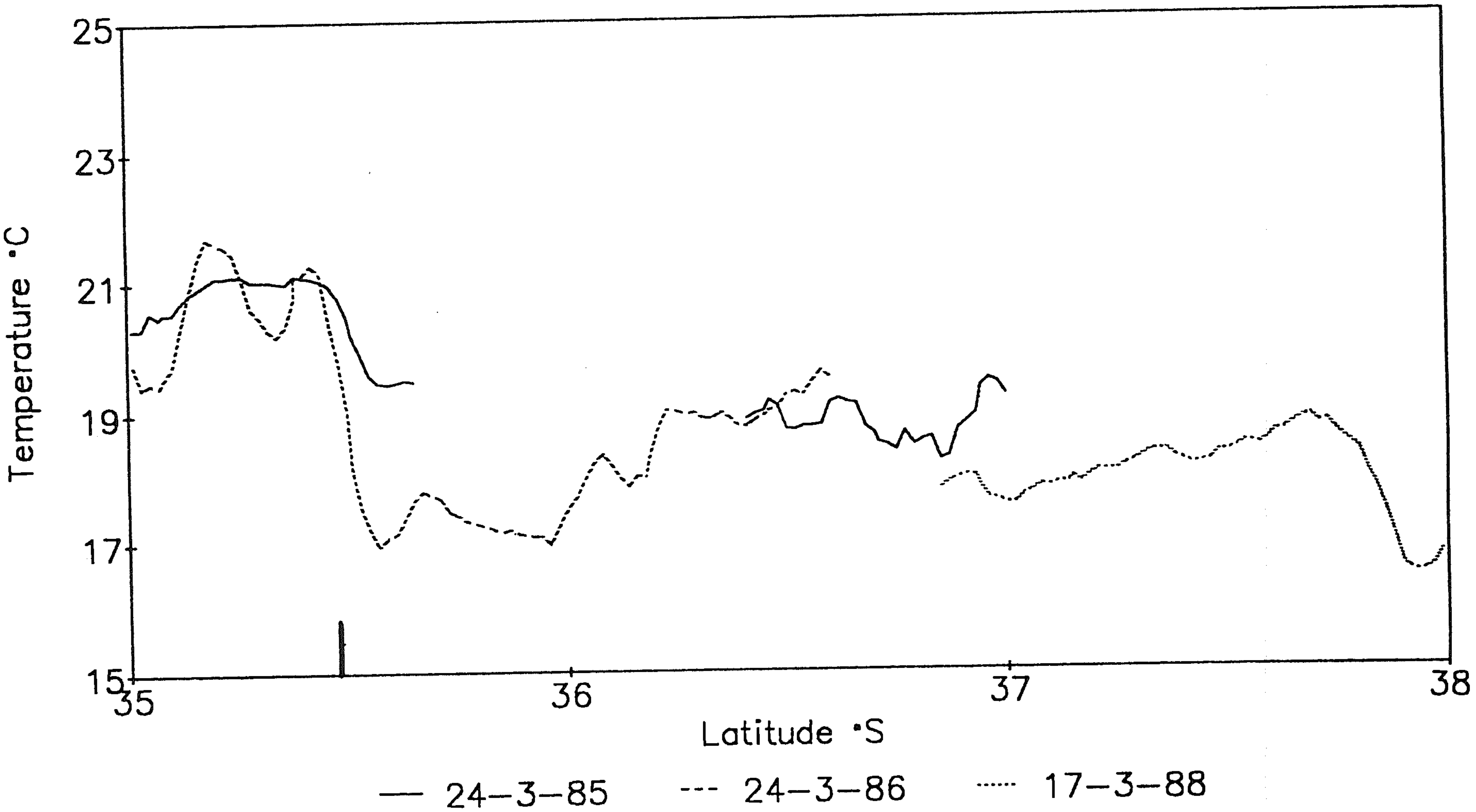
FIGURE 10



Westerly wind duration-Recruitment Barker Inlet

FIGURE 11

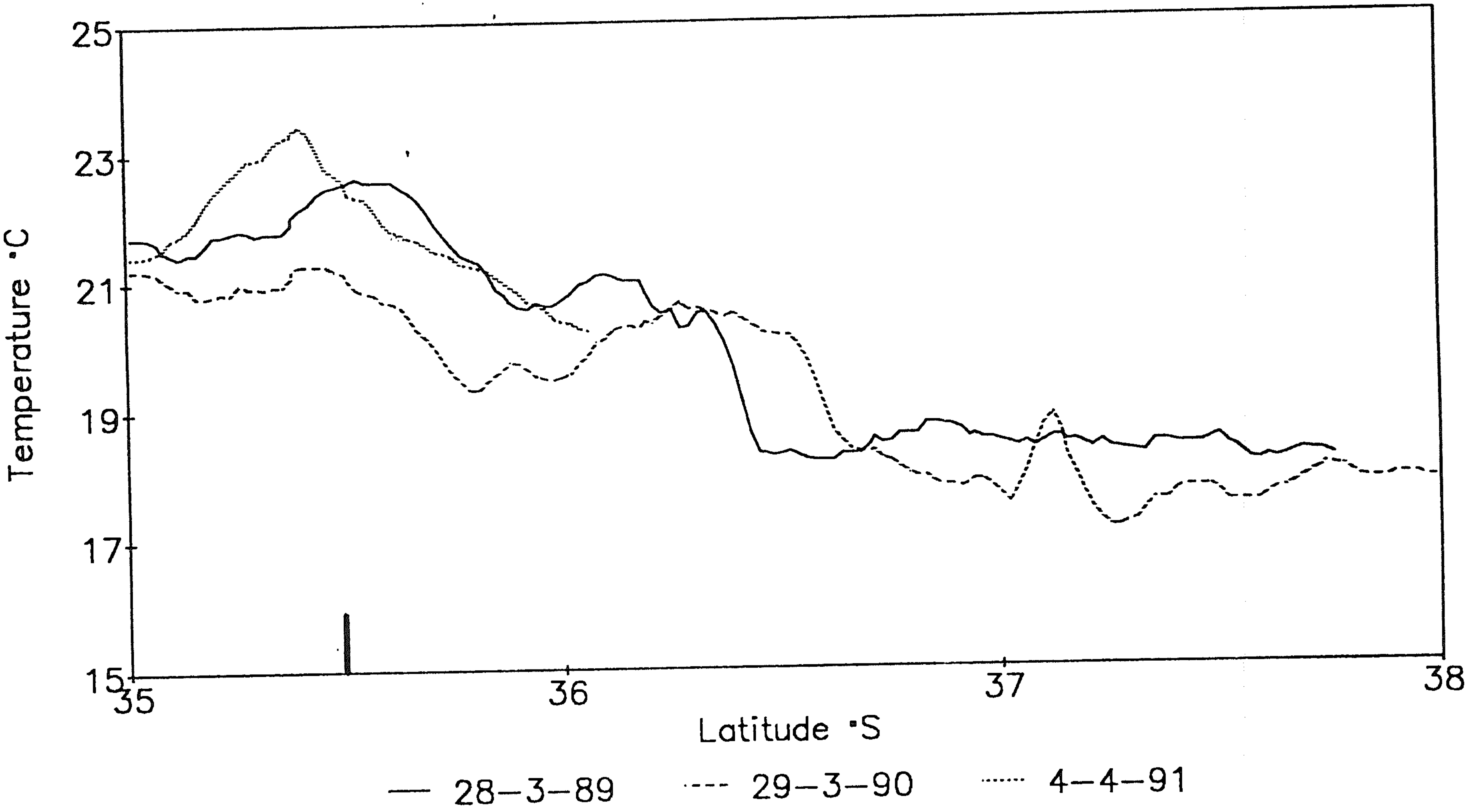
SST transects along 117° E



SST transects along 117°E for March in 1985, 1986 and 1987, derived from NOAA/AVHRR data. The vertical line marks the approximate position of the continental shelf-break.

FIGURE 12

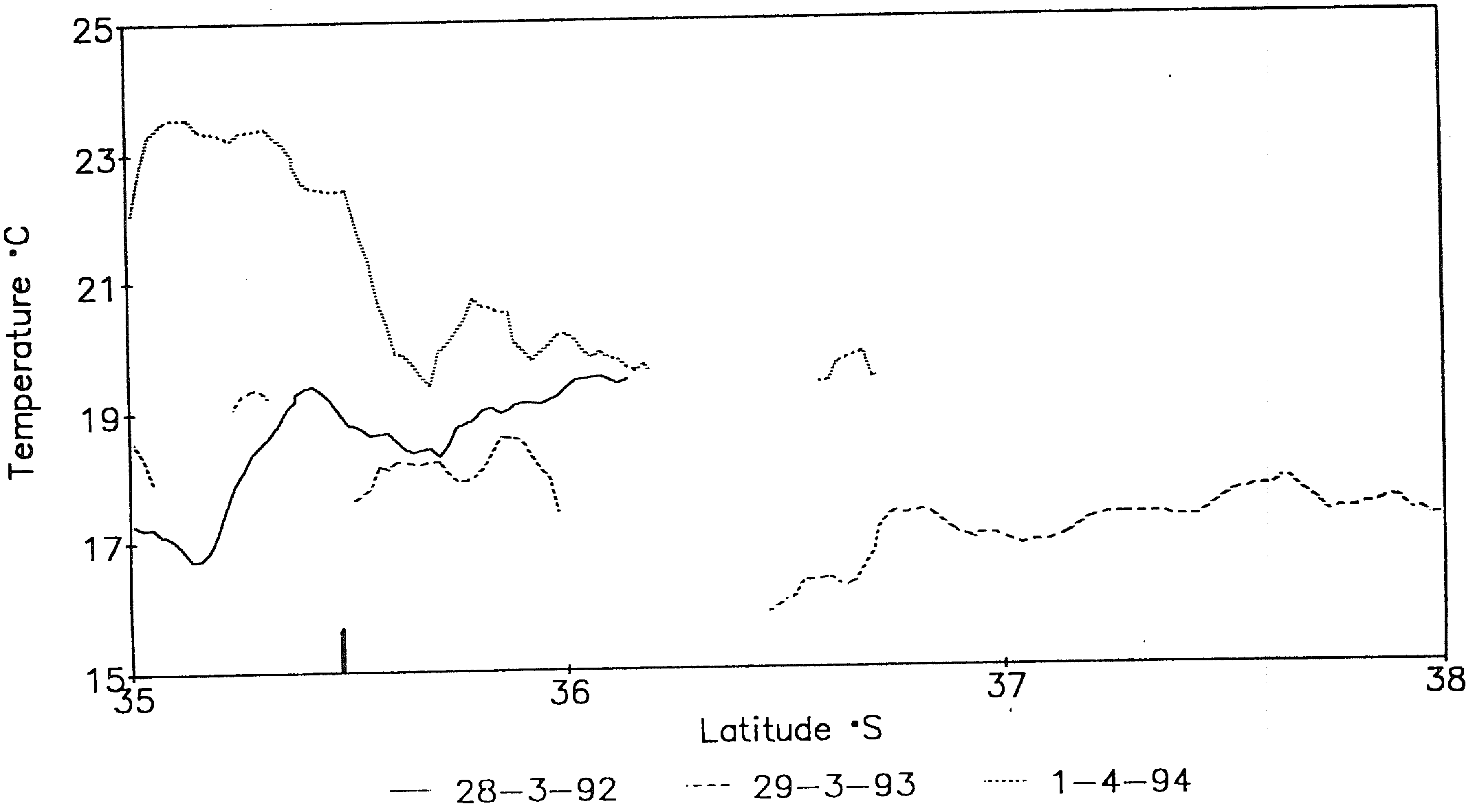
SST transects along 117° E



: SST transects along 117°E for March 1989 and 1990, and April 1991, derived from NOAA/AVHRR data. The vertical line marks the approximate position of the continental shelf-break.

FIGURE 13

SST transects along 117° E



SST transects along 117°E for March 1992 and 1993, and April 1994, derived from NOAA/AVHRR data. The vertical line marks the approximate position of the continental shelf-break.

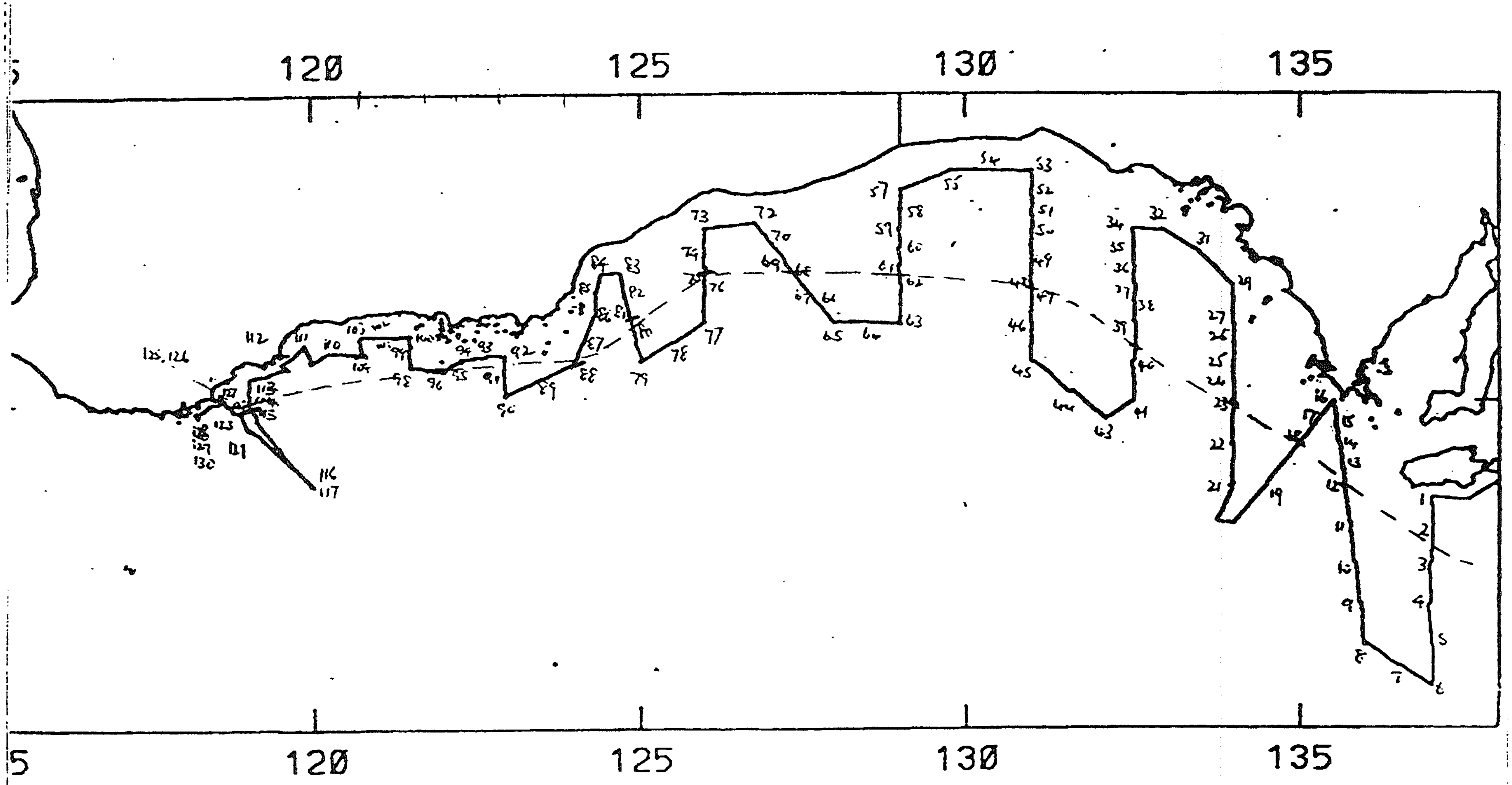


FIGURE 14

Track of ORV Franklin cruise 7/94

The approximate edge of the continental shelf shown as dotted line

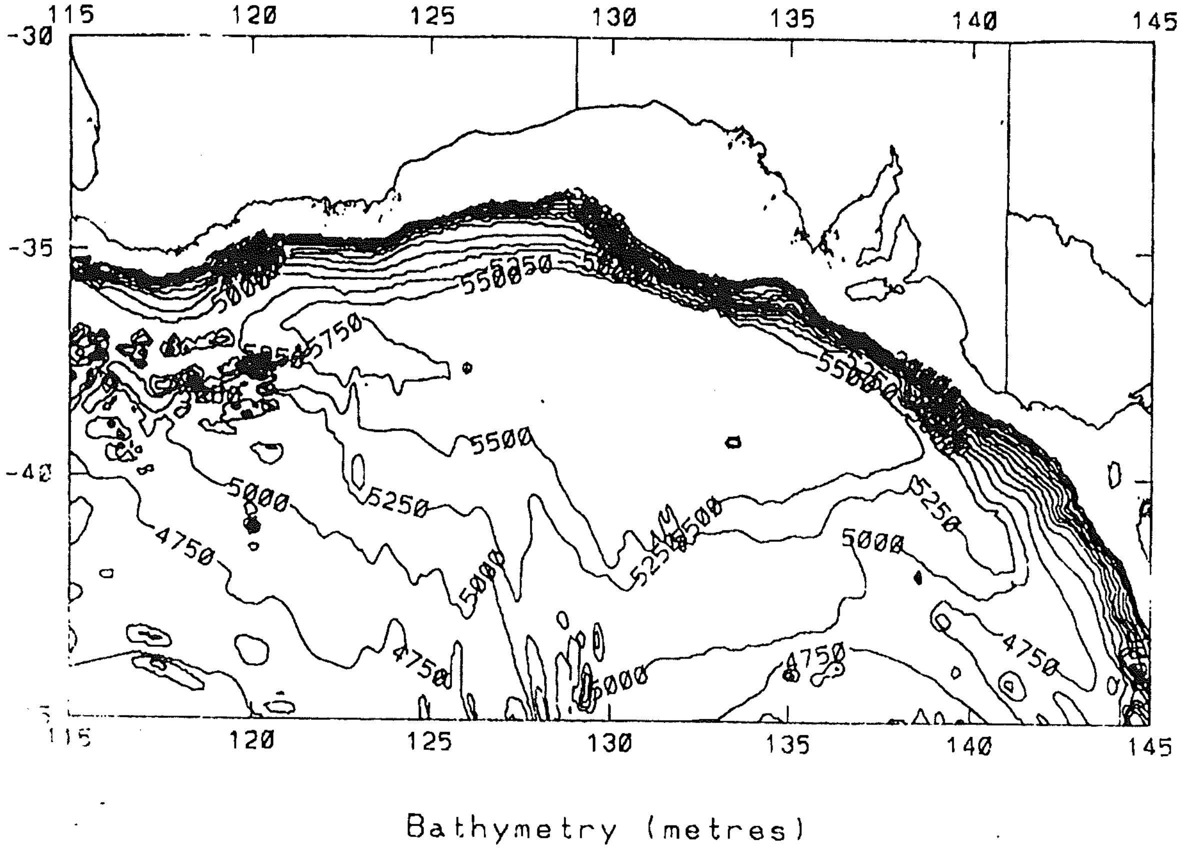


FIGURE 15

The bathymetry of the study region

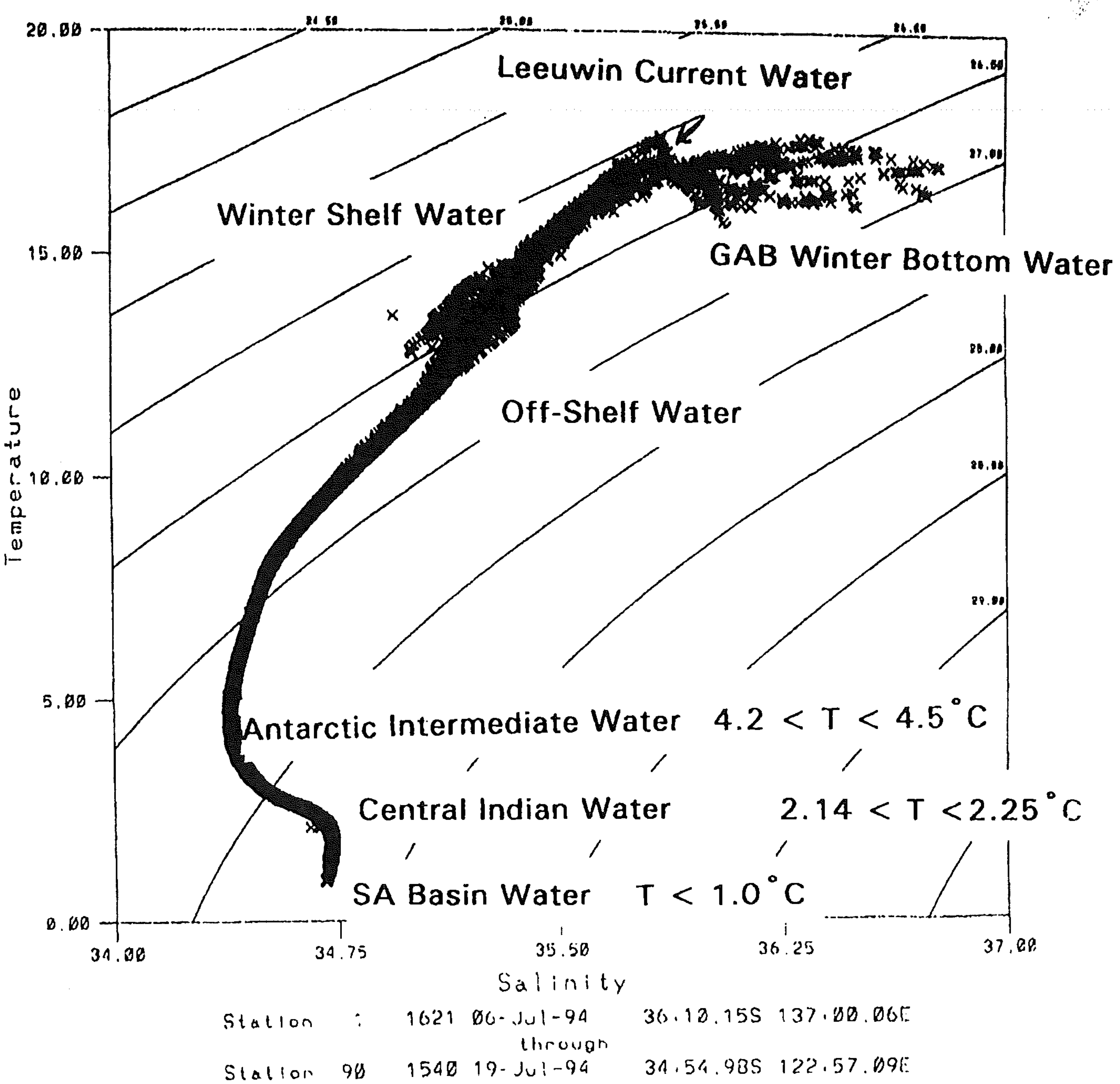


FIGURE 16

The temperature-salinity signatures of major water masses of the GAB and offshore region

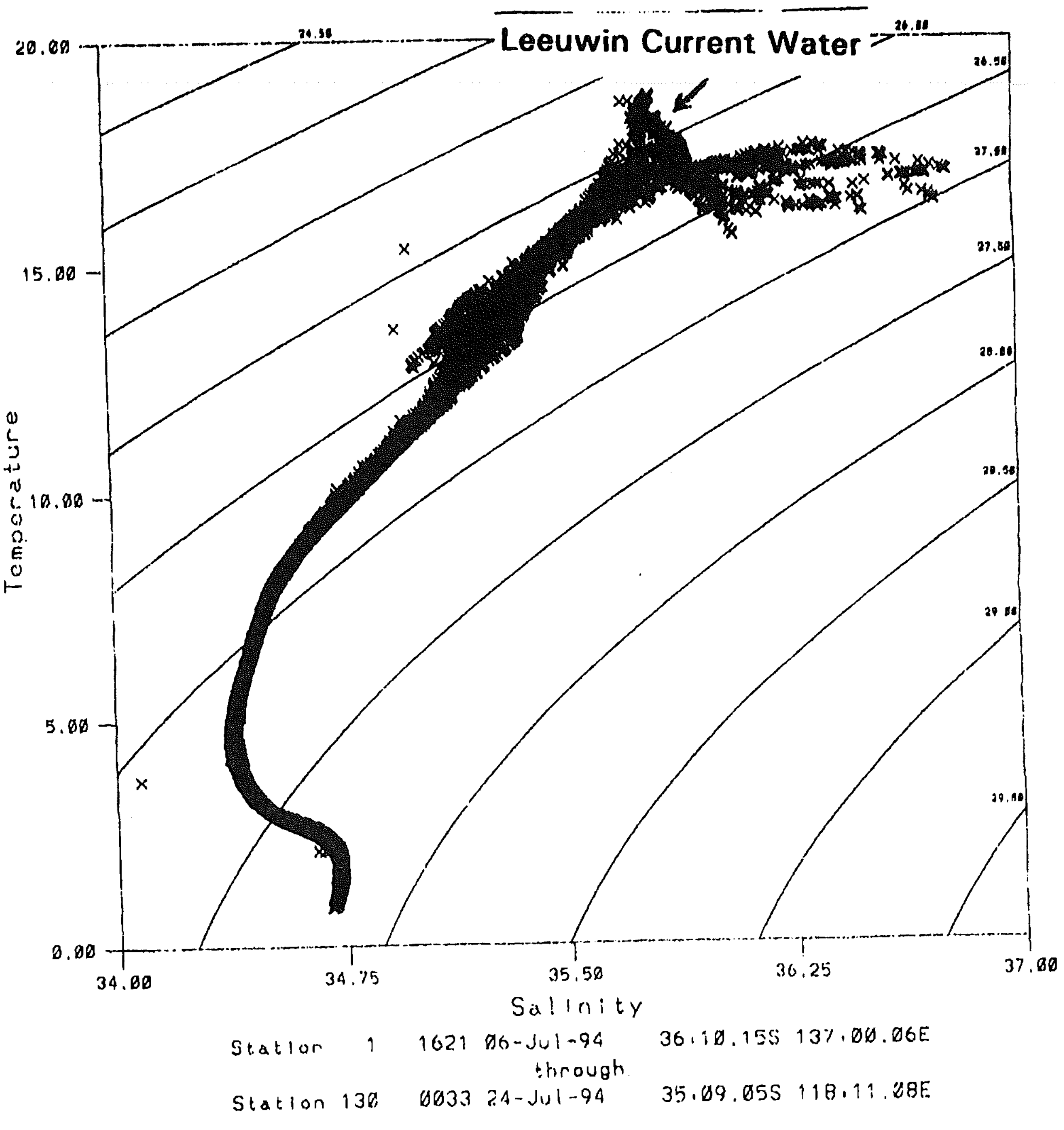


FIGURE 17

The established T-S signature of the Leeuwin Current

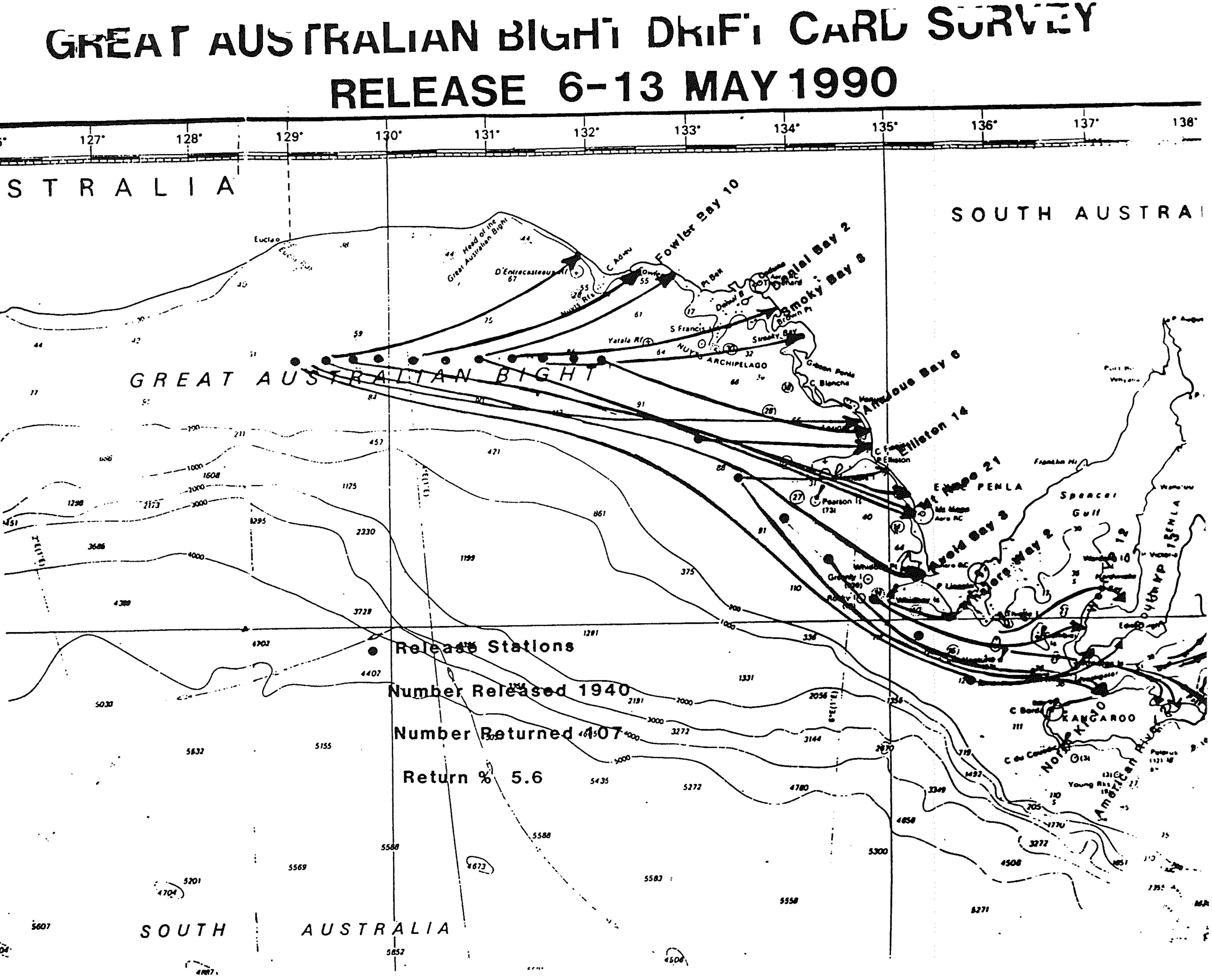


FIGURE 18

Trajectories of drift cards released in the GAB May 1990

APPENDIX 1

Listing of Australian Salmon recruitment numbers in Barker Inlet-South Australia and monthly mean sea levels at Albany-Western Australia

Year/Month	New Year Recruits Barker Inlet 1981-1993	Mean Sea Level (mm) Albany 1981-1993
811	0	665
812	0	611
813	4	712
814	20	892
815	0	865
816	4	904
817	0	860
818	0	825
819	320	783
8110	152	745
8111	16	742
8112	0	712
821	8	693
822	20	645
823	8	727
824	20	745
825	8	800
826	48	822
827	0	805
828	72	733
829	4	683
8210	0	640
8211	0	665
8212	0	716
831	0	644
832	0	777
833	1	671
834	0	875
835	0	878
836	0	976
837	0	841
838	0	870
839	0	817
8310	0	691
8311	0	654
8312	0	691
841	0	719
842	0	718
843	0	781
844	5	861
845	0	1019
846	0	927
847	0	817
848	11	811
849	748	752
8410	0	806
8411	26	706
8412	0	734
851	20	657
852	24	815
853	0	766
854	0	898
855	0	950
856	0	925
857	0	849
858	40	823
859	30	711
8510	28	684
8511	0	697
8512	10	713
861	6	703
862	0	750
863	3	817
864	8	752
865	15	880
866	1	812
867	0	788
868	8	761
869	4	689
8610	7	683
8611	4	652
8612	0	571
871	0	632
872	1	572
873	2	695
874	0	789
875	0	753
876	0	868
877	0	803
878	0	688
879	0	648
8710	0	617
8711	0	645
8712	0	651
881	0	645
882	0	682
883	0	700

884	0	803
885	0	938
886	0	963
887	0	865
888	3	828
889	3	887
8810	5	874
8811	3	706
8812	2	724
891	1	767
892	2	839
893	1	800
894	7	900
895	0	973
896	0	860
897	2	853
898	3	824
899	88	820
8910	74	785
8911	11	725
8912	0	711
901	0	732
902	7	752
903	1	756
904	3	920
905	0	880
906	4	828
907	0	825
908	386	725
909	556	691
9010	187	672
9011	57	696
9012	8	688
911	26	634
912	32	630
913	24	730
914	45	852
915	11	828
916	2	928
917	14	872
918	4	769
919	90	717
9110	36	667
9111	24	651
9112	11	660
921	4	602
922	4	694
923	0	692
924	14	789
925	14	796
926	0	899
927	3	797
928	1	783
929	44	648
9210	6	627
9211	9	674
9212	24	645
931	0	650
932	2	577
933	0	645
934	120	745
935	0	751
936	0	794
937	0	819
938	0	744
939	0	704
9310	1	646
9311	0	631
9312	0	630

APPENDIX 2

Research Summary ORV Franklin cruise 7/94

RESEARCH SUMMARY
CRUISE FR 7/94

1. Itenary

Sailed Port Adelaide	1215	Wednesday 6 July 1994
Arrived Albany	1030	Sunday 24 July 1994
Sailed Albany	1130	Sunday 24 July 1994
Arrived Fremantle	0900	Wednesday 27 July 1994

2. Scientific Program

SOUTHERN SHELF EXCHANGE, CIRCULATION AND PILCHARD ECOLOGY OFF THE SOUTH COAST OF WA AND THE GREAT AUSTRALIAN BIGHT

.To observe the current structure of the Great Australian Bight, its relation to the Leeuwin Current, and its exchange with the southern ocean.

.To determine the distribution and abundance of pilchard eggs and larvae across the south coast of Western Australia and the Great Australian Bight in relation to the Leeuwin Current.

3. Principal Investigators

Dr John Bye and Dr Peter Petrusevics
School of Earth Sciences
Flinders University of South Australia
GPO Box 2100 Adelaide South Australia 5001

Dr Rick Fletcher
WA Marine Research Labs
PO Box 20 North Beach Western Australia

4. Results

1. Great Australian Bight Outflow

CTD data from shelf and near off-shelf stations indicated the existence of a salinity dominated outflow, originating at the head of the Great Australian Bight. Outflow is a gravity current which flows in an easterly direction with a maximum surface to bottom salinity stratification of about 0.5. The eastward flowing current was observed to flow off the shelf at a number of stations in the eastern part of the GAB at depth of about 200 metres. Weaker, but persistent, salinity stratification was also observed at a number of stations along the shelf west of the head of the GAB as far as the Archipelago of the Recherche.

In the region of the shelf data suggest the existence of salinity stratified bottom lenses as a possible mechanism of salt release.

2. Mesoscale Structure

The deep ocean stations reveal the details of a cross-shelf structure similar to that suggested by bottle sampling of 25 years ago in which a pattern of onshore and offshore geostrophical motions extending down to about 2000 metres which characterise the Flinders Current was observed. Further west this structure is replaced by an alongshelf dynamic topography in which the eastward Leeuwin Current occurs in the upper levels, but a westward transport exists at depth. The ADCP data will provide valuable new insights into these systems.

3. South Australian Basin Water

The Central Indian Deep water was found to have a diffuse maximum in the range 3000-3500 metres below which the bottom water of the South Australian Basin was well defined.

4. Plankton Sampling

The plankton sampling section of the cruise was highly successful. Approximately 130 vertical tows, 100 surface tows, 20 oblique and 30 EZ net samples were collected during the cruise. Given the most favourable weather conditions more stations were completed than originally planned.

Preliminary observations indicate a high degree of temperature dependence on the distribution of pilchard eggs and larvae. Larvae were found in shelf waters of about 17 degrees whereas pilchard eggs were not found until the water temperature had exceeded 17.5 degrees. Thus no pilchard eggs were seen in the area east of Caiguna. Culturing experiments carried out onboard confirmed the development times as found in other studies of approximately two days to hatching at 18 degrees.

A large amount of information on other fish larval species, including Australian salmon and for invertebrates will also be available following examination of the collected material

5. Cruise Narrative

All dates and times are local

Ship departure was delayed until 1215 hrs Wednesday 6 July . During the afternoon test runs were carried with the vertical bongo (300, 500 micron), surface (1000 micron) and the EZ net (360 micron), all worked satisfactorily. CTD and larval sampling began Thursday morning south of Kangaroo Island and followed the route showed in the cruise track. To avoid damage to the CTD cable and avoid possible fouling of the prop oblique net tows were arranged to be made from the aft deck. This arrangement, made early in the cruise, worked satisfactorily throughout the cruise. By this stage the CTD, ADCP, thermosalinograph, sounder acquisition system, the underway fluorometer and profiling fluorometer were operational although some problems with communicating with WOCE CTD No 8 were experienced. At this stage the dissolved oxygen and profiling fluorometer output was not calibrated. It was noted that the CTD salinity values were about 2.1 high in relation to bottle data.

During Saturday 9 July about midday, after station 11, repairs were carried out to the ships main engine. This required the ship to drift for about 6 hours during which period opportunistic plankton tows were made with the 500 micron bongo net.

During Monday 11 July winds up to 30 knots and gusting 35-40 knots forced abandonment of deep water CTD cast and larval sampling at station 20. During this period the ship was forced to hove away from line of stations. Approximately 10 hours of time were lost. Due to frequent damage to the codend in the oblique (500 micron) tow the method of retrieval was modified by leaving the aft A-frame fully extended until the net was back on deck.

On Tuesday 12 July at station 25 the CTD cable was "kinked" which required repairs involving cutting and rejoining. Approximately 3 hours of time was lost. At this stage some modifications to the cruise track (essentially cutting corners) was made to make up for lost time and in anticipation of possible stormy conditions. After water sample analysis and CTD data were compared by Flinders University scientists a scaling factor of 0.94275 was coded into the CTD calibration which allowed some onboard first-cut analysis of CTD data to be made.

During the course of the week the reversing thermometer data were analysed. This showed a discrepancy of about 0.13 degrees between the thermometer and CTD data. This offset was subsequently coded into the CTD calibration data. CTD and larval sampling continued satisfactorily throughout the first week with good progress made with time due to unusually calm weather.

During the second week a bottle test cast was carried out at station 44. Salinity analyses showed that the bottles were not leaking (maximum deviation for 11 bottles was .008)

On Tuesday 19 July CTD #8 was replaced by CTD #2 as a result of noting a further shift in salinity values of 0.01 in CTD #8 between stations 54 and 55. Fluorescence data was lost since CTD #2 could not support the profiling fluorometer.

On Wednesday 20 July were advised that due to problems with spooling of the CTD cable on the winch there was concern that damage may result to cable and possibly the CTD. As a result, from station 91 onwards all CTD casts were limited to about 100 metres which effectively eliminated any further deep water casts. Later in the day, after station 92 near Bremer Bay, it was decided to proceed to a 5000 metre station in an attempt to rectify the CTD winch spooling problem. At this station separate casts with CTD #2 and #8 were made to compare performance. The re-spooling exercise improved CTD cable takeup marginally but not sufficiently to guarantee satisfactory operation in deepwater stations. During the final leg back to the shelf south of Albany two deepwater casts were made. For the remainder of the cruise CTD casts were limited to about 100 metres.

From about Bremer Bay (station 92) westwards the main thrust of the cruise was focussed on plankton trawls including a number of closely spaced EZ trawls. After a brief delay near Albany due to rough weather further plankton trawls were conducted before sailing in to King George Sound where the scientists from the Western Australian Marine Labs were picked up by the "Karen E" at about 1030 hrs on Sunday 24 July. The Franklin then proceeded to Fremantle conducting an ADCP survey of the Leeuwin current interface en-route. The ship docked at Fremantle at 0900 hrs 27 July 1994.

Considering the problems encountered early in the cruise and the difficulty with some of the equipment the cruise was highly successful from a joint oceanography and plankton sampling point of view. The success is largely due to the interdisciplinary spirit of co-operation shown between the oceanographers and biologists and support and long hours spent by both CSIRO and Flinders University scientists to resolve calibration problems with equipment.

Specific points to be highlighted are

1. **Lack of calibration of CTD #8**
This proved a challenge to Dr John Bye and Jodie Hammat in comparing the evolving CTD data with extensive Nansen bottle data from the South Australian section of the cruise collected approximately 25 years ago.

2. **Performance of the underway (Turner) fluorometer**
The underway fluorometer ran well for the first week after which numerous problems were experienced. This included a blown globe, blocked pipe and excessive gain which caused loss of sensitivity and meaningless Turner values. After 14 July the response of the instrument was very low thus casting doubts on the integrity of the data.

3. The **CTD cable spooling** became sufficiently irregular that the planned CTD program had to be abandoned after station 91. The effect was that deep ocean exchange could not be monitored over the latter third of the cruise as 100 metres was considered as the maximum wire-out length.

4. The **surface 1000 micron net** was deployed very succesfully throughout the cruise and an interesting and varied collection of marine species was obtained.

6. Scientific personnel

Peter Petrusevics	FIAMS	Chief Scientist
John Bye	FIAMS	
Vanessa Fahlbusch	FIAMS	
Jodie Hammat	FIAMS	
Esmee Van Wijk	FIAMS	
Rick Fletcher	WA Marine Research Lab	
Stuart Blight	WA Marine Research Lab	
Rob Tregonning	WA Marine Research Lab	
Jeff Dunn	CSIRO ORV	Cruise Manager
Erik Madsen	CSIRO ORV	
Mark Rayner	CSIRO ORV	
Dave Wright	CSIRO ORV	

7. Crew personnel

Neil Chesire	Master
Ian Seddon	Mate
Ian Menzies	Second Mate
Max Cameron	Chief Engineer
Peter Harding	Second Engineer
Don Roberts	Electrical Engineer
Ron Carr	Bosun
Bluey Hughes	AB
Joel Haigh	AB
Mick Barton	AB
Phil French	Greaser
Gary Hall	Chief Cook
Nat Dall	Second Cook
Reg Purcell	Chief Steward

Acknowledgments

Acknowledgments and thanks to the master, officers and crew for a very professional and helpful approach throughout the duration of the cruise.

Peter Petrusevics
Chief Scientist

July 1994

APPENDIX 3

ADCP Measurements ORV Franklin cruise 7/94

Summary of surface current structure on the Southern Shelf and in the adjacent Southern ocean.

Jodie Hammat

ABSTRACT

This project primarily deals with ADCP and CTD data sets obtained from the Franklin 7/94 cruise. This particular cruise spanned the Great Australian Bight region between Adelaide and Fremantle.

The ADCP data set supplies (E-W) and (N-S) components of water velocity. For the purpose of this study these components were averaged between each CTD station.
Based upon these calculations the aim of the study is to:

- Examine the surface current structure of the Great Australian Bight region.

Results have suggested that the easterly extent of the Leeuwin current is 124°E. ADCP data has revealed that the 'winter' Leeuwin current has a maximum surface current speed of 68 cm/s located off the shelf and along 118E. Based upon satellite imagery areas of turbulence (eddies) were identified between (34-36°S, 134-135°E).

Introduction

An oceanographic cruise on board the Franklin 7/94 conducted in July 1994 lead to the purpose of this study. The duration of the cruise was 21 days and covered the Great Australian Bight (GAB) region between Adelaide and Fremantle. Aside from oceanographical surveys, biological experiments were also conducted. Hence the outcomes of this cruise are not only important for oceanographical research, but also for the Southern and Western Australian fishery departments.

Numerous Conductivity (CTD) -Temperature - Depth (CTD) surveys were conducted throughout the duration of the cruise, along with a constantly running Acoustic Doppler Current Profiler (ADCP). Most of the surveys were on the shelf regions, however 15 occupied depth levels greater than 2000m and in some cases reached 5500m in the South Australian Basin.

The aim of this study is to analyse the surface current structure of the GAB region. Surface features investigated include; temperature, salinity and the average current between each station between each depth level. A final aspect of the surface structure is the sea surface temperatures (SST) obtained from satellite imagery. Aside from providing SST the images also depict possible flow patterns throughout the region, hence combining the actual ADCP derived currents and the probable flow patterns derived from satellite imagery, a complete representation of the surface current structure is obtainable.

Literature Review

Acoustic Doppler Current Profiler Theory

The main instrument used in this project is the Shipboard Acoustic Doppler Current Profiler (ADCP). The basic theory involved in operating an ADCP is outlined as follows;

A pulse of acoustical energy is transmitted in typically 3 or 4 narrow beams from various positions. These include; The bottom of ships hull, from a moored instrument or from a seabed. In this particular case the acoustical energy is transmitted from 4 narrow beams at the bottom of the ships hull. The 4 beams are 'orientated 90°apart typically with a 60° depression angle (30° elevation from straight down)', (Theirault, 1986), and is referred to as the Janus configuration. This configuration is used primarily to resolve the current velocities into horizontal (along track) and vertical (cross track) components.

As the acoustic signal travels throughout the water column it is scattered by small particles (particulate matter), temperature microstructure, turbulence or small air bubbles in the surface layer. These particles are assumed to drift with the current. The backscattered energy is received as a function of time at the transmitting transducer now operating as a receiver. ' The water motion introduces a Doppler Shift proportional component of velocity resolved along the beam, whose sign is positive or negative depending of whether the velocity is towards or away from the transducer', (Collar, 1993). As a consequence the doppler measurements provide profiles of the relative velocity between the transducer and the scatterers as a function of distance from the transducer.

This depth profile is preselected (range-gated) to provide a number of 'bins' (depth levels) in the vertical . A typical bin depth is 8m, 'the ADCP logging system collects the signals (pings) into 1-3 minute averages, termed ensembles. During this the GPS data is collected and processed into mean position and ships velocity', (Dunn, 1995)

To obtain a profile of ocean currents a further step must be carried out. This involves combining the data from all of the beams along with the ships heading and subtracting out the ships translation over the earth from navigational data ie; a Global Positioning System (GPS), (Joyce et al., 1982).

In summary the advantages of using an ADCP is that it provides continuos current measurements at more than one depth from a quickly moving ship, which consequently enables spatial velocity distributions.

Accuracy of Acoustic Doppler Current Profilers

A recent investigation carried out by (Didden, 1987) analyses the performance of a 115 Khz ADCP. The ADCP used aboard the Franklin was a 150 Khz as explained in Chapter 3.1, excluding the frequency difference Didden discusses some very relevant errors when considering the reliability of the doppler output, these include;

1- Unsteady wave-induced ship motion (roll, pitch, surge, sway, heave) can introduce large variance into the time record of the velocity signal. 'However the effect on the time-averaged horizontal ship velocity relative to the water is estimated to be a few cm/s' (Didden, 1987, pp.1237).

2- If the transducer is rotated through some angle then the effect on the velocity measurements can be quite severe. 'Since the alignment in the ships well is mostly difficult to control, experimental tests are necessary to avoid or correct errors', (Didden, 1987, pp.1241)

Didden (1987) concluded that the accuracy of ocean current measurements at ships speeds up to 6m/s is about 10cm/s.

Theirault (1987) researched the accuracy for both three and four beam ship mounted Doppler profilers. Theirault (1986b) in a separate paper, examines the spatial response of ship mounted four-beam and three-beam Doppler profiles

It has been argued that during rough sea conditions the reliability of the ADCP measurements decrease due to back ground noise generated from the air bubbles near the transducer, (Didden, 1987). This theory was further supported by (New, 1992) who has investigated this subject extensively, however for the purpose of this study the implications as a result of this problem are not discussed.

Dynamics and Water Mass Properties of the Great Australian Bight.

This section describes the relevant hydrographical features of the Great Australian Bight. The three major water masses that occupy the shelf and oceanic regions and the current system attributing to these characteristic will be discussed in detail.

Water mass (a), as shown in Table 1 is characterised by a warm tongue of water with low salinities. The Leeuwin current being the ultimate source for this water mass was first identified by (Cresswell and Golding, 1980). Their early findings concluded that the Leeuwin current travels southwards along the continental slope off Western Australia and then eastwards into the Great Australian Bight.
The change in depth associated with travelling into the Bight causes the Leeuwin current to shallow and broaden and consequently spin out to sea in one or more cyclonic eddies. These eddies can be easily identified in satellite images..

Cresswell and Golding (1980) also found that the Leeuwin current varies seasonally between autumn and winter. Maximum speeds of up to 1.7m/s were found at 119°E as the current is travelling eastward into the Great Australian Bight.

It is worth mentioning that the Leeuwin current is an eastern boundary current, the fact that its current speeds can reach magnitudes comparable to those found in western boundary current regions is considered to be unusual.

A recent study (Rockford,1986) has shown that the Leeuwin current follows the shelf break (200m contour) closely from 115°E to 130°E in an eastward direction. However the easterly extent of the Leeuwin current is also a subject of criticism.
Rockford (1986) suggests that the Leeuwin current reaches Southern Australia by May and extends to 130°E and terminates in October.
The Leeuwin current can sometimes be confused with a highly saline water mass occupying the central shelf regions of the Bight, which was first noticed by (Rockford, 1962 as cited by Rochford, 1986). From satellite images it is difficult to distinguish between the two.

This warm and more saline water mass is referred to in Table 1 as water mass (b) and known as the Great Australian Bight Outflow. The primary source for this water mass is a thermohaline current that originates in the central region of the Great Australian Bight. Rochford (1986) proposes that the water mass occupies the Central and Western section in the early and late Australian autumn with maximum salinities identified in May. 'The highest salinities and sea surface temperatures were found along a tongue extending South-Eastward to around 135°E' (Rochford, 1986).

Godrey et al, (1986) found that along the south coast of Australia a narrow shelf edge current exists and flows eastward along the entire distance. With cyclonic eddies being observed West of 124°E. Conversely anticyclonic loops were identified east of 124°E. Godrey et al, (1986) has identified high salinities on the shelf region between 125°E and 135°E. East of 135°E this saline water was not present. However a strong jet of unusually highly saline water appeared to flow off the shelf in a south easterly direction west of Kangaroo Island. Associated with this outflow is an 'irregular anticyclonic eddy South of Kangaroo Island',(Godrey et al, 1986, pp. 679)

I t was then concluded by (Godrey et al, 1982) that this strong jet of highly saline water originates from the head of the Great Australian Bight.

Table 1 (Rochford, 1986). Major water masses of the Great Australian Bight .

Temperature °C	Salinity psu	Water Mass
17-19	35.7-36.0	(a) Warm and Saline, a reliable indicator of Leeuwin current.
16-17.5	35.9-36.4	(b) Warm and Highly Saline, characteristics as a result of the Great Australian Bight outflow.
15-17	35.5-35.75	(c) Cold and low salinities, correspond the West Wind Drift

The Dynamics of the Southern Ocean region.

The water masses and current movements just mentioned concentrate primarily on the shelf regions of the GAB, however a small portion of the survey of CTD stations occupied the Southern ocean. This region is strongly influenced by the Flinders current and the resulting anticyclonic gyre centred in the South Australian Basin.

Flinders Current

The transport system known as the Flinders current was initially identified by (Bye, 1972) The system is located south of Australia and consists of movement away from the coast west of 135°E, and east of 135°E there is baroclinic transport towards the coast. The Flinders current contributes to the anticyclonic gyre located in the South Australian basin. At certain times of the year the Flinders current may in fact be absent and hence sensitive to seasonal variations (Bye, 1971).
The temperature and salinity characteristic of a particular body of water influence by the Flinders current may in fact 'vary by as much as 250m', (Bye, 1971, pp.)

Recently (Bye, 1983) has explained the Flinders current as follows;

1) A recirculation off south west Australia due to the eastward transport of the coastal Leeuwin Current that flows around Cape Leeuwin and into the GAB. The deep ocean recirculation that reinforces the westward flow of the global forcing of the Flinders Current. Which has a total transport of 8Sv.

In summary the study reported here has investigated the main oceanographical features of the GAB and surrounding oceanic regions. Further implications and results follow.

DATA

Introduction

The data used in this study was obtained from the Great Australian Bight region during a cruise in July 1994. The cruise commenced in Adelaide on 6th July and concluded in Fremantle on 27th July aboard the research vessel Franklin; the cruise will be referred to in later text as Franklin 7/94. The cruise track as depicted in Figure 3.1 shows the track varied a great deal. Stations are numbered 1 to 127 inclusive. Due to bad weather and spooling problems some stations were cancelled. Of the 111 CTD stations only 14 occupied depth level greater than 3000, with 3 stations occupying a depth level over 5000m. The remainder of the stations were predominantly located on the shelf area.

Along with a survey of CTD stations, a constantly running ADCP was in process throughout the duration of the cruise. Measurements that assisted the ADCP processing are the full resolution Global Positioning System (GPS), Precision Depth Recorder (PDR), and a thermosalinograph.

Particulars on the Franklin

The Acoustic Doppler Current Profiler (ADCP) used aboard the Franklin 7/94 and 10/94 cruises was a 150kHz Rowe-Diennes I Vessel Mounted unit. The instrument is designed to operate with the transducers facing downward in a concave Janus Configuration with beams 30 degrees off vertical and designed such that the transducers are aligned 45 degrees to fore and aft. 'Until mid 1994 the transducers were aligned fore and aft',(Dunn, 1995).

The Conductivity -Temperature-Depth recorder(CTD) used aboard the Franklin 7/94 cruise was a Neil Brown MK3 CTD. However due to errors in calibrating the MK3 CTD another CTD was used. The first instrument, being the current instrument CTD08 (a WOCE specification MkIIIC CTD by Go). The second instrument is the CTD02 (a MkIIIB by NBIS). Both instruments were used in conjunction with a 12 bottle , 5 litre Niskin Rosette.

Stations (1-88) and (117-130) inclusive were occupied by CTD08. Stations (89-116) were occupied by CTD02.

Accuracy of water velocity relative to the ship

As mentioned previously, errors associated with using a shipboard ADCP include the various components of ship motion, noise generated by the ship itself and transducer misalignment. The main source of error is in fact determining the ships actual velocity. It is worth mentioning that for 20 minute profiles, with 1150 pings averaged, the error in measuring the velocity of the water relative to the ship is reduced to the long term systematic bias (CSIRO, 1994).

As well as this there are the transducer alignment and gyro-compass errors which probably have a residual effect after calibrating (CSIRO, 1994).
The possible errors due to these factors are outlined as follows,

1) An error of '.3cm/s per m/s of ship speed, due to say .2° uncertainty in alignment angle is likely
2) An error of '.4cm/s per m/s of ship speed, due to say .0004 uncertainty in scaling factor.', (CSIRO notes, 1994).
Ultimately this results in .5 cm/s error per m/s of ship speed, or 3cm/s at a ships speed of 12 knots.

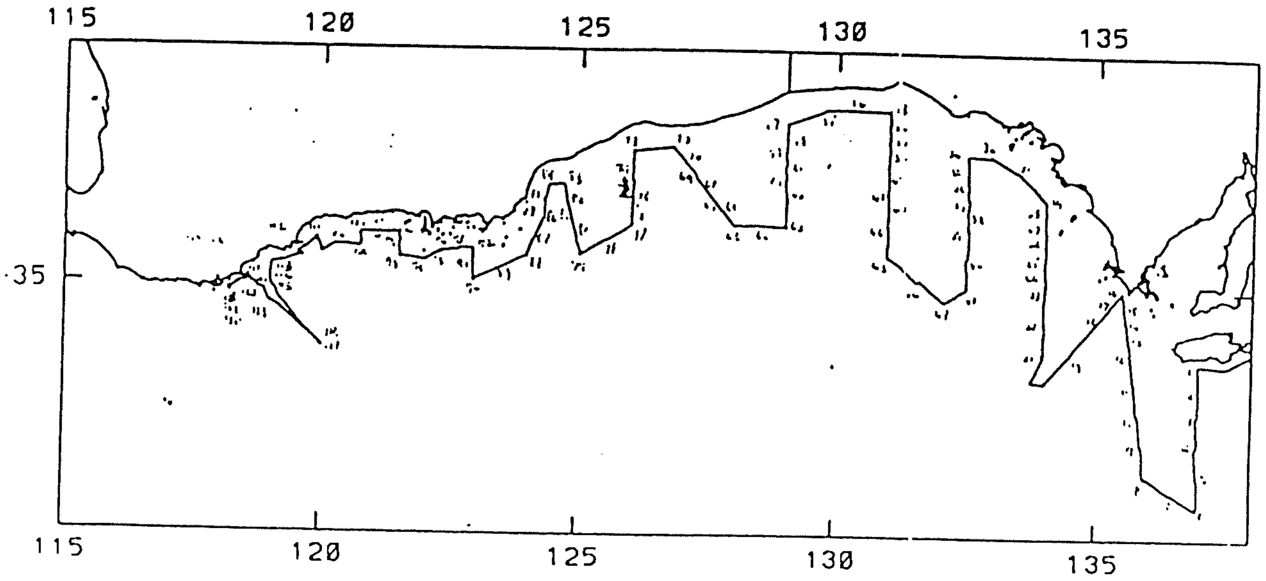


Figure 3.1: Cruise track for Franklin 7/94.

Materials & Methods

Introduction

The acoustic doppler data used for the purpose of this project was averaged over 20-60 minutes, which effectively reduces noise. The averaged profiles are produced by time-integrating the ADCP ensembles, which are then placed in ASCII files. This study uses 20 minute averaged profiles with GPS correction. The ASCII files contain information pertaining to calculating the bin depth, ships East-West and North-South velocities and the East-West and North-South velocity of currents relative to the ship for each bin. Other parameters such as the date, time(GMT), latitude, longitude and the bottom most accepted bin are also included. The relevant features of such a file can be found in (CSIRO notes,1994).

Obtaining absolute water velocities

The ASCII files do not contain the absolute water velocities, hence the first step is to convert the water velocities relative to the ship into absolute water velocities. This was achieved by applying a simple algorithm to the data set as shown in Figure 4.1. The algorithm was incorporated into a Fortran program and run for the entire data set.

Figure 4.1 (CSIRO,1994)

```
do j=1, lastgd
    Ucorrected(j)= unav +u(j)
    Vcorrected(j)= vnav+v(j)
endo
```

Where the ships E-W, N-S velocities are referred to as unav, vnav. The E-W, N-S current velocities relative to the ship are u(j), v(j) respectively. Ucorrected and Vcorrected refer to the absolute water velocities.

Averaging absolute water velocities

Introduction

This section outlines the procedure to calculate the average East-West, North-South absolute water velocities between each station for each bin depth. Hence the averaging time depends on the distance between stations and consequently the spatial resolution is directly related to the distance between stations.

Procedure for Averaging water velocities

The initial step involves converting the date and time(GMT) from the original ASCII 20 minute spatially averaged doppler file; into the total number of minutes from the 1st July 1994. This conversion was carried out using a Fortran program.

A separate file containing the latitude, longitude, date and time(GMT) of CTD stations was also converted to the total number of minutes from the first of July using the same Fortran program as above.

Averaging of the respective components of velocities was carried out between CTD and not during them. Reasoning for this, was based upon (Holbrook, 1989) suggestions. Holbrook, 1989 considered the difference between the instruments and has proposed that the 'quality of hull mounted ADCP recordings are higher when the ship maintains constant speeds', (Holbrook, 1989, pp. 21). When a ship is on station the engine causes bubbling of water beneath the ship which as a consequence increases the noise levels associated in the surface layers.

Hence in a separate Fortran program the two converted files were read in and certain requirements were enforced on the parameters such that averaging takes place between stations; not during them.
These include;

- If the ships speed is greater that .5m/s then averaging of the absolute water velocities takes place over each depth range.
- If not then it was assumed the ship was occupying a CTD station and averaging did not occur whilst occupying a CTD station.

The program was run for the maximum bin depth of 50. In regions where the water depth is shallow the absolute water velocities are averaged to the maximum allowable bin depth, hence the program was not necessarily run 50 times between each station.

Using a graphics package termed 'Spyglass Transform' ™, a series of vector plots were produced.

Calculating Bin Depth

To establish the current profile over a depth range, the depth calculation to the first bin (j) is essential. The original ASCII files obtained from the Franklin 7/94 cruise contain parameters that include (blen, plen, delay). These parameters are required for the calculation of the depth to first bin (j).

The depth to the centre of bin j is established by applying the relation

$$\text{depth}(j)=\text{draught}+(\text{plen}+\text{blen})/2+\text{delay}+\text{blen}*(j-1)+\text{blen}/10 \tag{1}$$

where
draught = 4m
blen = bin length
plen = pulse length
delay = delay after transmit (also known as DTFB- Depth to First bin)

The above listed parameters on both the Franklin 7/94 cruise are given below.

blen = 8m
plen = 8m
delay = 4m

Consequently by applying Eq.1, the depth to the first bin j is 12.8m and the bin depth intervals are 8m.

Surface structure of GAB

Introduction

Connelly, VonderBorch,(1967) as cited by Hahn ,(1986) have proposed that the Southern margins of Australia be divided into 3 sections (refer to Figure 5.1 for location); these include

- Kangaroo Island section: This section is located to the east of 135°E with a shelf break near to 145-165m and is approximately 40 -100km wide.

- GAB section: This section ranges between longitudes 124-135°E, the shelf is approximately 90-220km wide and is a smooth plain, 'the shelf break varies between 150m in the east to about 110m in the west', (Hahn, 1986, pp.11).

- Western Australian region: This final section covers the southern coast of Western Australian from west from124°E. The shelf break ranges in depths between 100-140m, the shelf is generally 20 -80km wide.

The above sections will be discussed in terms of temperature, salinity and current velocities.

Kangaroo Island Section.

Stations that occupy this region are 1-17 inclusive (refer to Figure 5.1 for location). Sea surface temperatures range between 13.60°C and 17.00°C and sea surface salinities vary between 35.11 and 36.03 psu. Stations 1-2 and 12-17 occupy the shelf regions and have characteristically warmer sea surface temperatures than the stations occupying oceanic regions; higher salinities are also found on the shelf regions. Figure 5.4 refers to the average surface velocities between respective stations, (as explained in Chapter 4.5). The region highlighted corresponds to the area of maximum flow and is located on the shelf region just below Port Lincoln. The flow is characterised by South

Eastward movement along the shelf break with a maximum surface velocity reaching 50cm/s, and is referred to in later text as (1)

Great Australian Bight region

Most of the CTD survey was carried out in this region; stations 18-88 occupy the area (refer to Figure 5.1 for location). As with the Kangaroo Island section the maximum sea surface temperatures and salinities are found on the shelf region. The maximum temperature recorded was 17.65°C located at 34.5°E,124.0°S, which is situated on the shelf and to the far west of this region. For the remainder of the shelf region the temperatures predominantly range between 16.2°C-16.90°C. However a warmer region located on the shelf is clearly identified east of 132°E with temperatures ranging between 16.90-17.23°C (Figure 5.2(a)).

The sea surface salinities show a complex situation. The region of maximum salinities occupy the head of the GAB region and the shelf areas east of 132°E; the maximum salinity recorded was 36.59 psu. It is important to note that the maximum sea surface temperature of 17.65°C found to the far west of this region corresponded to a relatively low salinity of 35.80 psu.
Examining the bottom salinities revealed that the maximum salinities are in fact located at the bottom depths of the shelf region. The maximum salinity is now 36.78 psu, this increase is evident along the shelf area east of 132 and extends across to 136°E.

Figures 5.2(a,b) illustrate contour maps of sea surface temperature and salinities, the arrows indicate possible flow patterns which were chosen subjectively based upon the temperature and salinity pattern presented in these diagrams. Figure 5.3 depicts a satellite image for the 5th July 1994 (Hertfield, 1994), the arrows indicated refer the three regions of strong flow and were extracted directly from Figure 5.4. The temperature scale indicated is incorrect; however the image show excellent features. These include, strong movement off the shelf between (35-36°S, 132-133°E) and a weaker movement off the shelf between (35.5-36.0°S, 134-135°E). Figure 5.3 shows also a region of very warm temperatures extending from 132 to136°E and occupying the shelf regions. Figures 5.2(a) and 5.2 (b) do in fact corresponds to the apparent movement as illustrated in Figure 5.3

To determine whether or not the actual flow is consistent with the arrows as indicated in Figures 5.2(a.b) a direct comparison between ADCP derived currents is essential. In reference to Figure 5.4 it is clear that there is a general eastward movement across the entire region particularly concentrating on the shelf break. The area of consistently weak flow is located at the head of the bight with current speeds less than 10cm/s. A region of strong flow off the shelf is located between (35-36°S, 132-133°E), the maximum surface current speed is 40cm/s in an south westerly direction, for the remainder of this chapter this region will be referred to as (2).

It is also evident that along 134°E strong eastward movement exists with a maximum velocity of 45cm/s. There also appears to be slight movement off the shelf below 36°S and along 134°E, but due to a lack of stations in this region it is difficult to determine the exact flow.

These findings fortunately do correspond well to hypothesised flow patterns deduced from the satellite image, however again due to a lack of stations it is difficult to determine the exact extent of the flow.

Western Australian Section

This region corresponds to the final leg of the Franklin 7/94 cruise. Stations were predominantly located on the shelf regions. Temperatures are considerably warmer than the previous sections. The warmest temperatures are located to the far west with a maximum of 18.69°C found well into the shelf region. The temperatures cool from west to east along this section with a minimum to the far east of 16.69°C.

As illustrated in Figure 5.4 the current magnitudes in this region are the largest found south of Australia. In fact a strong north easterly flow with maximum current speed of 68 cm/s was evident slightly off the shelf and to the far west of this section, this region is later referred to as (3). Another region that shows particularly strong flow is located off the shelf between (121-124°E, 34.5-35.0°S), the maximum surface velocity in this region is 58 cm/s and will be referred to as (4). A striking oceanic feature is a strong (45 cm/s) north westerly surface flow between (35-36°S, 118-120°E), and will be referred to as (5) for later discussion. A predominantly eastward movement was identified on the shelf region, with surface velocities about 15 cm/s.

(45 cm/s) north westerly surface flow between (35-36°S, 118-120°E), and will be referred to as (5) for later discussion. A predominantly eastward movement was identified on the shelf region, with surface velocities about 15 cm/s.

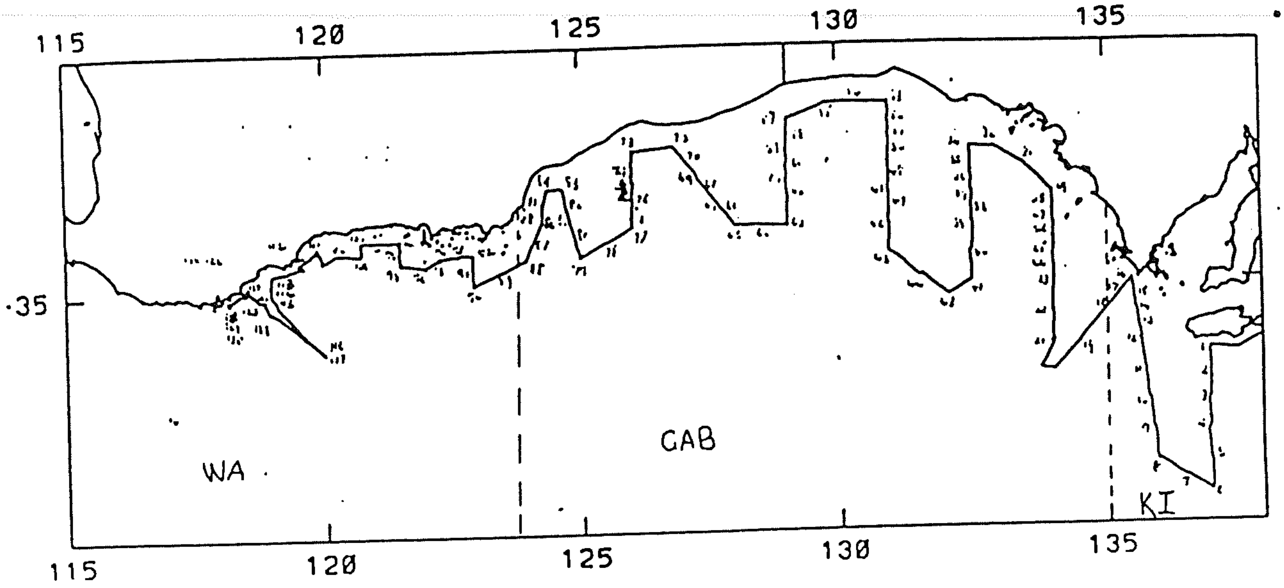


Figure 5.1: Franklin 7/94 cruise track, KI (Kangaroo Island Section), GAB (Great Australian Bight Section), WA (Western Australian section).

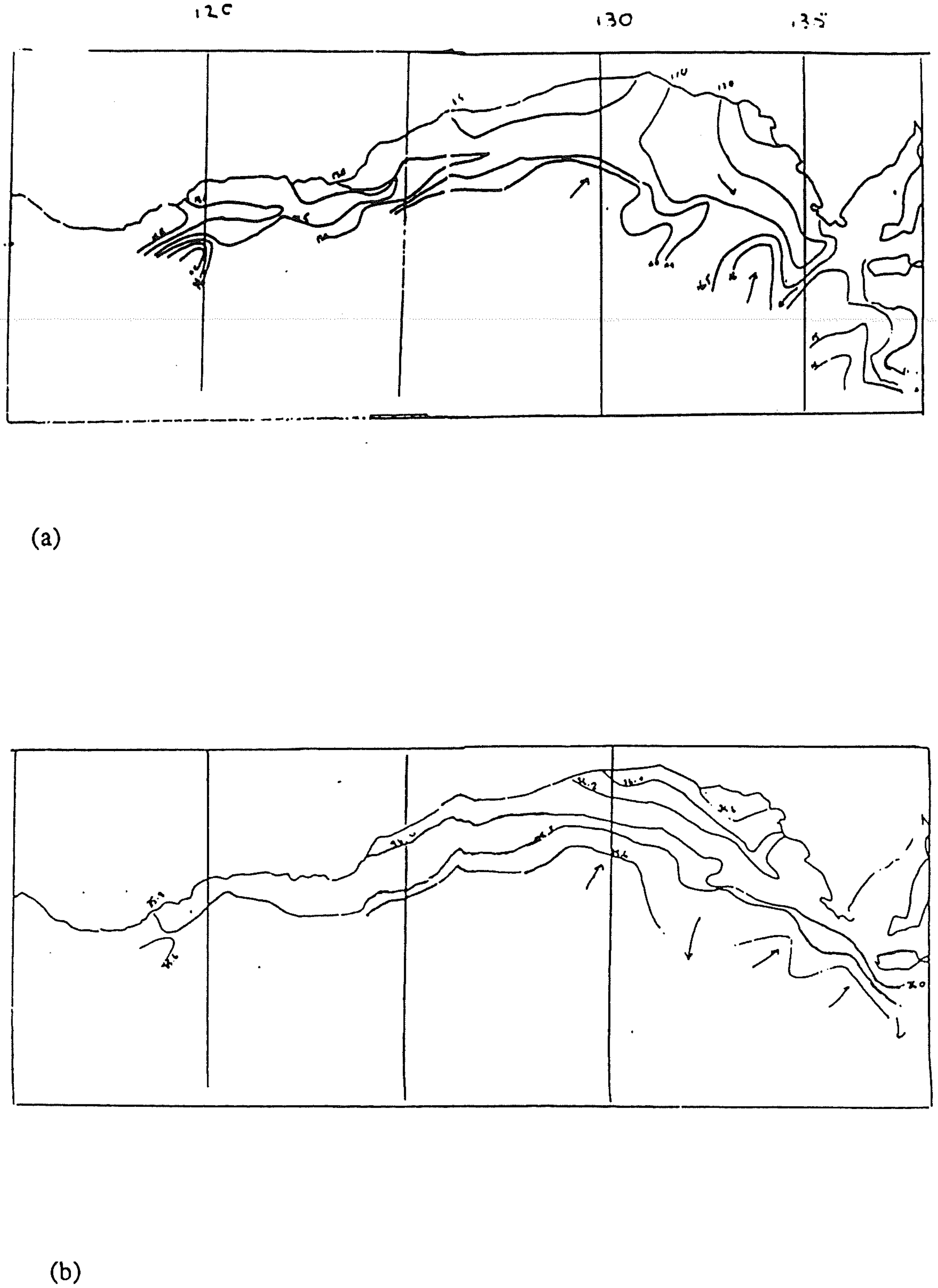


Figure 5.2(a,b). Contours of (a) sea surface temperature °C, (b) sea surface salinities psu.

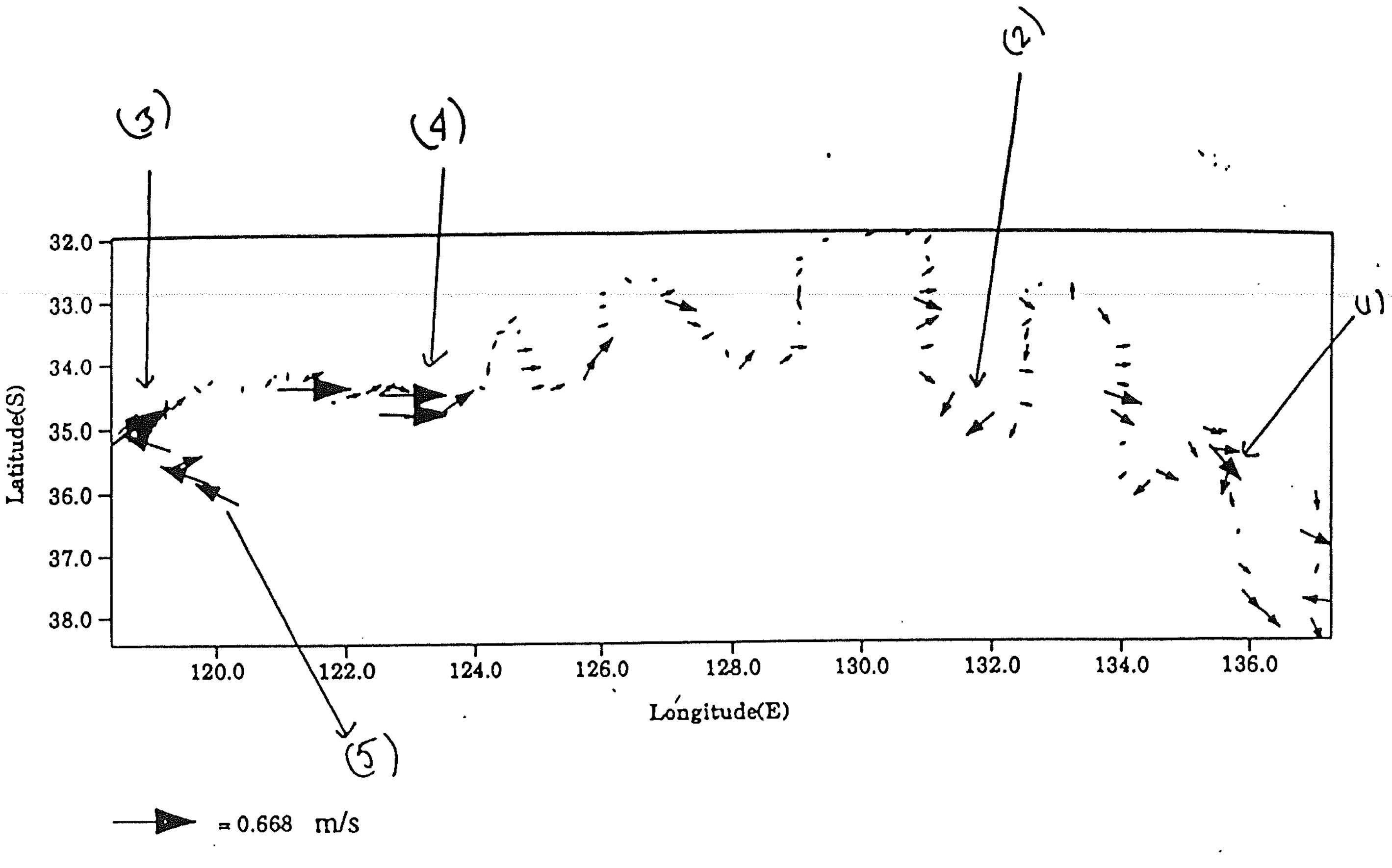


Figure 5.4: Vector (arrows indicate direction of flow between station pairs)
Depth = Near surface (12m)

Sub surface features of GAB region.

Introduction

This section describes the change in current magnitudes and direction throughout the water column. Figures (5.6-5.7) illustrate vector plots of the average velocity between each station, for depths 50,100,150 and 200m repsectivley. Regions that display no flow correspond to very shallow areas and consequently no results were obtained from the ADCP. The location of regions with strong flow have been previously referred to in the text numerically as (1-5). It is these locations that will be explained in terms of maximum current speed and direction.

Description of sub surface features

Tables (5.5-5.9) represent the average velocities for each specified region over a 200m depth range (refer to Figure 5.1 for station location). It is apparent from Tables 5.7 and 5.8 that a current shear exists. Differences of 47cm/s and 40cm/s occur between the surface and 200m for regions 3 and 4 respectively. The maximum current speeds also occupy these regions. The location displaying almost no current shear is region 2 (Table 5.6), region 1 shows no current shear for the top 150m, however the between 150 and 250m the change in current speed is 10cm/s.

The maximum velocity at 200m corresponds to a north westward flow with a speed of 26.60cm/s (Table 5.9)

An interesting feature of all 5 regions is the constant direction of flow throughout the top 200m.

Table 5.1: Region 1.   (Stations 12-13)

Depth (m)	Average Velocity cm/s
50	38 (S-SE)
100	36 (S-SE)
150	35 (S-SE)
200	25 (S-SE)

Table 5.2: Region 2 (Stations 43-44)

Depth (m)	Average Velocity (cm/s)
50	25 (S-SW)
100	23 (S-SW)
150	24 (S-SW)
200	23 (S-SW)

Table 5.3 Region 3, (Stations 123-124)

Depth (m)	Average Velocity (cm/s)
50	55 (NE)
100	26 (NE)
150	14 (NE)
200	8 (NE)

Table 5.4 Region 4, (Stations 98-99)

Depth (m)	Average Velocity (cm/s)
50	54(E)
100	36 (E)
150	24 (E)
200	14 (E)

Table 5.5 Region 5, (Stations 117-121)

Depth (m)	Average Velocity (cm/s)
50	41 (N-NW)
100	38 (N-NW)
150	31 (N-NW)
200	27 (N-NW)

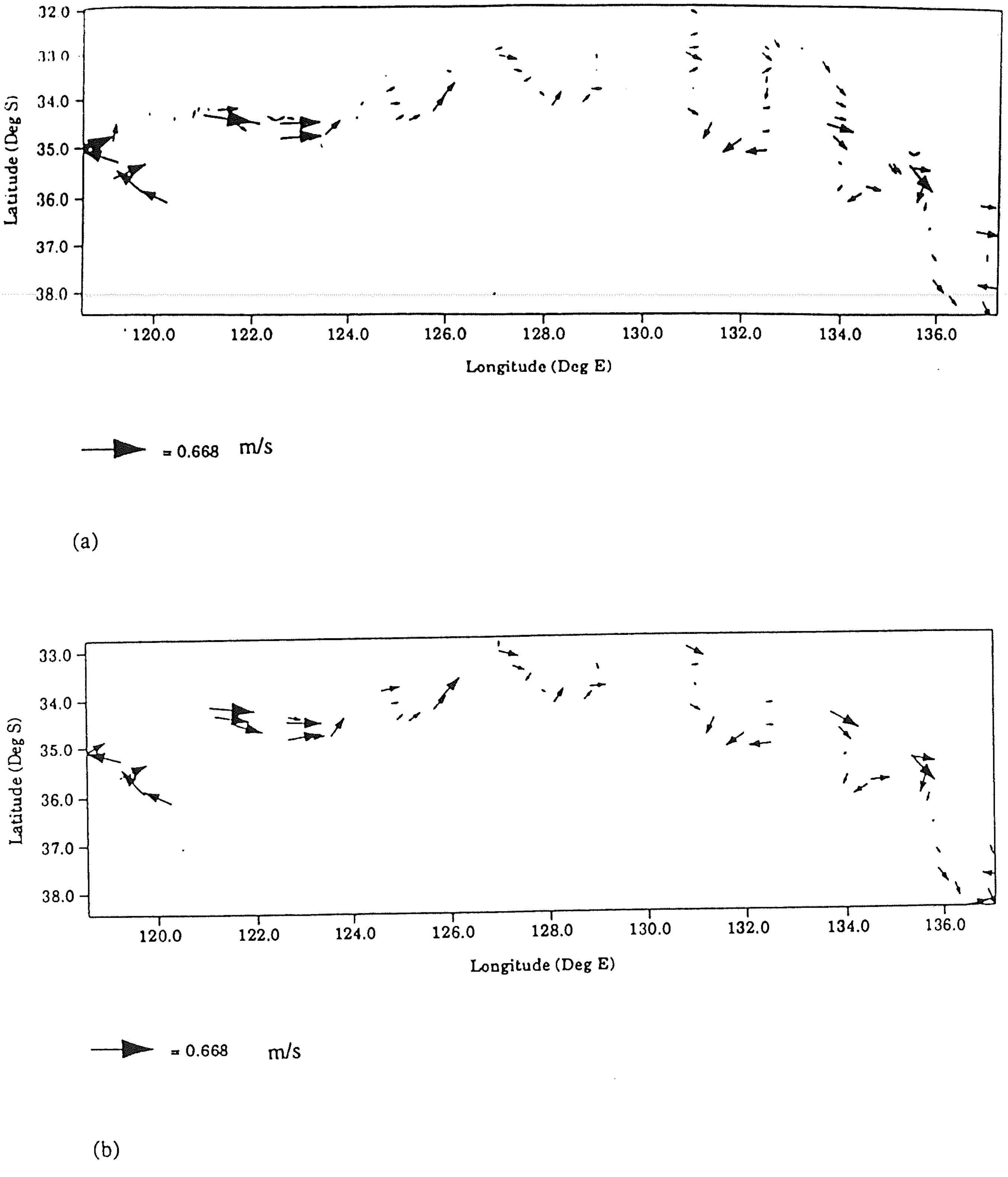


Figure 5.6(a,b): Vector plots (arrows indicate direction of flow between station pairs), (a) Depth = 50m, (b) Depth = 100m

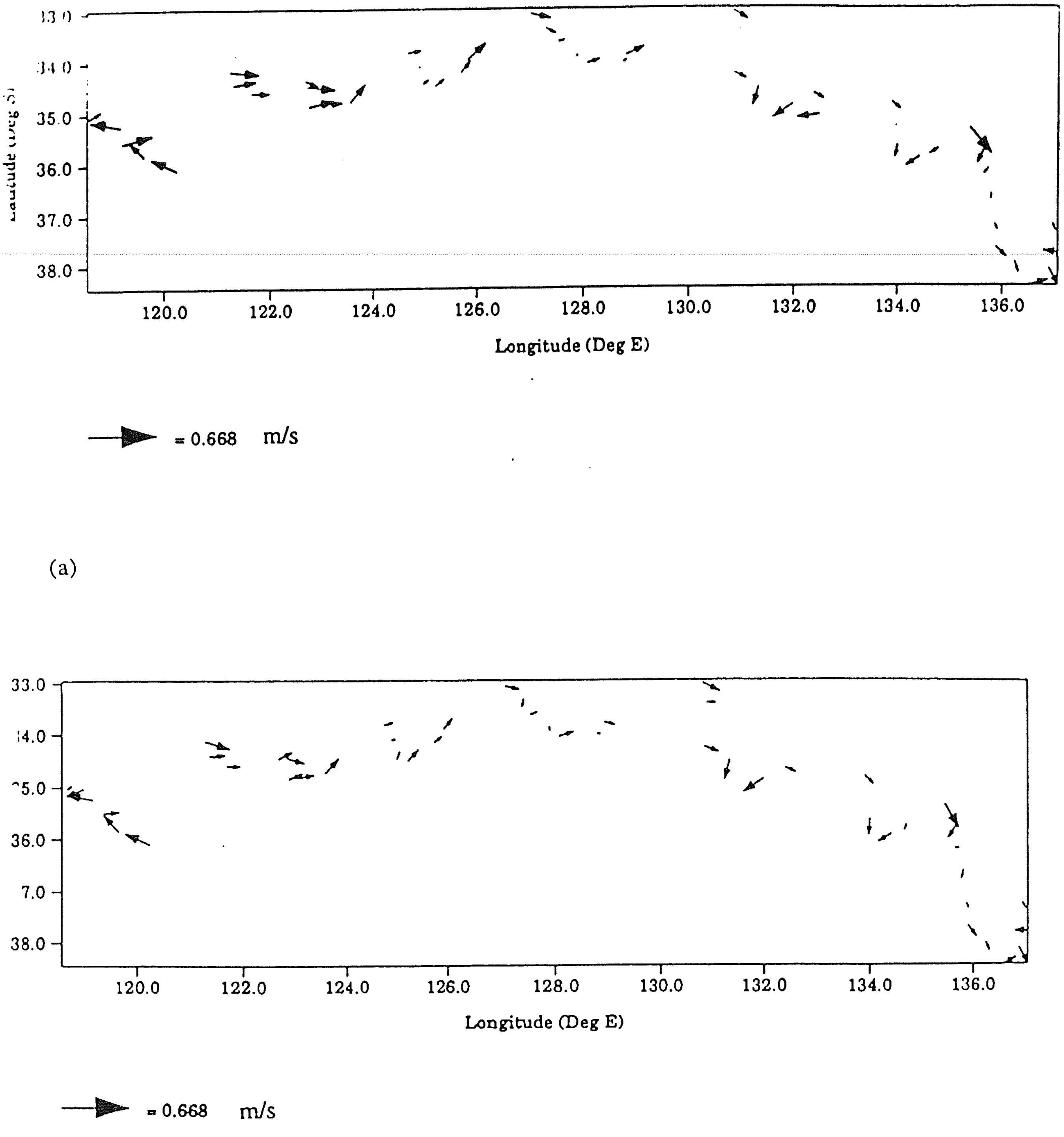


Figure 5.7(a,b): Vector plots (arrows indicate direction of flow between station pairs), (a) Depth = 150m, (b) Depth = 200m

Discussion

The objective of this study was to investigate the surface and sub surface current structure of the GAB region based upon ADCP data obtained on the Franklin 7/94 cruise.

Surface and sub surface characteristics of the GAB

Cresswell & Golding, (1980) (cited in Cresswell & Peterson, 1993) used the name Leeuwin current for the warm, low salinity water that flowed southward to Cape Leeuwin and then eastward towards the Great Australian Bight. The Western Australian region as previously mentioned is strongly under the influence of the Leeuwin current.

In July 1994 voyage by the Franklin showed that the 'winter' Leeuwin current is characterised by a maximum surface speed of 68 cm/s, just beyond the shelf edge between and along 118°E. Shelf movement is distinguished by eastward flow with weaker current speeds of 15 cm/s. Further east surface current speeds of 58 cm/s were identified between (34.5-35.0°S,121-124°E); again just beyond the shelf edge. Strong current shears existed between the surface and a depth of 200m in regions of strong flow, in fact the maximum shear found was 47 cm/s. The surface temperatures and salinities between 118°E and 124°E varied between 17.0-18.9°C, and 35.7-36.0 psu. Based upon satellite imagery offshoots or turbulent features were identified just south of 35°S and slighlty east of 125°E, on the 6th (start of the cruise) and 19 July (end of the cruise). The size of the offshoots were 33km wide and 65 km long on the 6 th July, and 45 km wide and 72 km long on the 7 th July. The offshoot identified on the 6 th July appeared to be newly spawned, and by the 19th the feature was almost fully developed, however the data set is not adequate to be sure of this.

Results obtained from June 1986-1987 on the Franklin are particularly relevant to this study since the instrument used to track the Leeuwin current was a 150 kz RDI ADCP. Cresswell & Peterson, (1993) concluded that the maximum surface speed of the Leeuwin current was more than 1 m/s beyond the shelf edge, and that the shelf current speed was approximately 50 cm/s. These results compare reasonably well with those obtained for July 1994. A point to note is that the current speed of 68 cm/s has been averaged for both the E-W and N-S components, hence a smoothing of the data resulted, consequently it is likely that surface speeds greater than 68 cm/s did exist in this region.

The easterly extent of the Leeuwin current is defined as 124°E (Petrusivics, unpub). A previous investigation by Rochford, 1986 found the easterly extent to be 130°E. Based upon ADCP data, the maximum flow which is assumed to be attributed to the Leeuwin current did in fact abruptly weaken from 124 °E.

The GAB region showed interesting features. Firstly, a continuos eastward movement particularly concentrating on the shelf edge was evident between 124 and 126°E. This is not a new finding; in fact Hahn (1986) proposed that the name of this flow be appropriately termed the 'South Australian current' (Hahn, 1986, pp. 278).

East of 132°E the GAB is characterised by warm sea surface temperatures (16.90-17.23°C) and very high salinities (36.59) psu. However the maximum salinities were in fact located at the bottom depths of these regions, reaching 36.78 psu.
Godfrey, Vaudrey & Hahn (1986); Hahn (1986) and Rochford (1983) all agree that this highly saline water mass originates in the central bight region due to a thermohaline current. Godrey et al (1986) and Hahn (1986) in a separate paper, suggest this saline water mass is advected south eastward along the shelf break, and appears to flow off the shelf as a strong jet west of Kangaroo Island. Results from this study appear to support this theory. In fact there is a definite south eastward flow between 134°E and 136°E located on the shelf region, in particular just below Port Lincoln a region of very strong flow was evident with surface current speeds of 50 cm/s. Sea surface salinities on the shelf below Kangaroo Island were over 36.0 psu and sea surface temperatures varied between 16-17°C, these characteristics are very similar to the temperatures and salinities at the head of the bight region.

Surface current speeds obtained from buoys and ships drift below Port Lincoln indicate a south eastward flow of ~ 50 cm/s (Godfrey, Vaudrey & Hahn, 1986). Results from this study strong support their findings.

Two remaining features which previously have not been referred to in literature are;

1) About 100 km off the shelf edge and along 120°E, a strong north westerly flow was identified, surface current speeds were 45 cm/s. This feature was mentioned in the preliminary analysis of ADCP data (Petrusevics, unpub.).

2) Surface current speeds on the shelf regions; particularly at the head of the bight are very weak (<10cm/s), the general direction of the flow is eastward.

Conclusion

The following general conclusions were drawn about the circulation in the study area South of Australia.

1) The Leeuwin current was identified between 118° and 124°E, and is characterised by warm sea surface temperatures (17-19.0°C) and a strong eastward flow with a maximum current speed of 68 cm/s, located off the shelf.

2) Between 124-136°E a general eastward movement, particularly concentrating at the shelf break was identified from ADCP data. Hydrographic data revealed a warm and very saline water mass located on the shelf region, between 132-136°E. It is difficult to distinguish this water mass from the Leeuwin current based upon satellite imagery due to their similar sea surface temperatures.

3) A region of strong flow characterised by surface velocities of 45 cm/s and movement off the shelf, was identified between (35-36°S, 132-133°E) this feature was clearly illustrated in satellite imagery.

3) A striking oceanic feature found off the shelf was evident in the Western Australian region , the north westward flow was characterised by surface velocities of 45 cm/s, however since only a few stations occupied this region, further investigation is required before suggesting the exact nature of the flow.

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APPENDIX 4

Australian salmon survey ORV Franklin cruise 7/94

Early life history of Western Australian Salmon, *Arripis truttaceus* (Cuvier): ageing and ecological distribution.

By

Vanessa Fahlbusch

November 1995

Flinders University

ABSTRACT

The hypothesized dispersal of the Western Australian Salmon, *Arripis truttaceus,* larvae across the Great Australian Bight was investigated on a voyage of the "O.R.V. Franklin" in July, 1994. Larvae were found within the Leeuwin Current and Great Australian Bight Outflow systems, the majority found along the edge of the continental shelf between Albany and Point Culver. Otolith microstructure was used to determine ages of the specimens, assuming that the first increment deposition was around the time of hatching, approximately 2 days after fertilisation. Estimated ages ranged from 20-263 days. Standard length (preserved) regressed against the estimated sagittal age revealed a linear relationship. The age estimates were used to determine approximate spawning dates which ranged from early March to the end of June. Data on flow rates of the Leeuwin Current were used to estimate approximate spawning locations. Otolith increment widths were used to determine the average growth histories, as indicated by sagittae. Growth histories consisted of slow growth for approximately 2 weeks, followed by a dramatic increase in growth rate, sustained until approximately 235 days old, after which the growth rate decreased consistently until capture. Increment counts were examined between and within sagittal and lapillus pairs. There was no significant difference in the counts obtained from within an otolith pair. Counts between otolith pairs resulted in lapilli underestimating sagittal counts by up to a half.

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TABLE OF ABBREVIATIONS

A.	*Arripis*
AI	Angas Inlet
AS	Australian Salmon
BI	Barker Inlet
CTD	Conductivity-Temperature-Depth Gauge
ENSO	El Niño - Southern Oscillation
GAB	Great Australian Bight
GABO	Great Australian Bight Outflow
LC	Leeuwin Current
"ORV Franklin"	Oceanographic Research Vessel Franklin
SA	South Australia
WA	Western Australia
WWD	West Wind Drift

GLOSSARY

Accretion Zone: Component zone of daily increment comprised of predominately aragonitic calcium carbonate (Watabe *et al.*, 1982).

Antirostrum: Anterior "thumb-like" projection of the sagitta, located dorsal to the rostrum (Secor *et al.*, 1992).

Birefringent: Having two different refractive indices (light deflection through a medium) (Tulloch, 1993).

Discontinuous Zone: Component zone of daily increment comprised predominately of organic matrix (Mugiya, 1987).

Growth Axes: Axes within the otolith along which proportionately rapid rates of deposition occur (Panella, 1980). Axes within the microstructure where increment widths are greatest.

Increment (Rings): Bipartite concentric ring comprised of alternate zones of the predominately calcium carbonate accretion zone and predominately organic discontinuous zones. Daily increments are increments which have been validated to occur at a daily rate (Secor *et al.*, 1992).

Increment Width: Linear measurement, comprised of one accretion zone + one discontinuous zone, usually measured along an otolith's major growth axis (Secor *et al.*, 1992).

Primordia: Initial deposition sites of organic matrix and calcium carbonate, usually located in the otolith core (Secor *et al.*, 1992).

Postrostrum: Posterior most projection of the sagitta (Secor *et al.*, 1992).

Rostrum: Anterior most projection of the sagitta (Secor *et al.*, 1992).

Standard Length: The distance from tip of snout along midline, to a vertical line through the posterior edge of the hypural plate (Leis and Trnski, 1989).

Sulcus: Sculptured groove along the medial face of the sagitta (Secor *et al.*, 1992).

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1. INTRODUCTION

1.1 ARRIPIS TRUTTACEUS

The Western Australian Salmon, *Arripis truttaceus*, belongs to the family Arripidae and is a perciphorm fish, in no way related to the true salmons of the family Salmonidae (Cappo, 1987). *A. truttaceus* in the past has also been incorrectly identified as *A. trutta* (Bloch and Schneider 1801) and as a subspecies of the eastern salmon was classified as *A. trutta esper* Whitley (1950) (Malcolm, 1960; Cappo, 1987). A recent review by Paulin (1993) of the Arripididae family confirmed the western and eastern salmon as separate species, rather than subspecies. The eastern salmon is classified as *A. trutta* whilst the western species is classified as *A. truttaceus*.

Adult western salmon can be found across southern Australia from Geraldton, Western Australia to Eden, New South Wales, including Bass Strait and Tasmania. The western salmon fishery is of great economic importance to both Western Australia and South Australia. The 1993/4 South Australian commercial catch was recorded as 524 tonnes with a value of $732,000 (Peterson, 1994). In Western Australia the total value of the commercial catch is around $1million, with the 1994/5 season's catch expected to be approximately 2300 tonnes (R. Lenanton, pers. comm., 1995). The meat is sold as fresh fish on the local market, canned, used as pet food and the heads are used as rock lobster bait. Salmon is a highly prized recreational fishery species, estimated to be at least 30% of the overall annual salmon catch in Western

Australia (R. Lenanton, pers. comm. 1995), and of similar value in South Australia (Cappo, 1987; K. Jones, pers. comm., 1995).

Intensive tagging studies have been undertaken on sub-adult and adult western salmon by Malcolm (1960), Cappo (1987) and Stanley (1986, 1988). It is known that spawning grounds in Western Australia are primarily along the southern and south-western coasts between Busselton and Esperance, with an area of intensive spawning centered around the Cape Leeuwin to Busselton area in late April and May (Cappo, 1987).

Nursery grounds for juveniles exist in Western Australia and South Australia and as far afield as Victoria and Tasmania. Nursery sites in South Australia include the eastern coast of the Eyre Peninsula, the Gulfs St. Vincent and Spencer, and the Coorong. Post-settlement larvae have been found in Barker Inlet of the Port River, South Australia (Latitude 34.8°S, Longitude 138.5°E), in June (Lenanton *et al.*, 1991; K. Jones pers. comm., 1995). In 1994 juveniles were first found in August (K. Jones pers. comm., 1995). Larvae and juveniles from nursery grounds are termed 0+ years (Malcolm, 1960; Cappo, 1987). Juvenile salmon are found over soft substrate in shallow, sheltered waters and are often associated with seagrass (Pullen, 1994).

To date egg and larval advection have been reported as being primarily by the Leeuwin Current as in Malcolm (1960) where he stated "embryonic, larval and postlarval life is quite unknown but in this period of drifting, and perhaps later

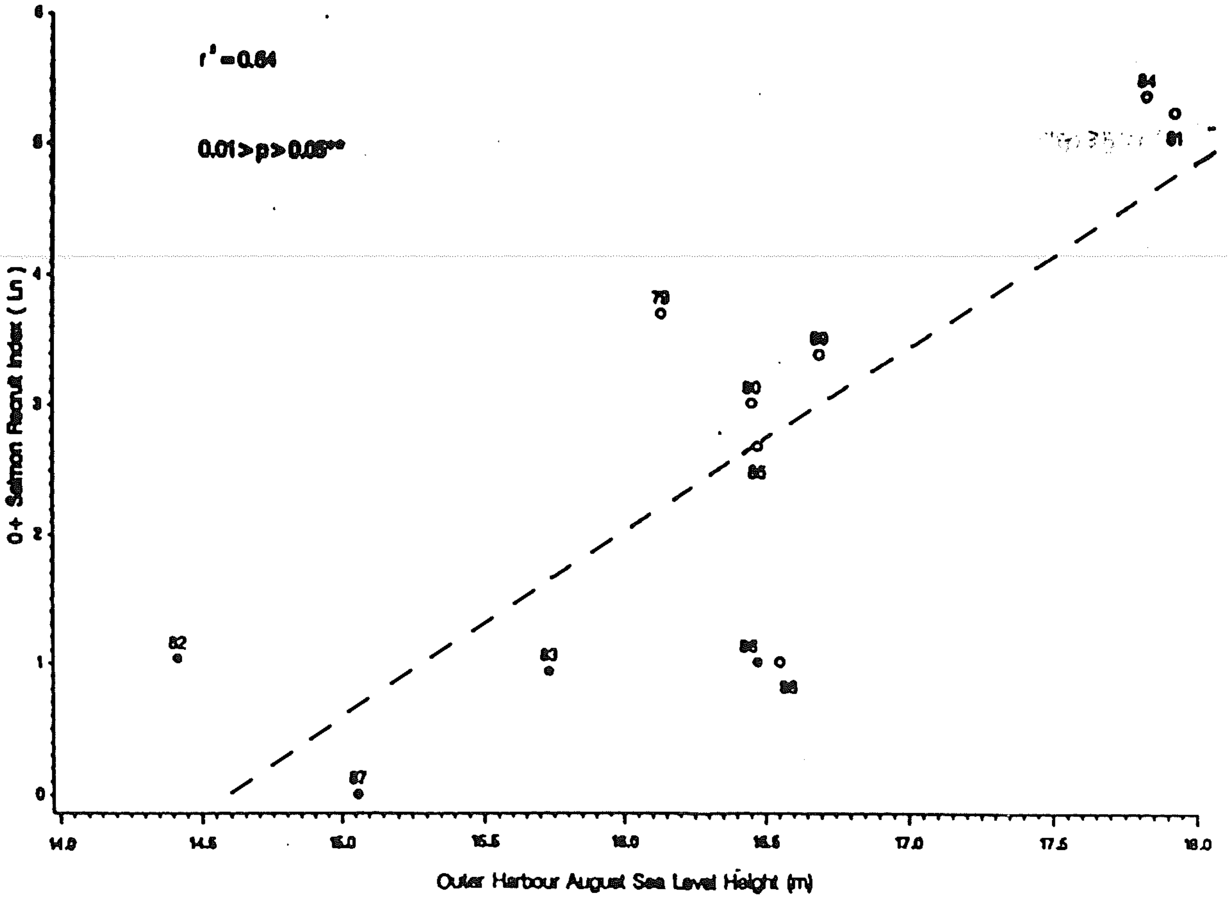


Fig. 1. Relationship between annual recruitment index of salmon in Barker Inlet and Outer Harbour sea level (1979-1989).

active swimming, eastward movement must take place to bring the young fish of "0" group to nursery areas in South Australia, western Victoria and the more westerly regions of Tasmania." He postulated the advection probably involved eggs and early larvae drifting, supplemented by an active migration of the young fish.

Recruitment levels of pre-settlement larvae into Barker Inlet, an important South Australian nursery area, during El Niño-Southern Oscillation (ENSO) years show a reduction of 5-18 times the recruitment levels of non-ENSO years (Lenanton *et al.*, 1991) (Fig. 1). This correlation suggests environmentally driven or influenced recruitment levels.

As the complexities of the recruitment process make it unlikely that all variables will be fully understood, it was evident that a general examination was required such that general concepts and baseline data could be considered.

1.2 LEEUWIN CURRENT

The definition of the Leeuwin Current is a rather general one. It is an eastern boundary current, driven pole-ward by a deep alongshore density gradient (Weaver, 1990) and lacks the characteristic upwelling usually associated with these particular types of currents (Godfrey and Ridgway, 1985; Pearce, 1991) such as the Benguela and Humboldt Currents. The waters are low in nutrients,

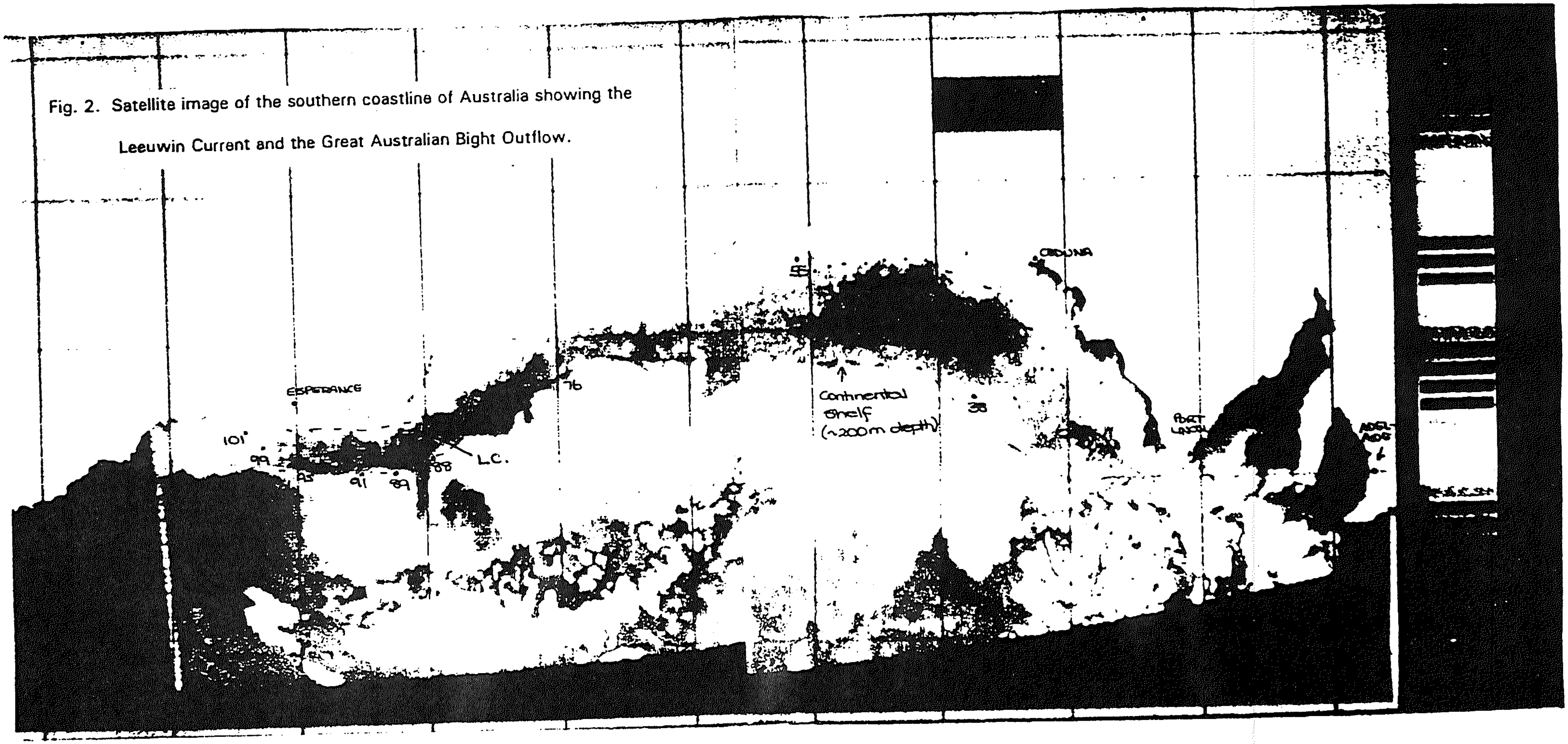


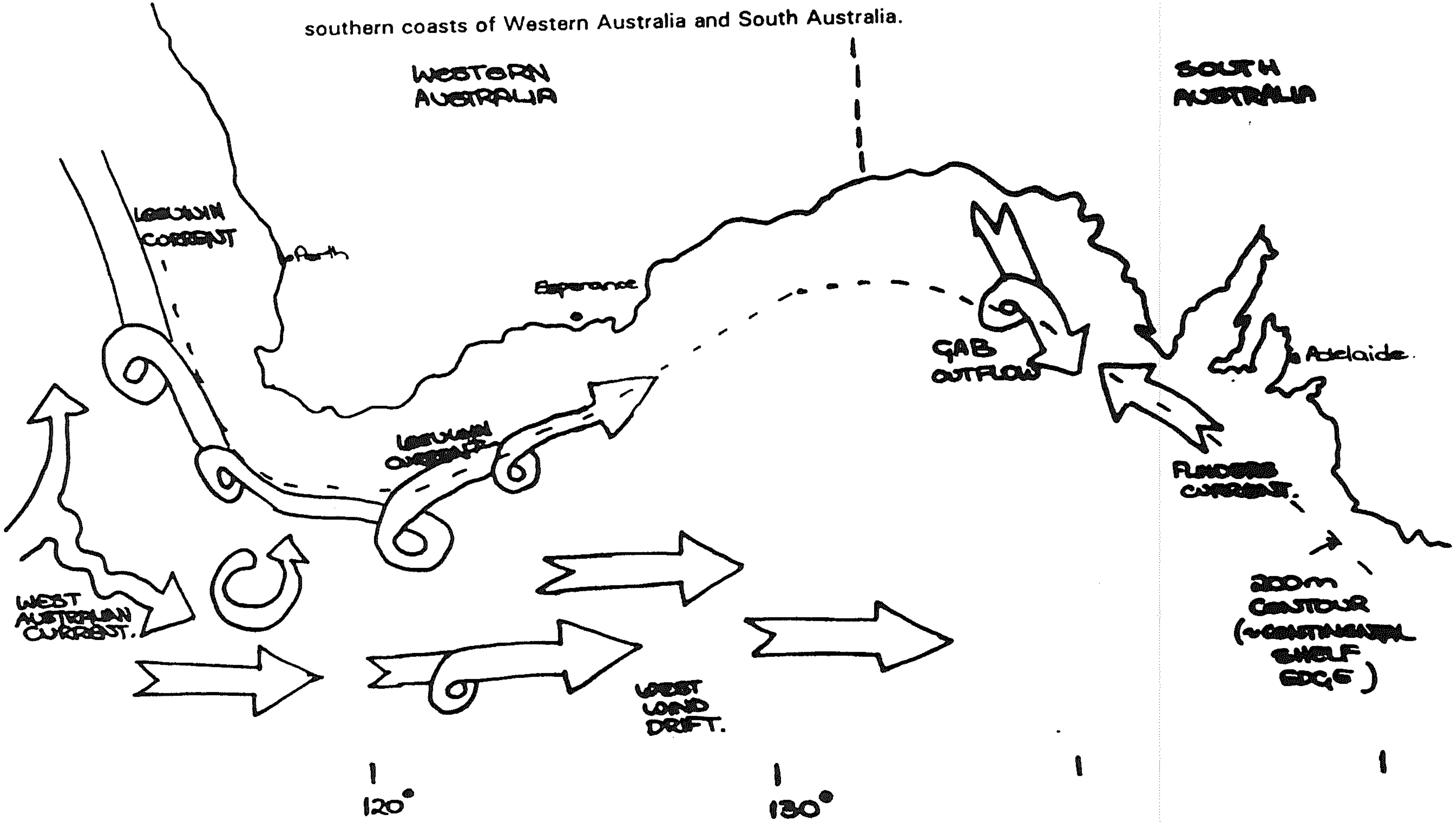
Fig. 2. Satellite image of the southern coastline of Australia showing the Leeuwin Current and the Great Australian Bight Outflow.

warmer and less saline than the local water masses, with their source in the warm, low-salinity tropical waters off north-western Australia (Cresswell, 1985).

Cresswell and Peterson (1993) stated that the leading edge of the Leeuwin Current progressed eastward between April and May at around 20 km per day and had a maximum surface speed of more than 1m/s. Rochford (1986) suggests the Leeuwin Current (Fig. 2) 'disappears' around 128-130°E, possibly absorbed into the West Wind Drift waters in this region. West Wind Drift waters may be the mechanism of its dissolution of the Leeuwin Current at the western end between June and August around 120°E. The Leeuwin Current may persist during some years until September - October (Rochford, 1984). It has been postulated the Leeuwin Current flows little further than the Recherche Archipelago (Latitude 34°S, Longitude 123°E) in the Esperance region (P. Petrusevics, unpublished manuscript, 1995) as defined by it's salinity and temperature signatures of 35.75<parts per thousand (ppt)<36.0 and 17<degrees Celsius (°C)<19 respectively (P. Petrusevics, unpublished manuscript, 1995), while a broader definition of the current results in it flowing well into the Great Australian Bight before becoming unidentifiable from the local waters through mixing.

Taking over from the Leeuwin Current within the Great Australian Bight, is the Great Australian Bight Outflow which dominates the local oceanography with similar or greater temperatures to the Leeuwin Current and salinities in the region of 35.9<ppt<36.6 (Rochford, 1986). This water mass occupies extensive

Fig. 3. Schematic diagram of the oceanographic influences along the southern coasts of Western Australia and South Australia.



regions of the central and eastern shelf and extends south-east from the central Great Australian Bight down along the South Australian coastline. As Rochford (1986) has noted, these two water masses with similar temperatures with both being found in the same region may have resulted in incorrect interpretations of satellite images in the past, with respect to the true eastward extent of the Leeuwin Current.

Anecdotal evidence from fishermen in Western Australia suggests there is a westerly directed current (from the east) around the southern and south-western coasts of Western Australia and across the Great Australian Bight during the months of November to January (Fig. 3), just before the Leeuwin Current exerts an influence over the general oceanography (Australian Fisheries, 1995; R. Lenanton, pers. comm., 1995). It is felt that this may have some implications on the main spawning grounds of *A. truttaceus* on a yearly basis.

The Leeuwin Current varies greatly from year to year in strength, duration and eastward extent but the reasons behind this are not fully understood. "Weak" Leeuwin Currents would not be expected to dominate local oceanography and may not even flow around Cape Leeuwin as a "distinguishable and separate" water mass. This would result in an overall egg and larval flow up and along the western coast of Western Australia with high levels of local recruitment and very poor advection and recruitment in South Australia. "Strong" Leeuwin Currents would be expected to dominate local oceanography with a strong and distinguishable flow around Cape Leeuwin, along the southerly coast and eastward into the Great Australian Bight, with the potential for taking eggs and larvae further east with poor recruitment in Western Australia and high recruitment in South Australia and possibly Victoria and Tasmania.

Just what constitutes a weak and strong Leeuwin Current is not strictly defined and characteristics defining the Leeuwin Current have never been clearly resolved. On a macro scale, current flow down the western, and across the southern coasts of Western Australia, during the months of April and May, with an average velocity of <1.0m/s would suggest a weak Leeuwin Current, while a strong Leeuwin Current during these months is one having an average flow rate of >1.0m/s.

2. OTOLITHS

2.1 INTRODUCTION

Structures which encode age information are bones (fin rays, vertebrae, cleithra, opercular bones), scales and otoliths (Jones, 1992). Scales are unreliable as they can be lost, regenerated and deposition ceases at older ages giving false readings (Jones, 1992). They are not formed on day one of larval development and are therefore useless for accurate larval aging.

Otoliths are formed at one of several possible specific events in the first few days of the larval life, soon after fertilization (sardines; Alemany and Alvarez, 1994), hatching (cod; Geffen, 1995; snapper; Kingsford and Atkinson, 1994) or at first feeding, the deposition being species-specific. They are not absorbed back into the body during times of stress (Jones, 1992). Otoliths consistently record daily information early in life and later, annual data. Daily increments have also been recorded in statoliths which are analogous to otoliths, in cephalopods and agnathans (Jones, 1992). The major disadvantage of using otoliths is that the specimen must be killed in order to obtain this information.

Otoliths are calcium carbonate ($CaCO_3$) accretions which occur within the labyrinth systems of fishes (Secor and Dean, 1989). They have a structure of accretion zones, predominantly of aragonitic calcium carbonate (Watabe *et al.*, 1982), and discontinuous zones, comprised predominantly of organic matrix (Mugiya, 1987).

A pattern of daily rings can occur within the microstructure of the otolith which can provide a direct and valid estimation of larval age. Daily ring formation has been validated for many species including the butterflyfishes *Chaetodon rainfordi*, *C. plebius* and *C. rostratus* (Fowler, 1989), bluefin tuna larvae *Thunnus maccoyii* (Jenkins and Davis, 1990), damselfishes *Pomacentrus moluccensis* and *P. wardi* (Fowler and Doherty, 1992), the anchovy *Thryssa aestuaria* (Hoedt, 1992), snapper *Pagrus auratus* (Kingsford and Atkinson, 1994), the sardine *Sardina pilchardus* (Alemany and Alvarez, 1994) and cod *Gadus morhua* (Geffen, 1995). Otolith microstructure can be used to determine not only an age estimate, but retrospective information on individual growth histories (Fowler, 1989), length at age data, estimated cohort spawning dates and the timing of settlement (Robertson *et al.*, 1988).

2.4 RESULTS AND DISCUSSION

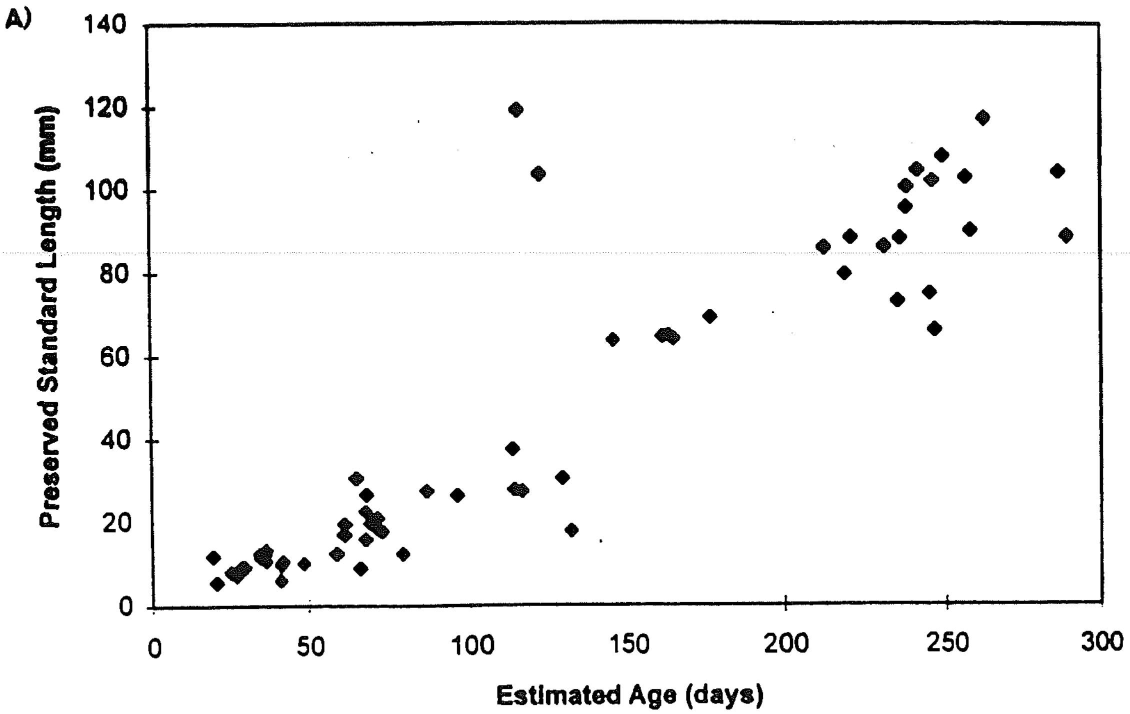
Ageing

Counts from both lapilli and sagittae were compared to determine the most consistent count. It was found lapilli counts were consistent with sagittal counts until the larvae were approximately 10mm in length. Counts within both lapillus and sagittal pairs, from the same fish, showed highly significant correlations between counts obtained when a linear regression was performed ($r^2=0.99$, $n=40$; $r^2=0.95$, $n=44$ respectively). Juvenile lapilli counts grossly underestimated the sagittal count, at times by a half. This result was most likely caused by poor resolution of the increments due to their densely packed arrangement, rather than an exaggerated count of the sagittae. The poor resolution of the increments may be due to the small size of the otolith. Sagittal growth is predominantly in length rather than in width, while lapilli remain almost round in shape. Sagittae have a major growth axis along which increment widths can reach as much as 30 µm. The largest lapillus increment width measured was 16 µm along the counting axis. The lapilli effectively do not "grow out" as sagittae do, consequently the increments were more tightly packed and their clarity severely impaired. Due to this finding all age calculations were from the higher sagittal counts.

Any future work on *A. truttaceus* larvae should be carried out using sagittae if over approximately 10mm until a method of exposing all lapillus increments is found. If larvae are less than this size, a check should be undertaken on the larger specimens to determine count accuracy, otherwise the lapilli would suffice with the benefit of much less preparation required also.

Estimated larval *A. truttaceus* ages ranged from 26 days to 132 days. Estimated juvenile *A. truttaceus* ages ranged from 148-265 days (Table 1).

Linear regressions performed on the preserved standard length and the estimated sagittal ages of *A. truttaceus* specimens yielded a significantly linear relationship ($r^2=0.82$, $n=65$) (Fig. 7a) while a regression performed on preserved weight and estimated sagittal age yielded a significant power relationship ($r^2=0.86$, $n=65$) (Fig. 7b).



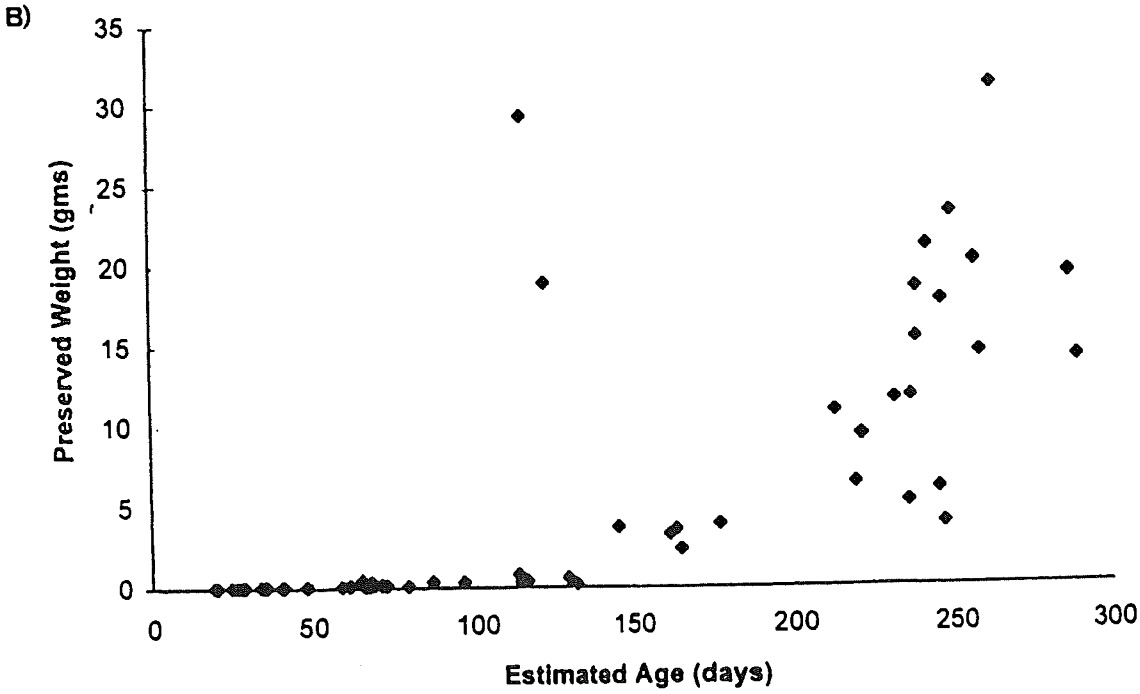


Fig. 7. Relationship between a) preserved standard length and estimated sagittal age and b) preserved weight and estimated sagittal age.

Back-calculated spawning dates

A. truttaceus **larvae were calculated as having been spawned mainly in the months of May and June. Seven specimens were spawned in March and April, being captured in tows 26, 38, 55, 76 and 127. All but one of the** *A. truttaceus* juveniles were calculated as having been spawned in the months of March and April. One specimen was spawned on the 28th of February.

The above spawning date calculations correspond reasonably well with the available literature estimates on *Arripis* spawning times (Malcolm, 1960; Cappo, 1987). Exact spawning times are not known but the above dates are within the proposed months. The data suggests continuous spawning occurred, rather than several isolated occasions. The spawning in 1994 for both species' was more prolonged than the literature suggests. It may be that the sampling has picked up the beginning and the end of the spawning extent, as well as the peak period. 1994, being an El-Niño year with the accompanying decrease in Leeuwin Current strength and anomalous weather conditions, may have experienced unique salmon activity with regards to spawning extent not previously identified in the general picture.

Table 1. **Back-calculated spawning dates of all specimens.**

- **AS = Australian Salmon**
- **Back-calculated spawning dates includes a 2 day correction factor**

Station Number	Sagittal age range (days)	Back-calculated spawning dates
26	AS: 92	April 10
38	AS: 129	March 4
55	AS: 65-114	March 21,22; April 7; May 7,10
81	AS: 71	May 7
91	AS: 60	May 20
93	AS: 53	May 27
95	AS: 61,67	May 13,19
96	AS: 20-41	June 8-29
99	AS: 61,69	May 11,19
101	AS: 68	May 13
127	AS: 116	March 28
Angas Inlet 3/11/1994	AS: 177-247	February 28; March 2-28; May 9
Angas Inlet 22/11/1994	AS: 213-263	March 3-30; April 5, 14,22
Barker Inlet 29/8/1994	AS: 146-166	March 7-19; April 4

Otolith Growth

A regression between lapillus width and diameter indicated their growth rate is linear ($r^2 = 0.95$, $n = 110$), maintaining an essentially round shape throughout. Regressions performed between sagittal width and diameter indicate a linear rate also ($r^2 = 0.97$, $n = 104$). As they are already a disc shape in very young fish there must be a period of disproportionate growth between first increment deposition and 5mm. In the specimens analysed the growth is maintaining the disc shape. Sagittae develop a highly convex-concave shape with growth, presenting difficulties in displaying the whole of the internal structure. Juvenile otolith growth exhibited more variance, with no significant relationships between either lapillus or sagittal width and diameter, nor when lapilli and sagittae were compared with each other.

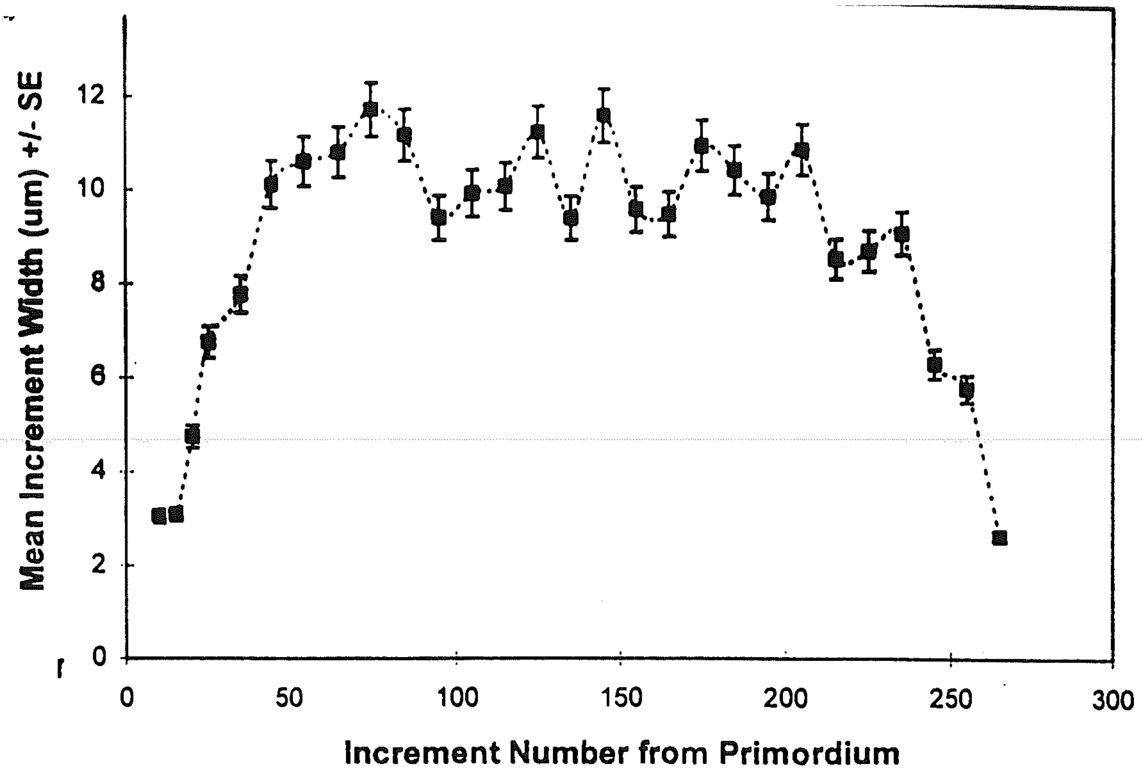
Preparation for displaying internal structure

The preparation method of the larger sagittae, used in this research, required several stages of grinding and counting into the otolith from the edge, but displayed the internal structure clearly and with minimum potential for error when counting increments. The disadvantage of this technique is that internal microstructure, such as increments, is lost due to the grinding, while sectioning of the embedded otolith retains the structure. Smaller sagittae required a small amount of grinding but all internal structure was retained. A drop of clearing oil on the otolith prior to counting greatly improved the clarity of the internal structure and removed many of the artifacts.

Lapilli were easily prepared. Leaving the otolith to sit in the clearing oil, (sometimes for up to a week for the larger otoliths), eliminating the requirement of grinding with no adverse effects on the otolith. It has been stated that prolonged storage in oil can cause degradation (Secor *et al.*, 1992), an event seen to happen mainly to damaged otoliths during this research. Those lapilli that did not clear readily required some grinding, which took very little time. Because of their shape this technique involved little chance of overgrinding.

Settlement mark or zone

Observations were made to determine whether or not a particular region or feature in the otolith could be related to settlement. To determine whether there was any change in increment width which may be related to settlement, increment widths were measured along the major growth ais. Some specimens exhibited a dark, double increment in the sagittae after which increment widths decreased dramatically and were more densely packed. This discontinuity marked a clearer peripheral region from the larger three dimensional remainder of the otolith. All sagittae of juveniles showed a decrease in increment width towards the edge, not all contained the double increment. Such dramatic changes in the otolith structure have previously been identified as reflecting changes in physiology and morphology (Brothers and McFarland, 1981). This change in increment width may not have occurred at the exact time of settlement but as a prelude to or in response to the settlement transition. Only validation, by early capture upon settlement into the nursery and otolith examination will enable a settlement mark, if present, to be identified and to be of future use in aging and population studies.



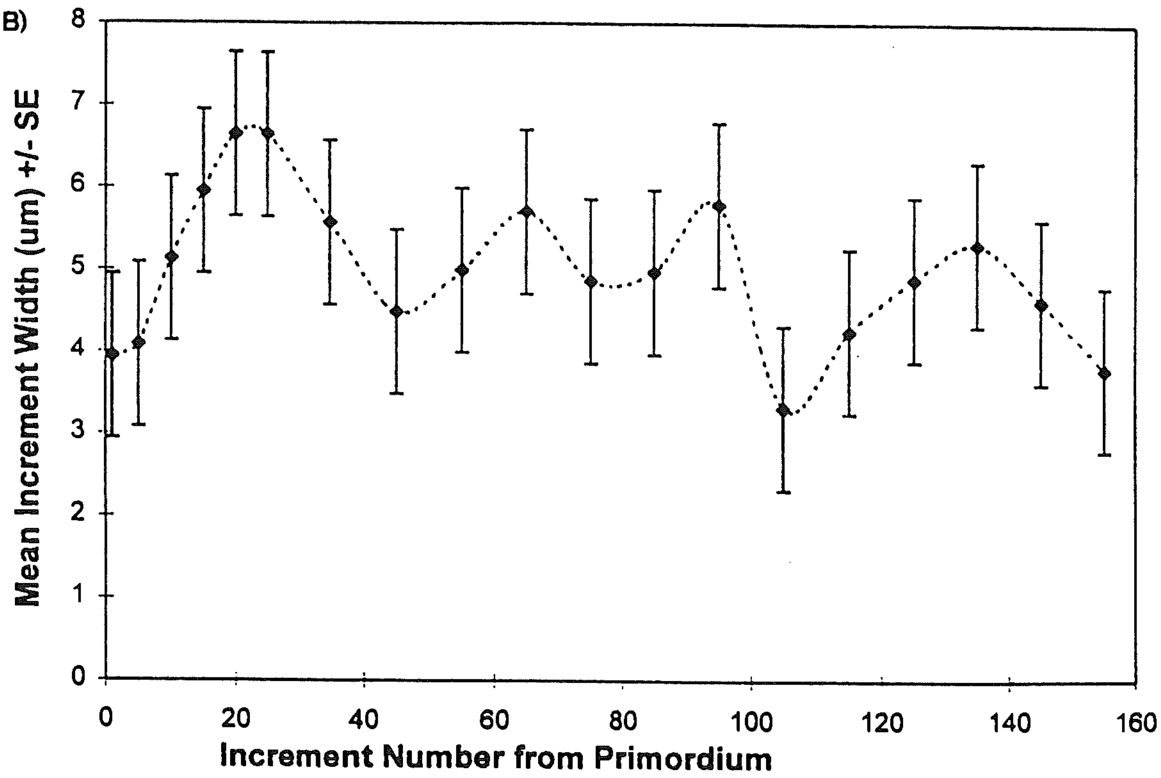


Fig. 8. Relationship between a) mean sagittal increment width and increment number as counted from primordium, and b) mean lapilli increment width and increment number as counted from primordium.

Increment Widths

The increment widths of many specimens were measured, and where possible both lapillus and both sagitta from the same fish were measured. A typical sagitta had a rounded posterior and lateral edges, leading to an anterior tip. A series of coincentric rings radiated from the primordium and followed a curved axis of maximum growth to the anterior tip (Fowler, 1989), The first few increments were approximately 2-3µm, after which they increased dramatically to a maximum of 13µm, fluctuating to as low as 8µm until approximately 235 days when the increments gradually decreased in width to approximately 2.5µm. The generalized description of growth is subject to individual variation which included continuous slow growth throughout, greater growth rates than general throughout, and peaks and troughs in growth. Lapillus widths were smaller than the sagittae with widths ranging between 3-7.5µm (Fig. 8).

3. ECOLOGICAL DISTRIBUTION

3.1 INTRODUCTION

Many fish species have life cycles that involve repetition of their behaviour, and movement each year to the same locations. Explanations for this distribution phenomenon include a particular current, which influences recruitment resulting in high and low levels such as the Western rock lobster, *Panulirus cygnus* (Pearce and Phillips, 1991) and the saucer scallop, *Amusium balloti*, in Western Australia (Joll and Caputi, 1991), dispersal such as reef fishes from the tropics down the Western Australian coast (Hutchins and Pearce, 1994), and preferred or requisite temperatures for spawning and feeding such the pilchard *Sardinops pilchardus* (Fletcher, 1991; Fletcher and Tregonning, 1992) and Western rock lobster (Chittleborough, 1976).

Cues for migration are generally unknown, yet many species return to the same location yearly, the young also finding their direction to the same places. What triggers and guides these animals is subject to continual investigation, yet spawning grounds and feeding locations remain constant year after year. *A. truttaceus* spawning and nursery grounds are the effectively the same locations today as they were when investigated by Malcolm (1960). Spawning occurs the same time every year, March - May, while the spawning grounds are in close proximity to the Leeuwin Current at a time when it is reaching peak flow and velocity which suggests a correlation between spawning, maximum strength and maximum dispersal potential by this current. The Leeuwin Current has been implicated in many life cycles of species found in Western Australia. A good correlation for the recruitment of tropical reef fishes at Rottnest Island with the strength of the Leeuwin Current, has been identified (Hutchins, 1991). First recruitment coincides with the strengthening of the Leeuwin Current in March and April and ceases in spring when the Leeuwin Current weakens (Hutchins, 1991). To better understand the life history of *A. truttaceus* and many other commercially important species, and therefore effectively manage remaining stocks, it is necessary to have some understanding of the processes that determine recruitment of new individuals into the fishery.

To this end, the aim of this research was to 1) **determine any relationships between the Leeuwin Current, salinities and temperatures and where the Australian Salmon were located and 2)investigate possible dispersal rates and** mechanisms of larvae from the spawning grounds.

3.2 METHODS

Potential larval dispersal distances from the spawning site were calculated on an average current velocity with respect to their capture location.

Dispersal rates were calculated from where larvae were captured to determine their possible arrival dates into Barker and Angas Inlets had they not been netted. Approximate distances from the station to likely nursery grounds were:

Station 26 and 38 to Barker Inlet ~450km
Station 55 to Ceduna ~325km
Station 76 to Barker Inlet ~1400km
Station 81-101 (Esperance) to Barker Inlet ~1350km
Station 127 to Barker Inlet ~1500

Larval potential dispersal rates from capture locations were calculated on average surface current velocities along the projected dispersal route and the potential distances that a larvae could travel per day.

Current velocities of 0.1m/s = 8.6km/day
0.2m/s = 17.3km/day
0.4m/s = 34.5km/day
0.7m/s = 60.5km/day

3.3 RESULTS

Using the definition of the Leeuwin Current as per Petrusevics (unpublished manuscript, 1995) (17<°C<19; 35.75<ppt<36), Australian Salmon were found at 8 stations within the Leeuwin Current (Fig. 9). 3 stations were located on the fringes of the current system where either the temperature or salinity differed slightly from the very narrow definition of Petrusevics, the probable result of mixing with the local waters (Table 2).

Stations 26, 38 and 55 were situated within the Great Australian Bight Outflow which has temperatures similar to those of the Leeuwin Current but salinities in the region of 35.9<ppt<36.4 in 1971 (Rochford, 1986) while in 1994 salinities were 35.9<ppt<36.75. These very high salinity Bight waters occupy an extensive area of the central and eastern GAB and are found well onto the shelf region and extend south-eastward along a tongue to around 135°E (Rochford, 1986), the approximate longitude of Port Lincoln.

Current velocities obtained from data collected during the trip (Hammat, unpublished manuscript) indicate an average shelf edge current of approximately 0.7m/s, diminishing onto the shelf to approximately 0.1-0.2m/s and out into

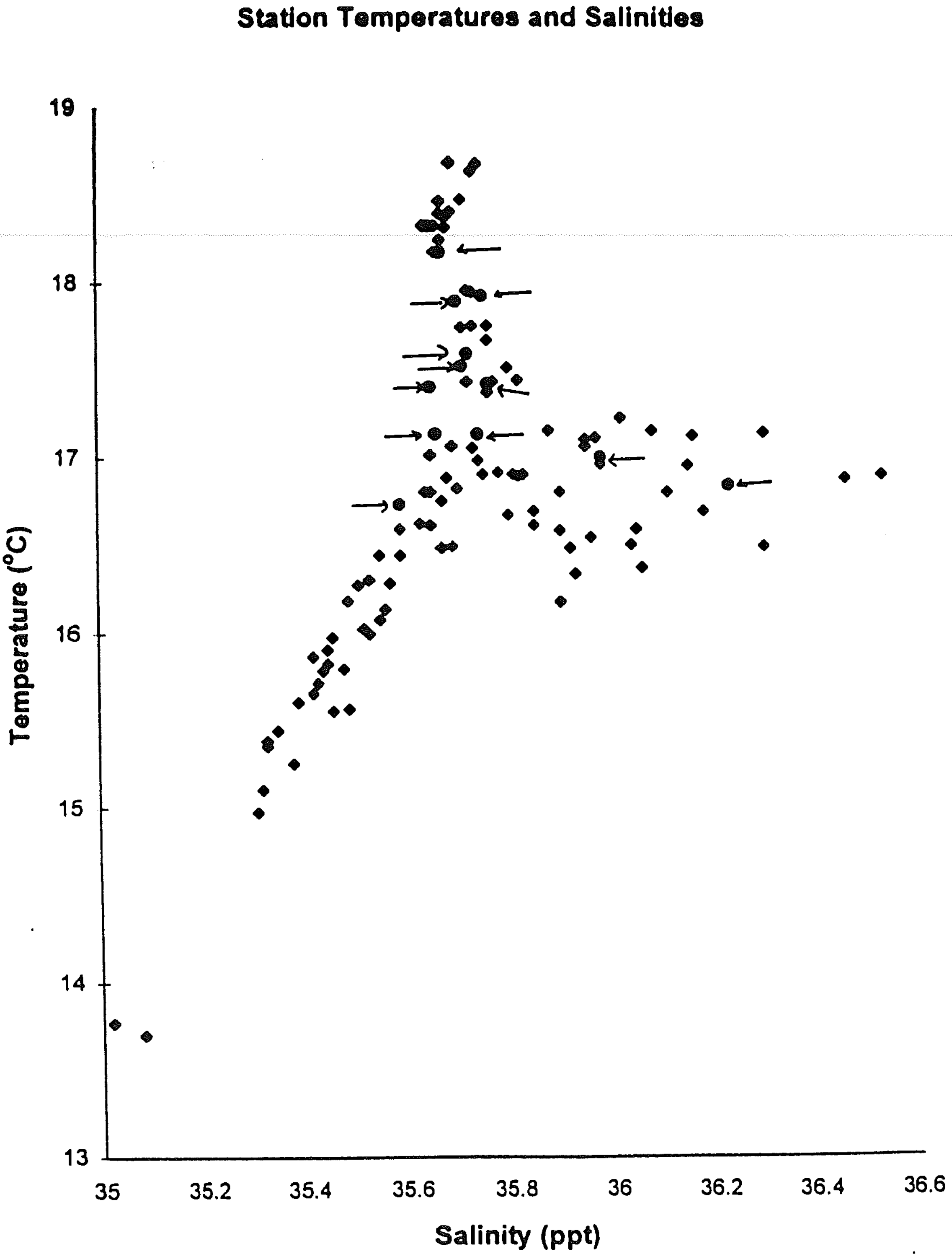


Fig. 9. Relationship between temperature and salinity values for all stations. Stations where *Arripis truttaceus* captured annotated by •.

more oceanic waters (Hammat, unpublished manuscript, 1995). Current velocity decreases dramatically from Longitude 124°E across the Great Australian Bight to an average 0.2m/s, until the Great Australian Bight Outflow. Currents in the vicinity of Stations 26 and 38 are an average 0.4m/s, the approximate location of the Great Australian Bight Outflow while the waters about Station 55 are almost stationary. All currents flow in an easterly direction, backed by the West Wind Drift, a surface current blown toward the east by westerly winds.

Figure 9 illustrates the relative positions of stations where *A. truttaceus* were captured with respect to the temperature and salinity values of all stations. All stations, except Station 55, where larvae were captured are in the higher temperature range of 16.5-18.5 °C and between salinities of 35.6-35.8. This may suggest more stations between Stations 76 and 127 in all probability should have produced larvae.

Table 2. Station temperatures, salinities and their relative position with respect to the Leeuwin Current.

STATION NUMBER	SALMON	TEMPERATURE (°C)	SALINITY (ppt)	POSITION OF STATION
26	SALMON	17.13	35.98	GAB OUTFLOW
38	SALMON	17.13	35.74	GAB OUTFLOW
55	SALMON	16.69	36.21	GAB OUTFLOW
81	SALMON	17.36	35.75	LC
88	SALMON	16.74	35.61	EDGE OF LC
91	SALMON	17.61	35.73	LC
93	SALMON	17.42	35.77	LC
95	SALMON	17.94	35.72	LC
96	SALMON	18.16	35.70	LC
99	SALMON	17.82	35.75	LC
101	SALMON	17.94	35.73	LC
127	SALMON	18.21	35.65	EDGE OF LC

Table 3. Possible distances traveled by larvae prior to capture; possible spawning sites and possible dispersal rates of larvae from station location to nursery locations.

- (Al: Albany, B: Bunbury, BI: Barker Inlet, Bu: Busselton, CL; Cape Leeuwin region, Esp; Esperance, H: Hopetoun)
- Distance traveled calculated from travel to shelf edge ~100km @ 0.1m/s =12days duration.
- Stations 99,101,127 well onto shelf experiencing reduced current velocities.
- Larval duration calculations based on distances from Albany to Adelaide ~1500km, Esperance to Adelaide ~1350km.

Tow No.	Age Range (days)	LC Speed (m/s)	Distance Traveled (kms)	Possible Spawn Site	Water Speed (m/s)	Larval Duration (days)	Nursery sites
26	92	.4	2750	Bu	.4	13	BI
38	129	.4	4000	?	.4	14	BI
55	65-114	.1	450-880	Esp; H	.1	39	Ceduna
81	71	.2	1000	CL	.2	85	BI
91	60	.7	2900	?	.2	80	BI
93	53	.7	2500	?	.2	80	BI
95	61-65	.7	2900-3200	?	.2	80	BI
96	20-41	.7	450-1750	Al; ?	.2	80	BI
99	61-69	.2	900-1000	B	.2	85	BI
101	68	.2	1000	B	.2	85	BI
127	116	.1	900	B	.2	90	BI

3.4 DISCUSSION

As Australian Salmon larvae are dispersed from Western Australia to South Australia, the described current conditions of an easterly direction and velocity, support the long held belief that the Leeuwin Current aids egg and larval dispersal (at least as far as the Recherche Archipelago in 1994). This researcher's hypothesis is that dispersal, in conjunction with advection within the West Wind Drift induced surface current system, the Great Australian Bight Outflow water mass, and with some active swimming in an easterly direction by the larvae is a credible explanation for the dispersal of larvae to South Australia and Victoria. La-Niña years experiencing a strong Leeuwin Current flow may extend well into the Great Australian Bight with the West Wind Drift influence felt at a higher latitude, due to the reduced pressure acting on the atmospheric conditions allowing the winds to "spread out". This condition will then allow transport of eggs and larvae further into the Great Australian Bight and possibly increase the numbers of eggs and larvae found well onto the shelf. This influence may result in more advection and recruitment into nursery grounds along the coast from Murat Bay, to Coffin Bay near Port Lincoln, as well as high recruitment levels in Adelaide and Victoria. It would be expected that recruitment levels in Western Australia are lower during these years as the majority of eggs and larvae are removed from that state and taken east. This inverse recruitment relationship has been seen (R. Lenanton and K. Jones, pers. comm., 1995). El-Niño years of weak Leeuwin Currents with a limited eastward extent, and the maintenance of the West Wind Drift influence further out to sea, would be expected to result in localized entrainment and limited dispersal of eggs and larvae within Western Australia resulting in high recruitment levels there and low levels in South Australia and Victoria. 1994 was classified as an El-Niño year. The above hypothesis was supported by the very low recruitment levels seen in Adelaide in 1994 while very high levels were recorded in Western Australia (K. Jones and R. Lenanton, pers. comm., 1995).

Larval duration rates calculated in Table 2 would be expected to be maximum values as they are based on current dispersal only. Active larval swimming and regions of greater current velocity will decrease the number of days taken to traverse the distance between the spawning sites/stations and nursery grounds. The approximate month of arrival of these larvae into the nursery site at Barker Inlet is mid-late October based upon these values. The peak recruitment into this nursery area in 1994 was September (K. Jones, pers. comm., 1995), albeit in very low overall numbers.

The position of larvae at Stations 26 and 38 within the Great Australian Bight Outflow and relatively strong currents, combined with an easterly directed wind, suggests several possible nursery site destinations including Port Lincoln, Barker Inlet, the Coorong and, if entrained within the core of the outflow, down the south coast into Victoria.

The position of Station 55 larvae, with respect to the current systems and prevailing easterly winds, suggests their destination could be any of the bays from Murat Bay to Streaky Bay. If entrained within the Great Australian Bight Outflow they may be transported to Barker Inlet, the Coorong or even Victoria. The age of these 7 specimens indicates possible spawning sites of Point Culver, Hopetoun or the Esperance region.

Larvae captured about the Esperance area, Stations 76 - 101, were all entrained within the Leeuwin Current which had a high velocity and an easterly direction. This positioning would suggest possible nursery sites, if dispersed along the continental shelf edge, of Port Lincoln, Barker Inlet and the Coorong. If these larvae were to be washed further onto the continental shelf they may be dispersed as Station 55 or moved within the outflow waters as Stations 26 and 38.

The individual captured at Station 127 is estimated to be old enough to have been spawned at Bunbury, or even further north, and traveled around Cape Leeuwin already. It's position within the current system suggests similar dispersal locations as those larvae from Stations 76 - 101.

Estimated spawning localities are within the range suggested by the available literature, between Busselton and Esperance, with the majority of localities predicted about Busselton and Cape Leeuwin.

As larvae were captured in small groups and as single individuals, no firm conclusions can be drawn concerning whether *A. truttaceus* larvae school while in the plankton. Spawning behaviour by the adults such as in the site chosen will affect the vulnerability of the pelagic eggs and larvae to predation. As *A. truttaceus* adults spawn in a school (S. Blight, pers. comm., 1994), the influence of the Leeuwin Current may reduce the predation rates upon eggs and larvae by dispersing them away from inshore beaches where schooling fish feed and where high rates of cannibalism by the adults on their back-run from the spawning grounds can occur. The dispersal of dense egg patches may decrease the vulnerability of the eggs and larvae because predators could converge on such patches and feed selectively. The groups captured may have been formed as a consequence of current flow, rather than an active choice to school, as schooling would present greater rates of intraspecific competition for food items and possibly cannibalism. Alternatively schooling offers the protection of safety in numbers from predators. Either hypothesis is feasible for the larvae, from a survival view point.

Temperature can have a major impact on activity of the organisms. The warmer the temperature the more active the larvae are and may affect the timing of transition from the inactive yolksac feeding stage to the active feeding stage. Mid-range temperatures (18°C) means the larvae will require less ingested energy on a daily basis than larvae from warmer ecosystems (Houde and Zastrow, 1993) while achieving a balance with assimilation efficiency. The *Arripis* larvae captured were in locations which present the opportunity for maximum food assimilation while minimizing required dietary intake levels. As the Leeuwin Current is nutrient poor it is unlikely it will support high levels of primary production, therefore providing little food for organisms entrained within it. The less food required daily means a greater chance of survival and less risk of starvation for the individual larvae.

SUMMARY AND CONCLUSION

The sampling in 1994 over a 3 week period resulted in very few larvae being captured. This may be explained by the possibility of very few larvae being transported across the Great Australian Bight, due to that year being an El-Niño year, where recruitment of *Arripis truttaceus* larvae into nursery grounds in South Australia was severely reduced. Other possible reasons for the low capture rate are net avoidance or larvae were being swept out of the path of the oncoming net by the pressure bow wave. The larvae captured may also be the weakest and latest larvae from the spawning, and consequently could not swim fast enough to avoid the net.

Arripis truttaceus larvae appear to have been spawned in one continuous episode and the majority of the specimens were entrained within, or on the edges of, the Leeuwin Current. The temperature ranges larvae were located at ranged from 16.74-18.21 °C, the salinities 35.6-36.21 ppt. The ages of these larvae, and those captured in the nursery grounds of Barker and Angas Inlets, Adelaide, indicate spawning occurred from March through June arriving in Barker and Angas Inlets in mid- to late October at the latest.

The average growth history of *Arripis truttaceus*, as recorded within the otolith microstructure, is one of slow growth for 1-3 weeks after first increment formation, followed by increased growth rates, which are usually sustained until either approaching or entering the nursery grounds where growth rates decrease and increments are densly packed. This generalized view is subject to individual variation with some individuals showing sustained slow growth throughout the migration, sustained high growth rates throughout and many growth histories exhibiting peaks and troughs throughout.

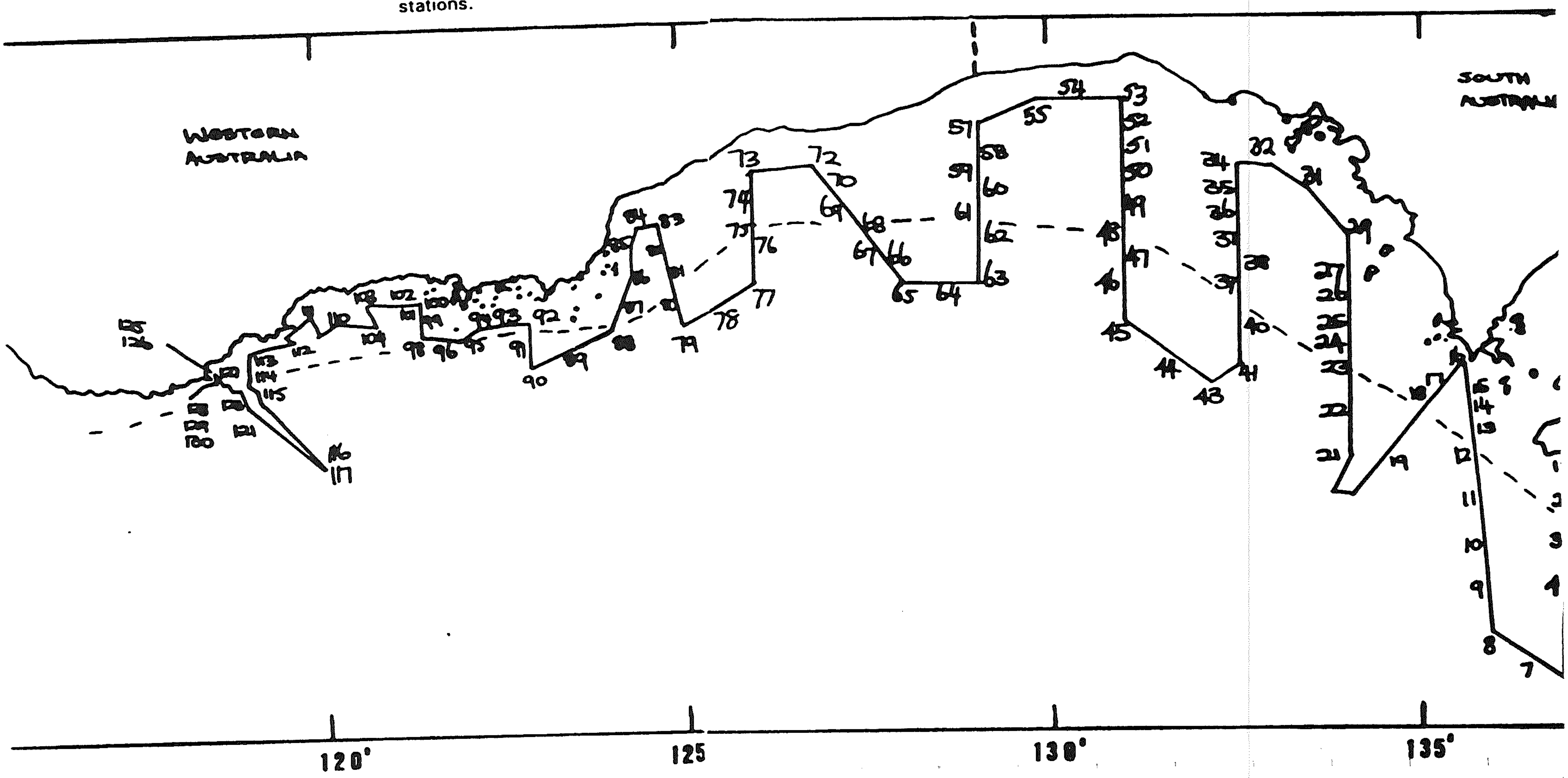
Of the two otolith pairs used in this research, the lapilli and sagittae, the sagittal increments gave a more accurate age count, in days, than the lapilli, which underestimated ages in fish over approximately 15mm and 60 days. The sagittae required more preparation, in order to expose their internal structure so an age estimate could be made, than the lapilli, this added effort being a trade off for a more accurate count.

An understanding of the causes of larval mortality and recruitment demands thorough understanding early life history traits. Much more knowledge is yet to be gleaned from larval surveys, particularly for poorly understood, yet economically important fish species such as *Arripis truttaceus*. Effective management strategies are based on this knowledge.

APPENDICES

APPENDIX 1.

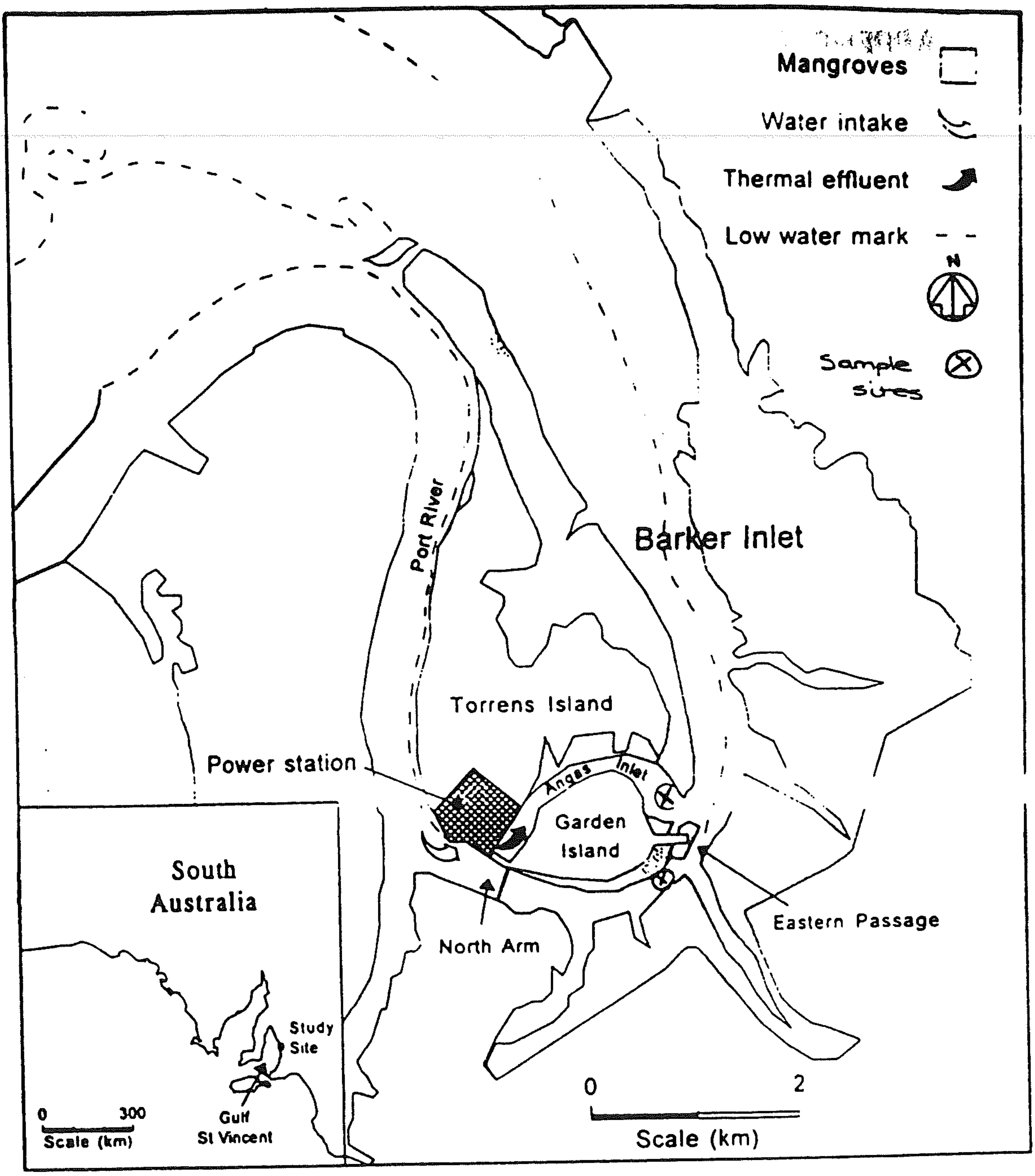
Cruise plan for July 1994 aboard the "O.R.V. Franklin", showing stations.



APPENDIX 2. **Station dates and co-ordinates where Australian Salmon were found.**

STATION NUMBER	DATE (JULY 1994)	LATITUDE (°S)	LONGITUDE (°E)
26	12TH	34.1500	134.0000
38	13TH	33.4518	132.3013
55	15TH	32.007	129.4578
76	18TH	33.2943	126.0035
81	18TH	33.5354	124.4996
88	19TH	34.3122	124.0047
89	19TH	34.4297	123.2769
91	20TH	34.3820	122.5698
93	20TH	34.2400	122.4000
95	20TH	34.3130	122.0998
96	20TH	34.3602	122.0134
99	20TH	34.1795	121.3112
101	21ST	34.0997	121.1434
127	23RD	34.5959	118.2201

APPENDIX 3 Map of Barker Inlet and Angas Inlet sampling sites.



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