A FINAL REPORT TO THE FISHING INDUSTRY RESEARCH COMMITTEE ON THE RECRUITMENT INTO COMMERCIAL STOCKS OF THE SAUCER SCALLOP *Amusium japonicum balloti*

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This final report presents results of a research program into the scallop *Amusium japonicum balloti* in Queensland. The program was funded jointly by a grant from the Fishing Industry Research Trust Account and the Queensland government. Opinions expressed in the report do not necessarily represent government policy. Major sections of the results of the program are being prepared for separate publication. These when published will be forwarded to the Fishing Industry Research Committee.

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Abstract

The scallop *Amusium japonicum balloti* (Bernardi) is fished commercially along the central Queensland coast. Annual landings over past years varied tenfold creating severe problems in supply for fishermen, processors and the wholesale/retail market outlets. Scallop catch fluctuations appear to be caused by variable annual settlement and the patchy distribution of scallop larvae. Environmental factors such as wind, current, water temperatures and winter rainfall play an important role in determining the next years scallop catches. These factors can be directly linked to spawning periods and scallop larval dispersal.

QUEENSLAND SAUCER SCALLOP

FINAL REPORT

1.0 General Introduction: "The Fishery"

A commercial trawling fishery of the scallop *Amusium japonicum balloti* (Bernardi), hereinafter to be referred to as *A. balloti*, exists along the central Queensland coast from approximately Port Clinton at latitude 22°30'S and longitude 150°50'E to just south of Double Island Point at latitude 26°S and longitude 153°10'E.

Historically, catch area records are not clear but the fishery in the early 1950's operated in three distinct regions. The first area includes offshore of Tin Can Bay and within 6km offshore along the length of Fraser Island. The second covers Hervey Bay mainly close to the coast south and east of Bundaberg. The third is offshore of Yeppoon from Cape Manifold to Cape Capricorn. Detailed data on scallop landings, between 1968 and 1980 are, however, available (Matilda and Hill 1981). Within this period, scallop whole weight landings varied tenfold from 4,000 tonnes in 1972/73 to 400 tonnes in 1976/77.

The trawlable areas have increased since 1976 to include most of the area between latitudes 22°30'S to 26°S within the limits of the 55m contours. Major new areas fished are now offshore of Bustard Heads, Round Hill and Lady Musgrave Island. The expansion in fishing areas occurred primarily because fishermen increased the mesh strength of their scallop nets from 36 to 150 ply. This allowed fishermen to trawl in areas previously considered untrawlable (Dredge 1980). The large catch in 1978 is attributed to the inclusion of the above mentioned new grounds. However, there is still a large fluctuation in landed weight from year to year with the average yearly landings being 2,000 tonnes whole weight

(Dredge pers. comm.).

This following paper considers problems associated with annual fluctuations in scallop stocks with regard to the physical and biological factors affecting larval mortality, dispersal and settling.

2.0 Physical and Chemical Properties of the Area

2.1 Currents

The East Australian Current flows southward and is fed by the south equatorial current and the trade wind drift passing through the Coral Sea. Water from the Arafura Sea flows south to Fraser Island bringing warm tropical water down the coast between January and March (Wyrtki 1962). However, warm waters from the Coral Sea continue their southward flow until June. Currents south of 22°S set predominantly southward between 156°E and the 600m depth line at a rate of between .4m/s - .8m/s. Inside the 600m depth line currents are variable because of influences of shallow water, river systems, tidal flow and large and small eddy systems. In many areas currents set easterly with a northerly flow close to the coastline. Offshore currents set southwesterly up to .8m/s in March to May, however, in winter months southerly sets are weakest and northerly sets may be experienced when southerly winds are more frequent. Thus a northerly current can dominate seaward forcing inshore water northward in July-September (Rochford 1959, Wyrtki 1962).

Hervey Bay is a semi-enclosed embayment with the runout from the Bay being primarily in the region of Lady Elliot Island and Lady Musgrave Island (Woodhead 1970). To the north of Hervey Bay currents in the Capricorn channel move in a northerly direction creating eddies offshore. Landforms such as Fraser Island to the south, the Swains Reef system and other island chains to the east including Heron and Lady Musgrave Islands, create barriers enclosing the area.

2.1.1 Sea Drifter Releases

Inshore currents were investigated by releasing 665 current surface drifters at 19 stations between Bundaberg and Cape Capricorn (Plate 1). These drifters were released in groups of 35 over a period of 43 hours on June 24, 25 and 26, 1981. Over a period of six months, 146 drifters (22%) were returned. Of these, 74% were returned within one month (Table 1). Figure 1 shows the landing areas of single or groups of drifters. Twenty-six drifters were found floating at sea with the rest being washed up on beaches. Dates of findings were especially well recorded on the tip of Fraser Island. Lighthouse personnel moved daily along beaches in that vicinity and at times actually observed drifters in the surf as they arrived.

Figure 2 represents the current movements over the period June 26 - September 26, 1981, when 94% of drifters found were returned. Findings at sea as well as on land were especially valuable giving accurate directional drifts. Time of landings within groups showed definite eddy systematics. A definite outflow of the Bay was between Lady Musgrave and Lady Elliot Islands, with entry into the Bay inside the spit off Fraser Island. Drifter returns show currents within Hervey Bay combine to create a large eddy system with smaller eddies forming off Bustard Heads and Round Hill. The predominant direction of flow is south to southeast. However, close along the coast there is a northward current. Woodhead (1970) found similar eddy systems to exist in October-December. However, there is a shift at the northern extremes off Cape Capricorn for currents to move south to southwesterly as the northerly winds

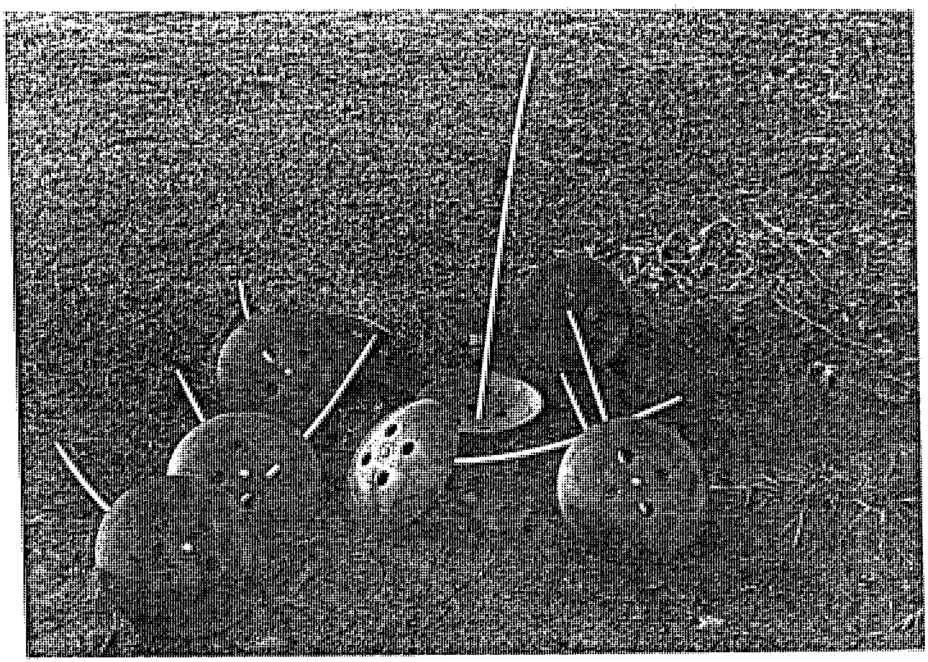


Plate 1. Sea surface drifter for recording regional current directions and speeds.

Table 1. Surface drifter release and return timetable. Six hundred and sixty-five drifters were released on June 26/27, 1981 and after six months 146 or 21.94% were returned.

Time scale 1981	Months at sea	Number of drifters returned	% caught per month	% returned per month of total returned	Cumulative % returned per month of total returned
June 26 -July 26	0-1	108	16.24	73.97	73.97
July 27 -August 26	1-2	19	2.85	13.02	86.99
August 27 -September 26	2-3	10	1.50	6.84	93.83
September 27 -October 26	3-4	4	0.60	2.73	96.56
October 27 -November 26	4-5	4	0.60	2.73	99.29
November 27 -December 26	5-6	1	0.15	0.68	99.97

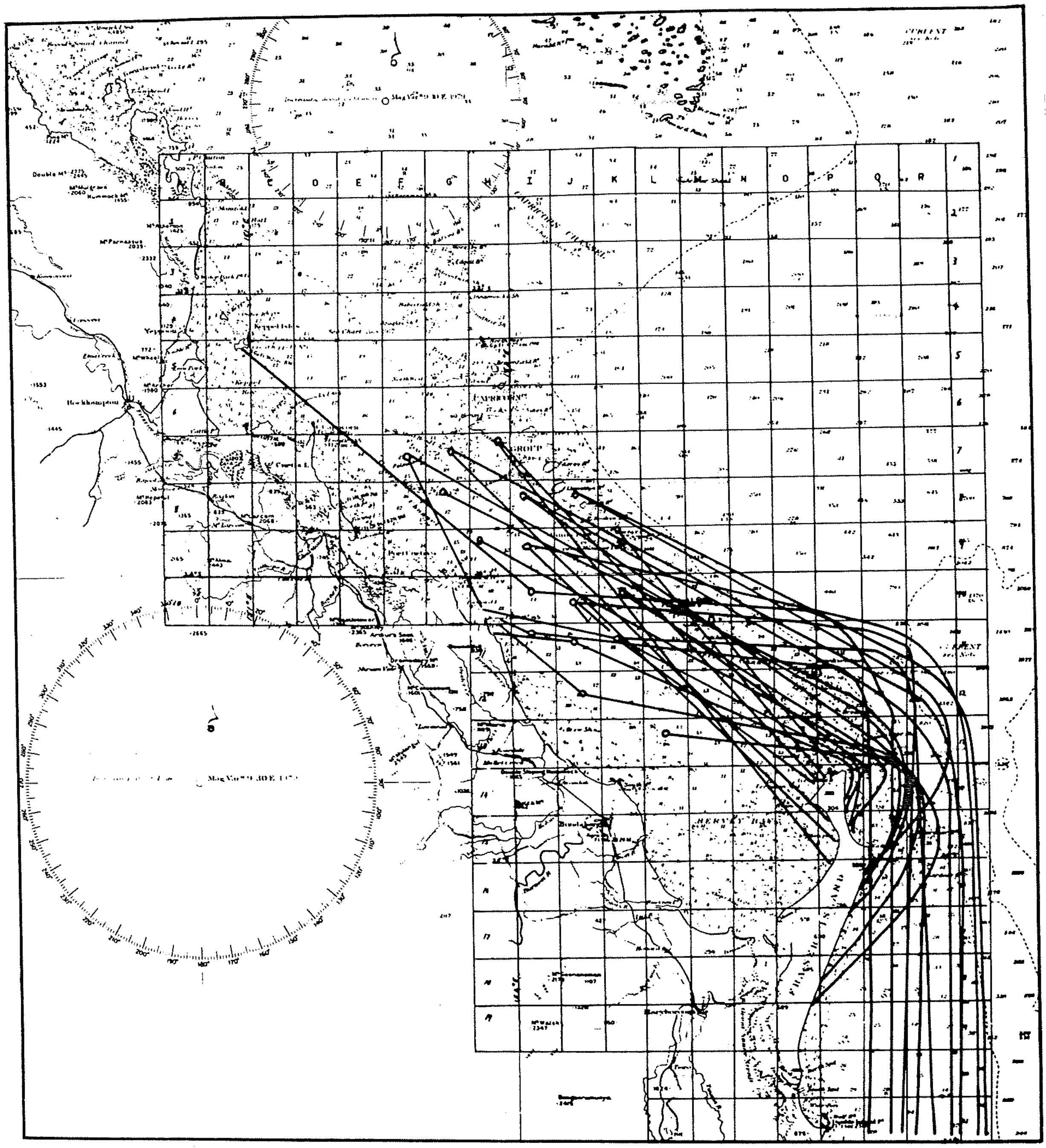


Figure 1. Release stations, possible routes and recovery sites of sea surface drifters.

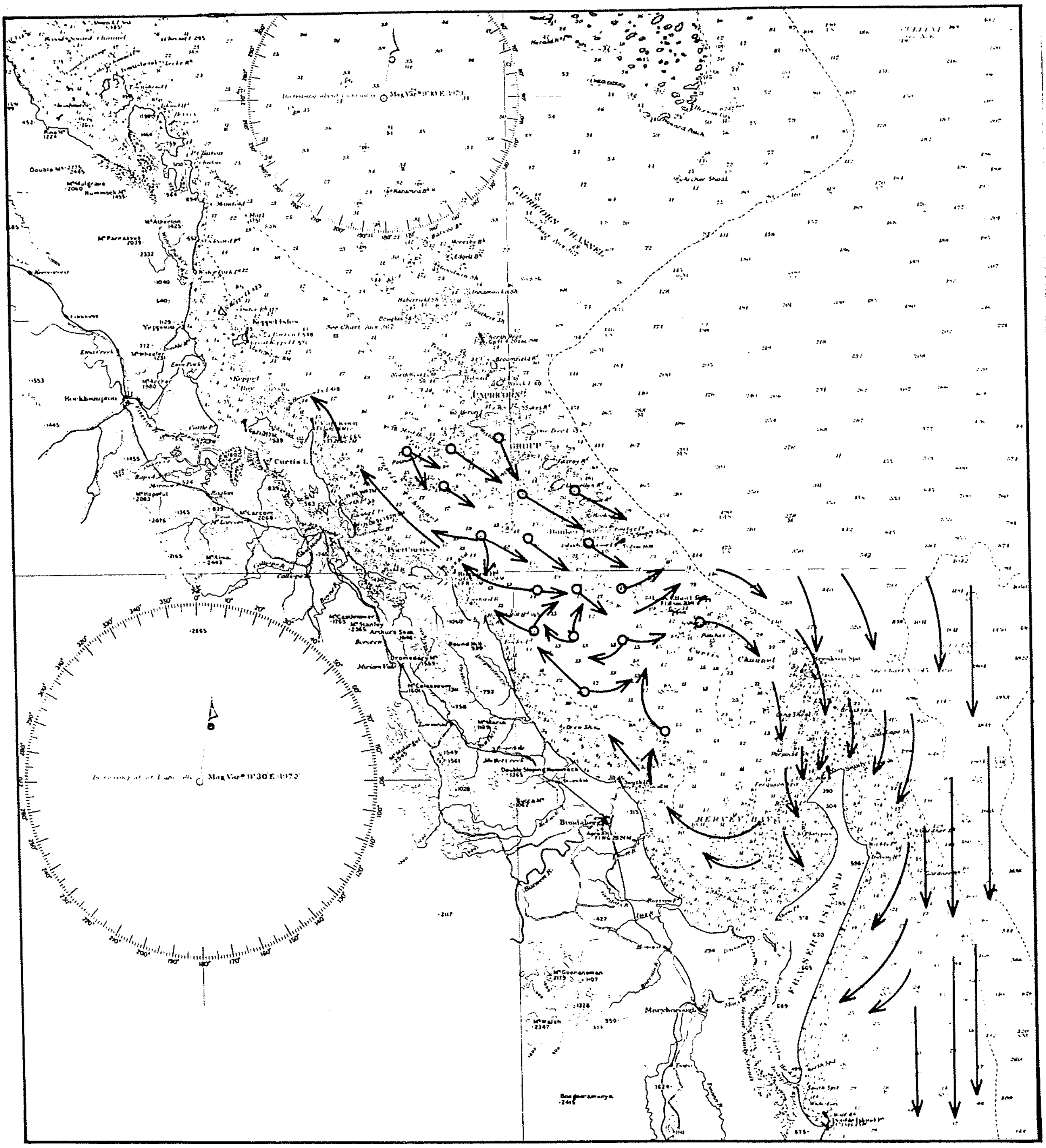


Figure 2. Current systematics of the Hervey Bay-Yeppoon region from June 26 - September 26, 1981.

increase in late spring. The northerly currents running along the coast are thereby diminished. Seasonal variability in current strength is an inherent component of the East Australian Current and during June to August southerly currents are weakest. In that period, northerly currents reach their greatest strength and slowly increase in frequency. This is due to the prevalence of southeasterly and southerly winds at this time (Department of Transport, Marine Information Manual Australia, 1976).

Currents within the Barrier Reef are produced by the prevailing winds, which are mainly seasonal, and currents set roughly in the direction of these prevailing winds fairly through the various channels (Department of Transport, Marine Information Manual Australia, 1976). Evidence from the present drifter series release indicates that current sets close to the coast are wind induced to some extent. However, Woodhead (1970) concluded that prevailing winds did not have a predominant effect on drifter movement offshore, and considered currents were the dominant force.

2.2 Tides and Tidal Streams

On the east coast the offshore current is the predominating factor in movement of water. Generally, tidal streams set through the openings in the Great Barrier Reef in a westward or southwestward direction on the rising tide and on an eastward or northeastward direction on a falling tide. In wide openings tidal streams are slight but when restricted to narrow openings rates of between 2 and 3 knots are experienced if the moon has a high declination at springs (Department of Transport, Marine Information Manual Australia, 1976).

Streams are appreciably increased nearer the inner edge of the Great Barrier Reef. Directions also change so that the streams tend to set towards the nearest large openings in the reefs on the falling tide and away from them on the rising tide.

From April to November tidal streams generally set continuously in a northerly direction, except in channels, within the reef at a rate of 1 to 1.5 knots in the Bundaberg to Yeppoon region. Tidal streams however are generally weaker than currents and the total set experienced is the result of the combined effects of wind driven current and the tidal stream. Thus the northerly set during the season April to November coincides with the southeast trade winds.

Close inshore where currents are weakest and winds variable the general water movement is northerly. However, eddies occur and further from shore currents are more effective; the general flow of water is southward to southeasterly.

Tidal ranges in the Hervey Bay to Bundaberg region are up to 3m whereas to the north at Yeppoon they reach a maximum of 4.5m.

2.3 Winds

Winds along the central to southern Queensland coast predominantly flow from the southeast from January to July and August (Department of Transport, Marine Information Manual Australia, 1976). Wind strength data indicates southerly winds tend to be somewhat stronger than northerly winds (Heatwole *et al* 1981). Wind direction, frequency and force obtained from the Bureau of Meteorology was collated for Sandy Cape, Lady Elliot Island, Bustard Heads and Cape Capricorn (Figures 3 and 4). The predominant wind direction and frequency pattern at Cape Capricorn, Bustard Heads and Lady Elliot Island, is quite different from that at Sandy Cape. Here southwesterly winds prevail because of land falls. Winds do decrease in intensity in all regions in August-November. This period is dominated

Figures 3 & 4. Wind vanes indicating wind direction, speed and frequency in the regions (Figure 3) (a) Sandy Cape, (b) Lady Elliot Island, (Figure 4) (c) Bustard Heads, (d) Cape Capricorn.

Explanation of Figures

1. Direction of the wind is towards the centre.

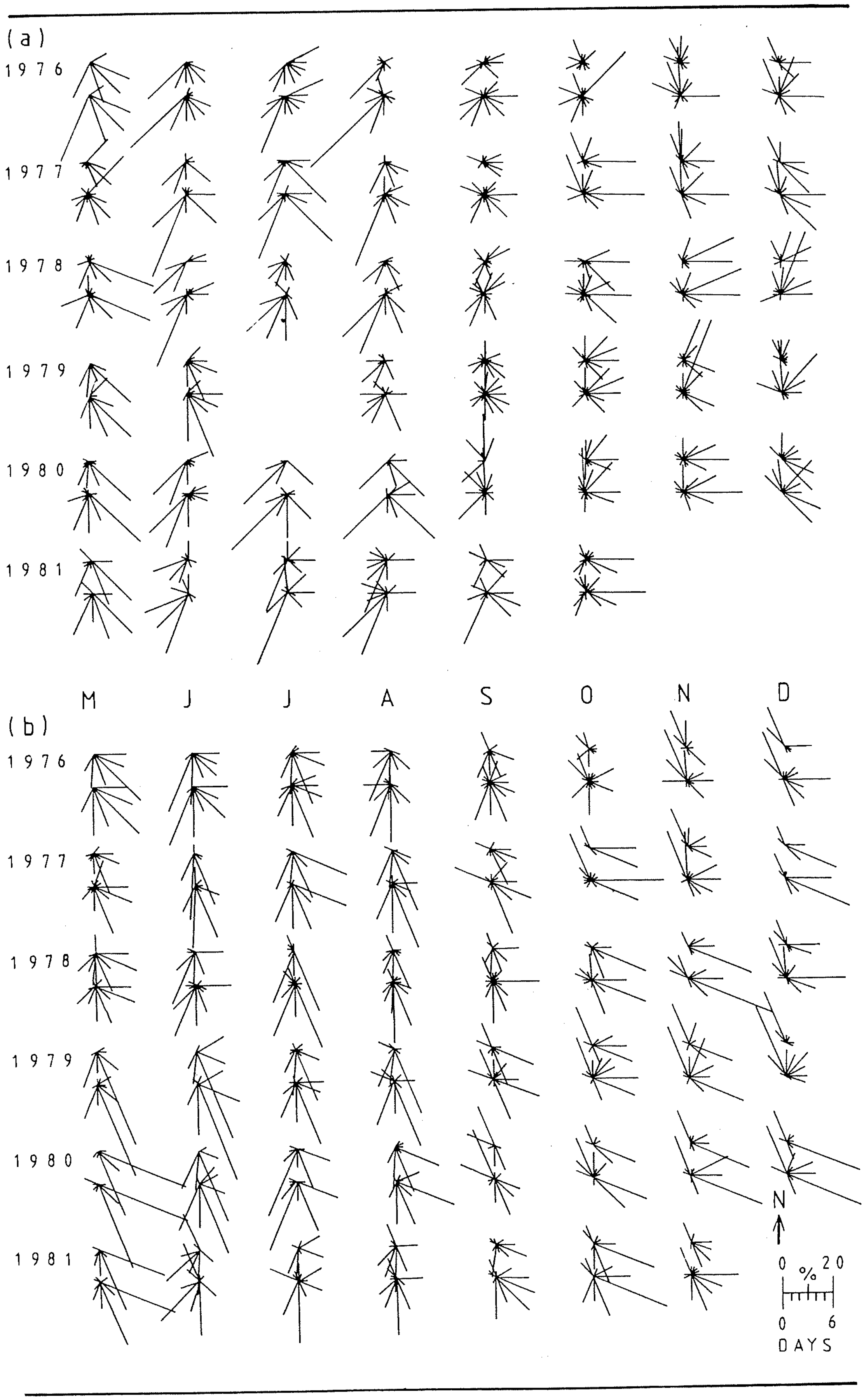
2. Frequency of wind direction is proportional to the length of the line - 0.9cm = 6 days or 20% of a 30 day month.

3. Wind speed (force) -

   Top figure of each set 10 knots

   Bottom figure of each set 0+ knots

   (conversion factor utilised: 1 knot = 0.51m/s)


(a)
1976
1977
1978
1979
1980
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M
J
J
A
S
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(b)
1976
1977
1978
1979
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N
0
%
20
0
6
DAYS

Figure 3

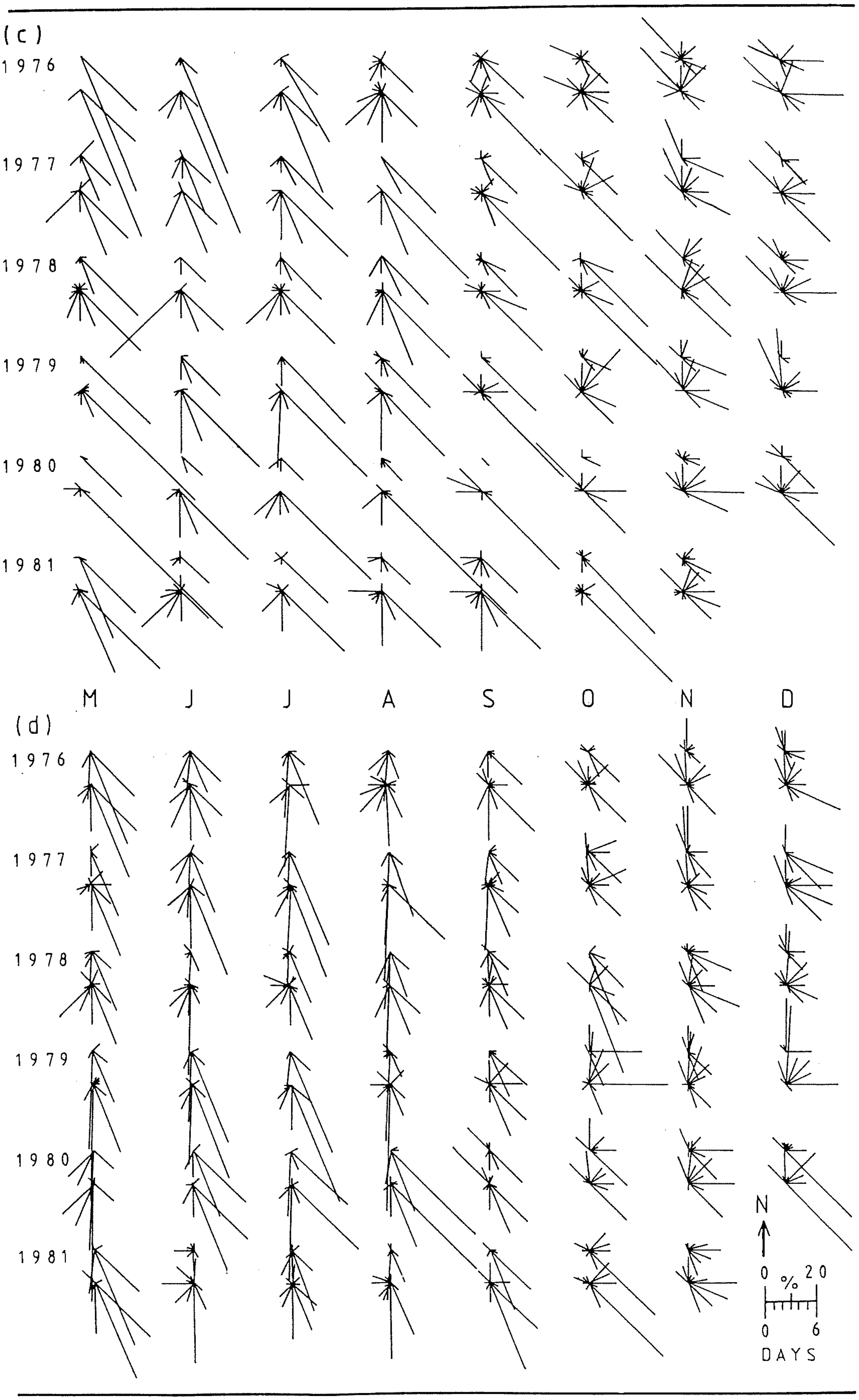
(c)
1976
1977
1978
1979
1980
1981
M J J A S O N D
(d)
1976
1977
1978
1979
1980
1981
N
0 % 20
0 6
DAYS

Figure 4

by variable winds with a change to northerly winds. This variability creates a degree of horizontal dispersion throughout the region. Since inshore currents are influenced by wind direction this would account for the wide distribution of drifters. Winds however are shown to be very localised (Figures 3 and 4). Thus there is a much greater dispersal of drifters than first indicated when analysing general wind patterns.

2.4 Rainfall

Centres within the region surveyed have marked differences in monthly rainfall (Figure 5). Differences in rainfall also occur within months from year to year, between and within different centres. Yeppoon has the highest mean rainfall (1357mm) over 100 years and Cape Capricorn the lowest (803mm). The mean yearly rainfall in Bundaberg is 1159mm and in Bustard Heads 1172mm. Rainfall across the study region predominantly occurs in summer, December-March, with Bundaberg and Bustard Heads recording means for that period of 678 and 674mm respectively. Winter rainfall is much less with Bundaberg recording a mean of 54mm for July over 100 years (Bureau of Meteorology). However, there is a wide variation in winter rainfall from year to year. Records for July rainfall in Bundaberg vary from 26mm to 82mm over the period 1960-1978.

Monthly rainfall variation was compared to whole weight landings over a period of years. Rainfall was not significantly correlated with whole weight scallop landings except for August of the previous year (Figure 6). For August of the previous year a correlation coefficient of -0.6378 was obtained with a 0.019 level of significance. August mean rainfall varied between 5 and 77mm from Bustard Heads to Bundaberg over the 13 year period, 1967-1979.

It is significant that, within months, the total rainfall may occur

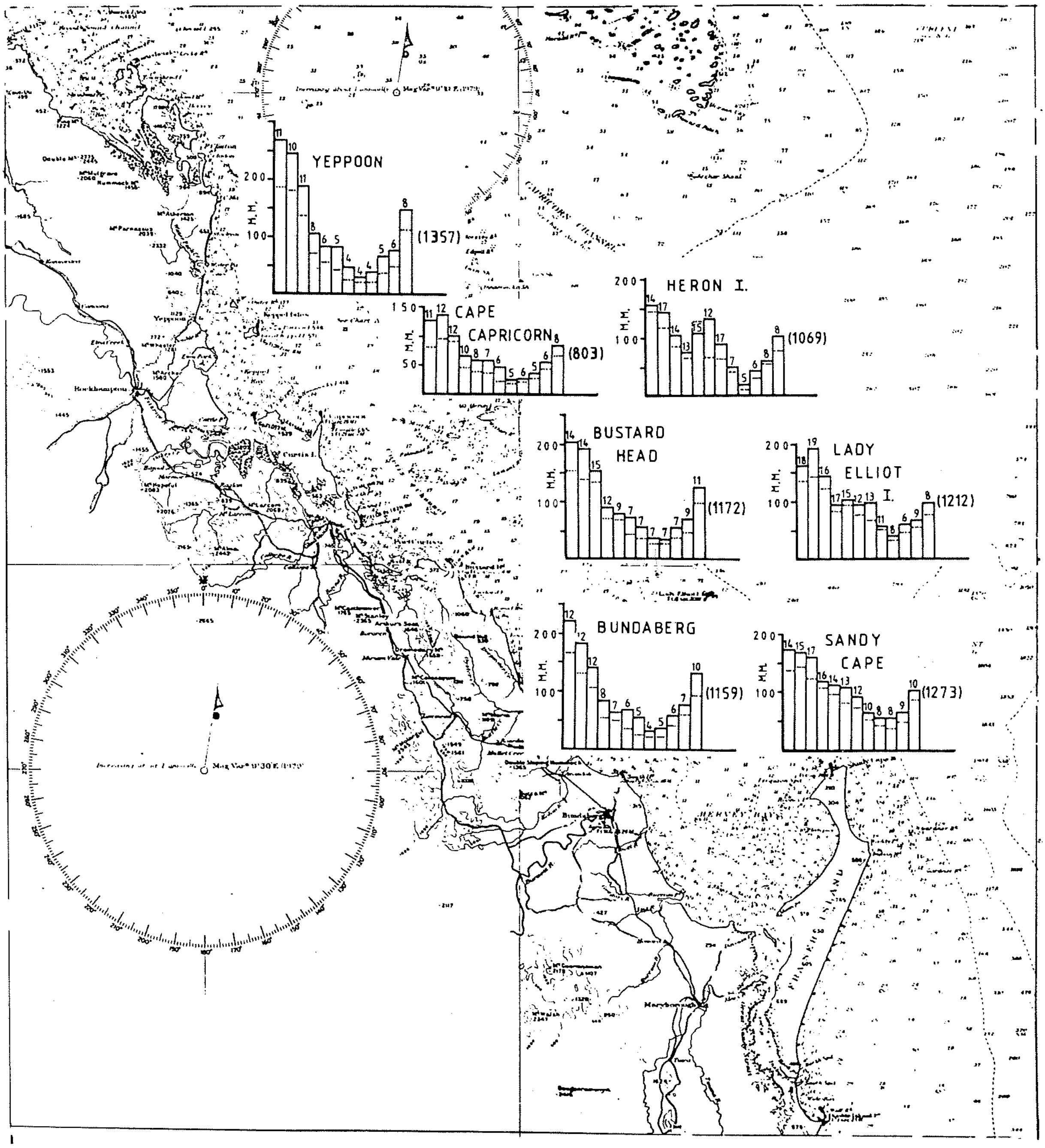

Figure 5. Monthly rainfall figures for the region, 1981 (mm). (---) = median over 100 years; (——) = average yearly rainfall over 100 years. No. = mean no. days rainfall over 100 years.

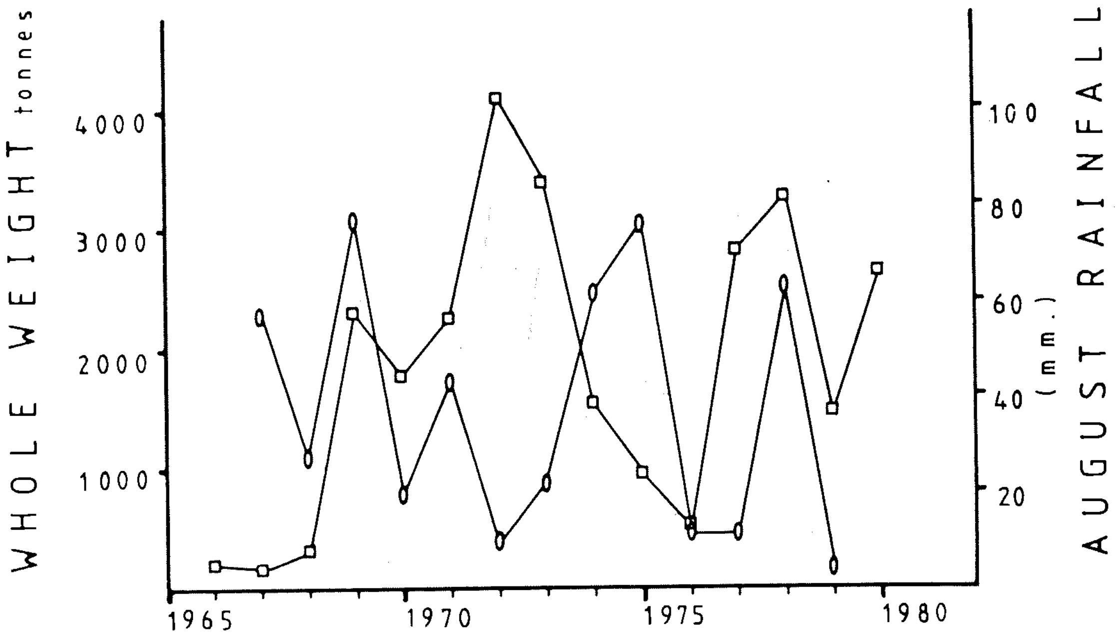

Figure 6. Whole weight landings vs August rainfall over a 13 year period. ▢ = scallop landings (tonnes); O = August rainfall (mm).

over a period of 3-12 days. This indicates that there is an even greater difference between yearly rainfall figures for that month than first shown. On July 10, 1978, Bustard Heads recorded 94.2mm of rainfall, however the mean for the month was only 61mm. The August mean over 70 years for Bustard Heads is 38mm with a median of 27mm rainfall. The mean of recorded days of rainfall over 70 years is 7 for August. Thus mean monthly rainfall figures must be regarded with some caution. Daily figures should be examined before drawing any conclusions as to the effect of rainfall on the scallop population.

August is a major spawning period (Figures 7a, b, c). It is thus noteworthy that a correlation exists between scallop landings and the previous year's rainfall in August. When August mean rainfall is below 20mm there is a definite increase in landings in the next year (Figure 6). In 1972, 1976, 1977 and 1979 the mean rainfall in August was below 20mm and scallop landings consistently averaged around 3,000 tonnes (Figure 6). In years of rainfall above 50mm, 1969, 1974, 1975, 1978, scallop landings were below 2,000 tonnes. When high rainfall was experienced two years running in 1974 and 1975 landings were below 1,000 tonnes (Figure 6).

2.5 Seawater

2.5.1 Water depth

The average seawater depth of the scallop fishing area under study is between 27m and 40m with patches and channels up to 55m. Inshore areas are as shallow as 10m. The majority of the area is gently sloping, increasing in depth from the shore to 40m towards the outer edges of the reefs where depths subsequently drop off the shelf.

Figure 7

(a) Temperature recordings, mean gonad weights and % mature females (see Section 4.3) from Bustard Heads in the period August 1978 - July 1980.

(b) Temperature recordings, gonad weights and % mature females from Bagara over the period November 1977 - November 1978.

(c) Temperature recordings and % mature females from 15km offshore of Burnett Heads over the period July 1980 - November 1981.

⊢⊣ = possible spawning periods

◇ = gonad weight (g)

□ = temperature (°C)

○ = % mature females in female population

Gonad weights and some temperature data is reproduced with permission of M. Dredge (1981).

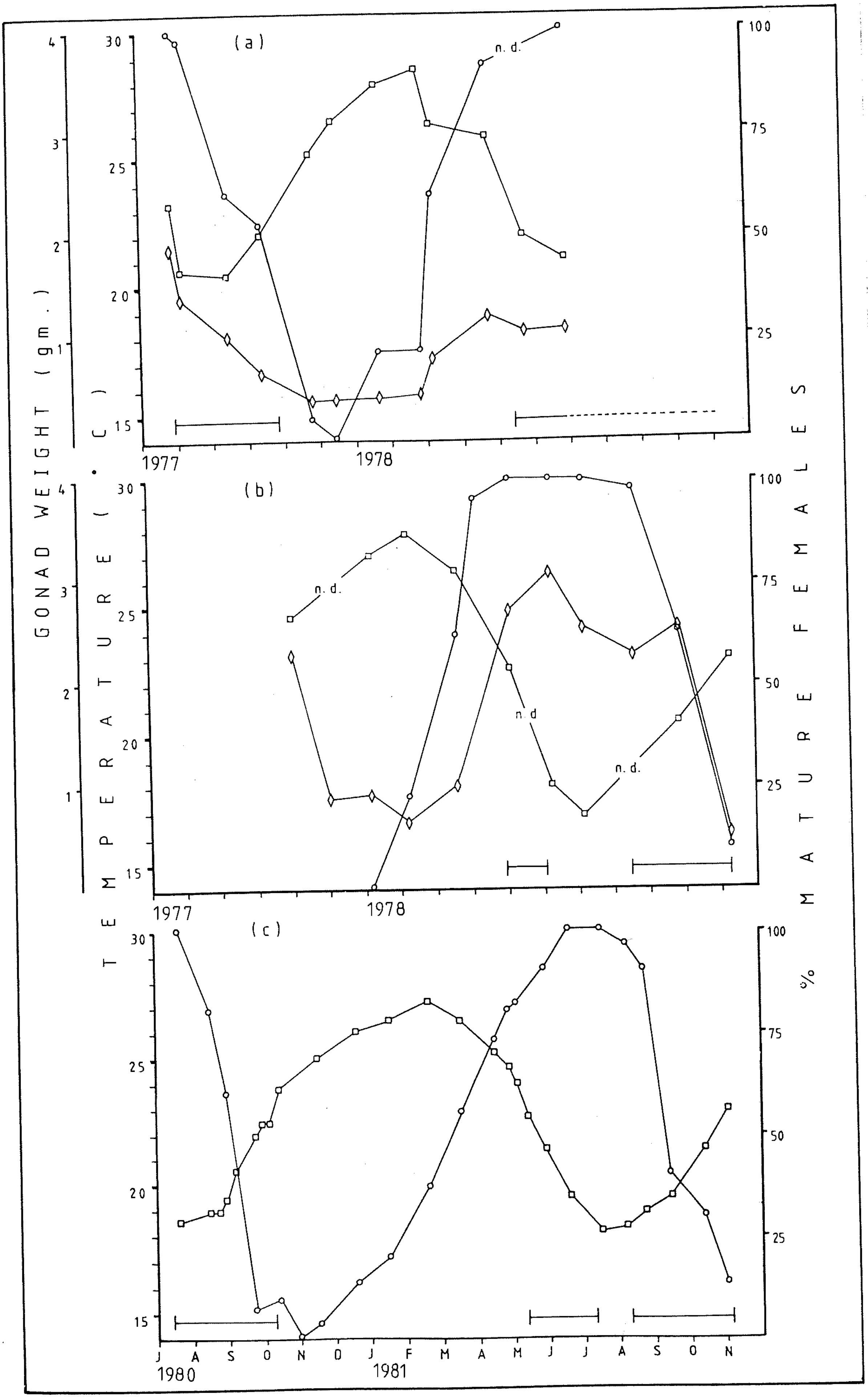
GONAD WEIGHT (gm.)
TEMPERATURE (°C)
% MATURE FEMALES
(a)
(b)
(c)
n. d.
1977
1978
1980
1981
J A S O N D J F M A M J J A S O N

Figure 7

2.5.2 Temperature

Seawater temperatures in the area range from 28°C in summer to 17°C in winter with temperatures generally rising in late July to August and falling in late February to March (Figure 7). The maximum difference between the surface and bottom temperature was 2°C throughout the year.

2.5.3 Salinity

Salinity recordings (Table 2) show total mixing of bottom and surface waters up to 25km offshore of Bundaberg from July 1980 to November 1981, in depths of 20m. Dredge (1981) found similar mixing of surface and bottom waters between July 1977 and June 1978 up to 15km offshore of Bustard Heads and up to 2km offshore of Bagara, near Bundaberg. The lowest salinity recordings in this study were in 1981 in January, February and March, i.e. 32, 30 and 31$^{o}/_{oo}$ respectively. This was to be expected with the onset of normal Queensland summer rains. However, winter rains in the August-October period of 1982 did produce a drop in surface salinity to 33$^{o}/_{oo}$.

2.6 Substrates

Sampling of substrates was undertaken from Bundaberg to Heron Island, over an area of approximately 10,500 sq. km. Samples were taken within 18.52km^2 grids. Three samples were taken within each grid to ascertain the variation of substrates within each grid. All samples were sieved mechanically through a series of 6 sieves of sizes 4, 2, 1, 0.5, 0.125 and 0.063mm. All seven samples from each sieving were weighed. Methods

Table 2. Mean surface-bottom salinity recordings (°/∘∘) taken 20-25km offshore of Bundaberg at a depth of 20m.

1980

J	F	M	A	M	J	J	A	S	O	N	D
						35.6	35.9	35.6	35.4	32.0	-
						(2)	(3)	(3)	(3)	(2)	

1981

J	F	M	A	M	J	J	A	S	O	N	D
30.0	31.0	35.5	36.0	35.6	35.5	34.5	32.9	33.0	32.6	33.5	-
(1)	(2)	(1)	(2)	(1)	(2)	(3)	(3)	(3)	(2)	(1)	

n = number of recordings taken per month; figure = mean; mean variation of samples = ±0.4°/∘∘

Not clear whether
(i) sample depth is 20m. or
(ii) bottom depth is 20m.
What range in S‰ from surface to bottom.
What is meant by surface - bottom salinity?
and how can single figure indicate
total mixing of bottom and surface waters.
Surely with planktonic larvae and
demersal adult stages surface and
bottom S‰ measurement would be
preferable!
Why no December measurements?

of analysis of samples were adopted from Morgans (1956). A cumulative % by weight of each sieve sample was calculated and a Phi (ø) scale utilised for analysis (Morgans 1956). The medium (Mdø) corresponding to the 50% value on the y-axis is read in ø terms and translated into microns. These are shown for each area sampled in Figure 8.

Analysis of samples shows the majority of the region between Hervey Bay and Heron Island is sand with a mixture of fine shell grit. In the near vicinity of coral islands grain size increases greatly while along the shoreline there is a decrease in grain size. In the case of near-shore areas the smaller particle size of substrates is attributed to river outflows and shallow water turbulence effects.

The question arose as to whether commercial scallop catches were associated with a particular substrate type. Thus scallop catch data, collected by Dredge (unpublished data), over a four year period, 1977-1980, was compiled and compared to substrate records. Major commercial scallop catches are consistently taken in the Bustard Head region at grids 8G, 9G and 9H, and 10H and 10I (Figure 8). This encompasses substrates between 200 and 500μ particle size. However some commercial scallop catches were recorded throughout the region on substrates between 150 and 1100μ grain size. Cursory examination of substrates outside the sampled region revealed widespread areas with substrates within this range. In the areas 15L and 15M (Figure 8) major commercial catches were taken in 1978, but not since. Thus, given favourable climatic conditions (i.e. wind, currents, rainfall) these areas of suitable substrate type may provide additional grounds in some years.

Scallops were found, though not in commercial quantities, on an even wider range of substrates. Settlement was found just off Bundaberg on 125μ grain size substrates, however 100% mortality was recorded within the first year of settlement. This area changes annually with

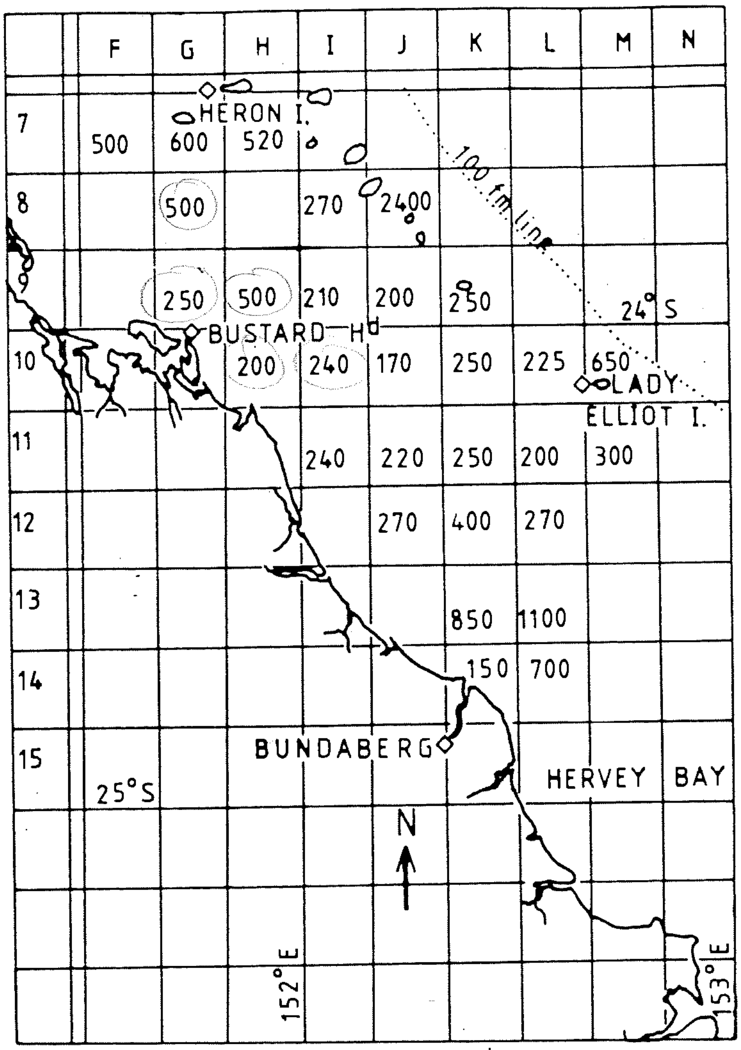

Figure 8. Numbers within grids = Cumulative 50% point of grain size (microns)

Substrate sample type	Grain size (μ)
Coral and shell fragments	4000
shell and fragments	2000
coarse shell grit	1000
fine shell grit and coarse sand	500
sand	250
fine sand	125
silt	63

river run-off and it is not known if high mortality is caused by periods of low salinity or by fine silt reducing the feeding efficiency of scallops. Scallops were recorded within all grids surveyed in varying numbers on substrates between 125 and 1200μ grain size.

3.0 Handling Methods

3.1 Capture and Handling of Adult Scallops for Laboratory Studies

Scallops required for laboratory studies were caught with otter trawl nets and placed into holding bins on board ship. No more than 20 scallops were held per bin (600 x 350 x 250mm) in 25 litres of seawater. Seawater was changed at least every two hours and bins were kept in the shade. Scallops were transferred into 2,000 litre tanks supplied with running seawater upon arrival at the laboratory. Using these methods the maximum mortality incurred was 7%. Over 70% of collecting trips incurred mortalities under 3%.

3.1.1 Handling Problems with Spawning Adults

Premature spawning was initially a problem on board ship when capturing male and female scallops with mature gonads. It was found that premature spawning, depending upon the maturation level of gonads, could occur within 20 minutes of a 1°C temperature increase. Temperature rise also had to be avoided since one spawning scallop in a bin caused multiple spawning to occur. Therefore, adults had to be placed in a seawater medium 2-5°C below ambient bottom water temperature but not below lethal levels of 14°C. Sperm in the water was also found to induce females to spawn. Thus, male and female scallops were kept in separate containers. Sexes were easily distinguished in ripe adults by the colour of the gonads, pink to red in females, creamy white to beige in males. Males were found to be more sensitive to temperature increases and usually spawned first. Therefore males were used as an indicator of adequate cooling. Similarly, care had to be taken to ensure water temperatures in laboratory holding tanks were not above ambient bottom seawater temperatures. Different sexes of scallop with mature gonads, when brought into the laboratory for reproductive studies were also always held separately.

3.1.2 Laboratory Holding Conditions

Scallops were held in external circular fibreglass holding tanks of 2,000 litre seawater capacity, with an internal diameter of 2.52m, a bottom area of $5m^2$, and a depth of 0.5m. Tanks had continuous forced aeration via five 15cm long airstones distributed evenly around the tank. Non-filtered seawater, 35 ± 2°/₀₀, was pumped directly into the holding tanks. To reduce light levels and high summer temperatures, tanks were protected by a pergola covered with 80% shadecloth. Heavy duty, clear plastic sheeting over tanks eliminated seawater dilution by rainwater. Maintenance was minimal, requiring only the feeding of scallops with the algae, *Platymonas (Tetraselemis) suecia*, three times weekly at the rate of 20 litres per tank, with an algal density of $6 \times 10^5 \pm 2 \times 10^5$/ml per feed, and weekly siphoning off of bottom debris from holding tanks (Plate 2). Water temperatures were dependent upon the time of year and ranged from 16-26°C. Daily fluctuations were ± 1°C.

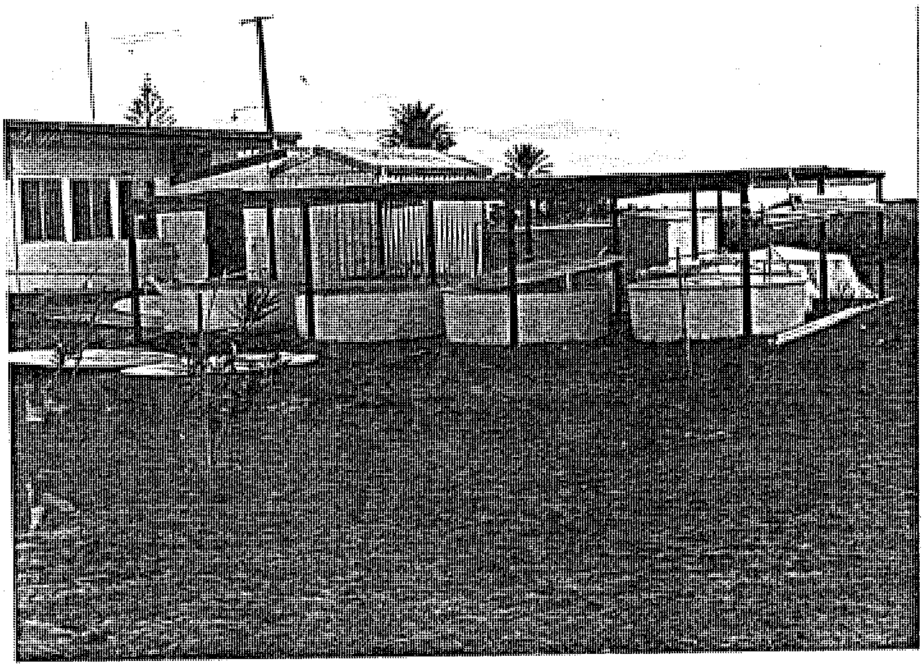

Plate 2. Scallop laboratory and outdoor scallop holding area.

4.0 Biological Nature of *A. balloti*

4.1 Density and Maturation in the Laboratory

Adult scallops were brought into the laboratory and held at different densities, to investigate the effect of density on gonad maturation, growth and survival over a period of four months. Scallops were held at densities of 5, 10, 20 and 30 per m^2 in $2.5m^3$ of seawater. Table 3 shows appreciable mortalities occurred at densities above 10 per m^2. At densities of 5 per m^2 survival over four months was 92%.

Growth of scallops from May to August was less than 10mm shell height at all experimental densities (Table 3). At the beginning of the density experiments in May temperatures were 16.5°C and these increased to 21°C by the end of August. Thus growth of scallops is minimal during winter months and is not affected by density.

Maturation of gonads occurred at all densities. The percent maturation varied between 100% at densities of 5 per m^2 to 68% at densities of 30 per m^2 (Table 3). This complements previous work by Dredge (1981) which showed scallops increase gonad weight over the winter period (Figure 7a, b). Thus food consumed was being utilised for gonad maturation instead of shell growth during the winter period.

4.1.1 Adult Scallop Field Density Studies

Measurement of field densities of scallops by trawling is suspect. Trawling trials were conducted over an identified commercial ground off Bundaberg in July 1981 over a distance of 2,672 metres at 1.02m/s using a net with a swathe width of 26.66m. Trials showed a maximum natural scallop bed mean density of 1.01 scallops per m^2. However, scallop

Table 3. Maximum holding density determinations for adult scallops in outdoor tanks, over a 3-4 month period (May-August).

No. trials	No/trial	Density/m²	% Survival	* Shell growth (mm)	% Maturation
3	25	5	92	<10	100
3	50	10	83.4	<10	73
3	100	20	65.2	<10	73
** 3	150	30	14.5	<10	68

* Growth rates were not significantly different at all densities and were <10mm over a three month period.

** Length of trial was 1 month.

trawl catches and diving observations show scallops occur in patches. Dredge (pers. comm.) found that the ratio of variance to the mean per trawl shot was 89.1 (n = 42) suggesting contagious distributions. Diving observations, taken while riding trawl nets, showed that scallops, to some extent, can avoid capture by swimming out of the path of the net. Observations indicate that trawling gives an underestimate of the density of scallops on trawling grounds.

4.2 Juvenile Growth and Maturity

Juveniles are defined here as animals lacking gonad development. Growth of *A. balloti* using the Von Bertalanffy curve, ($Lt = L\infty\ [1-e^{-k(t-t_0)}\ Pt]$; where $L\infty$ = 105, k = 0.050, t_0 = 0 and Pt = time at liberty), shows scallops attain a size of 90+mm in the first year (Williams and Dredge 1981). Evidence of gonad development was found in 18% of scallops between 60-69mm shell height and in 52% of scallops between 70-79mm shell height (Dredge 1981). No evidence of gonad maturation was found in scallops less than 60mm shell height in this study. Thus it is considered reasonable to consider animals below 60mm shell height as juveniles.

There is little published information on rate of growth of scallops below 60mm shell height. Animals less than 60mm shell height were held for up to three months from September to December. The maximum growth recorded was 6mm during that period. It is considered that inadequate types of food were available to sustain growth.

Field samples taken in 1981 showed a mean growth rate for scallops 40-70mm shell height of 12-18mm per month from September to December. However, trawl gear net size is thought to have a bias towards catching larger shell thus extrapolation of juvenile growth rates from trawl catch data must be viewed with caution.

Presence/absence samples of scallops less than 60mm shell height showed that the length of juvenile life is less than 3 months (Figure 9). Juvenile populations were only found from August to October (Figure 9). In 1978 Dredge (1981) did not record the presence of juveniles until November. The effects of temperature on gonad maturation (see Section 4.3, Monitoring Gonad Development) could account for the variation in time of occurrence of juveniles from year to year. In June 1981, out of a total catch of 1421 scallops, 5 scallops of less than 30mm shell height were recorded indicating a possible extension of the spawning season under favourable conditions. These are not shown in Figure 9.

4.2.1 Juvenile Dispersal

Juvenile catches were always interspersed with adults. However up to 70% of a population found over a $2km^2$ area in August 1981, was of less than 30mm shell height (Figure 9). In one short trawl of 0.5km the catch in one net comprised 65 juveniles and two adults. Juveniles were mainly found in patches. This patchiness is indicative of the dispersal mechanism of larvae by the action of current and wind.

4.3 Monitoring Gonad Development

Considerable difficulty was experienced in obtaining mature females which were ready to spawn at certain times of year. Maturation levels were determined by the external appearance of the gonads. Mature female gonads envelop the digestive loop and are turgid and pink to red in colour. Mature male gonads are creamy white, lustrous and turgid (Dredge 1981). Even trained observers can still err in determining maturation levels using this method. However it is the only quick and reliable method for

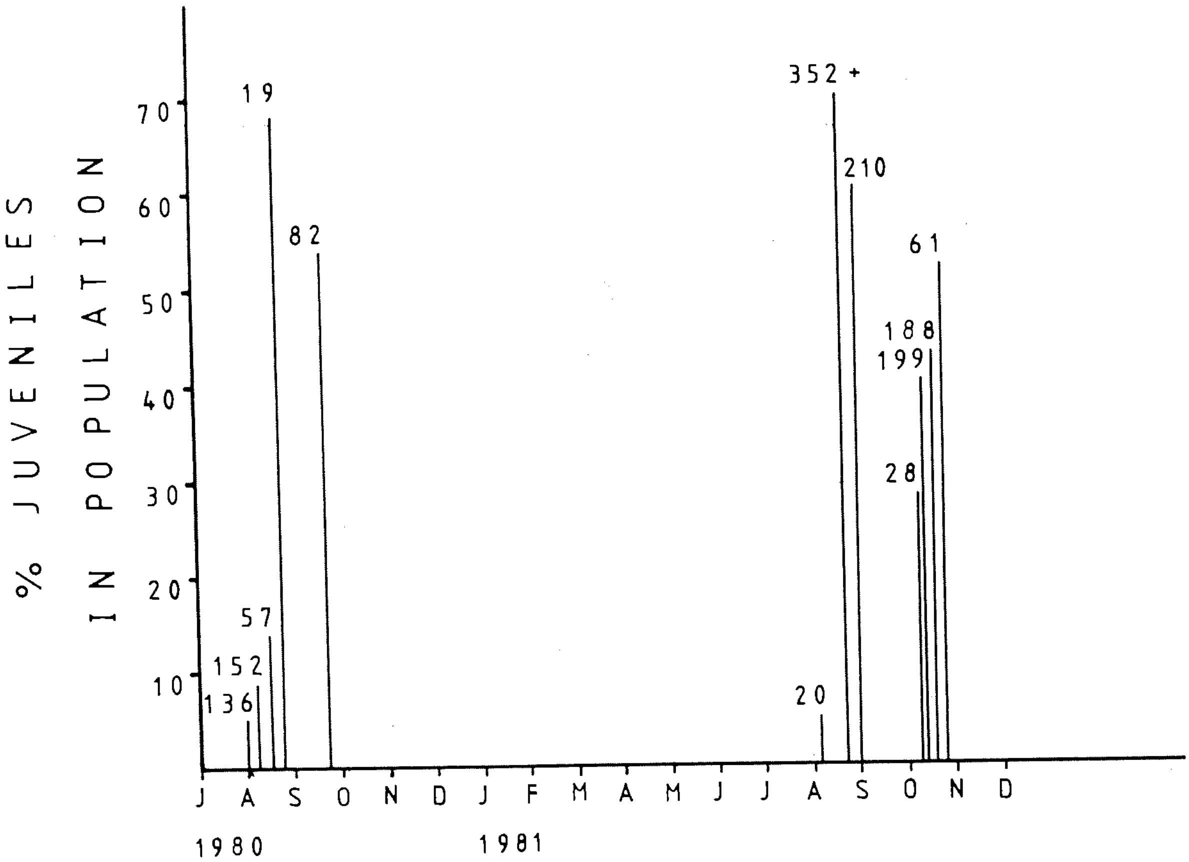

Figure 9. Juvenile scallop populations found during two seasons.

No. + = <30mm shell height.

No. = >30mm but <60mm shell height.

No. = actual number of juveniles out of total catch.

Not clear what this refers to in ~~table~~ figure?

use with live animals. Provided at least 30 such mature individuals are captured some males and females will be ready to spawn.

Mature gonads are found in 60-80% of the female population by April increasing to 100% between May and June (Figure 7). Maturation of gonads takes between 10 and 12 weeks depending upon temperature. As temperatures rise (Figure 7), e.g. to 20°C during the spawning season, rematuration of gonads occurs. This rematuration takes between 4 and 6 weeks at these higher temperatures.

4.4 Spawning

A. balloti does not spawn naturally below 18.5°C or above 23°C (Figure 7). Spawning may begin at 18.5°C but as water temperatures increase spawning frequency increases. Scallops spawn completely at 22.5-23°C. There is a brief period of quiescence before rematuration begins (see Figure 7b).

There is evidence of a minor or partial spawning in the period May to June, when water temperatures are falling from 23°C to 18.5°C. Water samples collected on June 17, 1982, contained larvae approximately two weeks old. In early June, as water temperatures fell from 21°C to 19°C, scallops held in the laboratory partially spawned and fertilisation and embryonic division of cells was evident. Using the growth model of Williams and Dredge (1981), juveniles of less than 60mm caught by trawler (Figure 9) in early August 1980 and 1981 were estimated to have been spawned in May or June. Data on gonad weight and percentage mature females suggest that early winter spawnings are partial spawning periods (Figure 7). What effect early spawning has on the total stocks of scallops is unknown. The major spawning period in which scallops spawn completely is in spring (August-October). The length of the spawning season varies annually being dependent upon the rate of water temperature increase (Figure 7). In some years low temperature prolong the natural spawning season.

4.5 Scallop Longevity (life expectancy)

What about your own study?

Williams and Dredge (1981) indicated that scallops live more than 2 years. Heald and Caputi (1981) state that *A. balloti* in Shark Bay, Western Australia, has a life expectancy of generally less than 3 years from larval settlement. *A. balloti* is thus classified as a short-lived species. Generally this is true for tropical and subtropical scallop species (Williams and Dredge 1981; Heald and Caputi 1981).

4.6 Scallop Movements

Dredge (1980) states "scallops exist in an elongate bed with the longer axis lying parallel to prevailing tidal flow". Trawling trials confirm this to be true. Thus passive orientation to the current is evident as in other scallop species (Thorburn and Gruffydd 1979). Tagging and recapture data from Shark Bay, Western Australia shows movement of *A. balloti* to be less than 10km after 315-445 days (Heald and Caputi 1981). In the Bundaberg area the maximum movement recorded was less than 20km and most moved distances of less than 10km (Williams and Dredge 1981). Further evidence of the restricted movement of scallops are findings by fishermen of (old) dead shell in large patches which appear to have died naturally rather than from fishing activities. Several anecdotal reports of this nature are acknowledged from reputable fishermen. However, no documented evidence is available.

What about your own study?
Why not tagging component?

4.7 Larval Stages and Growth

Embryonic development is similar to that described in detail for *Aequipecten irradians concentricus* Say (Sastry 1965) and *Anadara sp.* (Imai 1978). Rearing techniques and development stages will be fully described elsewhere (G. Campbell, in preparation). Briefly, the unfertilised eggs of *A. balloti* are circular in shape, bright pink in colour with an average diameter of 63μ. Yolk lobe formation is completed within 45 minutes of fertilisation and first cleavage within 1 hour. Cleavage is unequal and formation of the circular blastula occurs within 7 hours. A rotating ciliated gastrula appears approximately 16 hours after fertilisation. Trochophores form within 24 hours and the first "D-shaped" veliger develops within 40 hours. "D-shaped" veligers are approximately 105 x 80μ in size and within 15 days they settle out of the plankton to the bottom at a size of about 200 x 160μ.

In 12 successful rearing experiments all larvae settled to the bottom of holding tanks overnight. This occurred after a period of 14-16 days after hatching. Thus larvae only spend a short time in the plankton and settlement occurs *en masse*.

5.0 Discussion

5.1 General Distribution

Although *A. balloti* is recorded as far north as Cape Tribulation at approximately 14°S, and as far south as the New South Wales border at 28°S, a viable commercial fishery only exists in the Bundaberg-Yeppoon region between latitude 21°S and 26°S. Integral components within this region are large eddy systems, and Fraser Island and Barrier Reef islands which form prominences and barriers. These landforms and local currents direct larvae into the Bundaberg-Yeppoon region; the result being the concentration of scallops within the area. In other areas of the world the greatest concentrations of scallop are also associated with coastal prominences and eddy systems, and are generally found along flowlines of currents (Allen and Costello 1972; Mottet 1979).

Conditions are not stable in the Bundaberg-Yeppoon area and changes in velocity and direction of oceanic currents vary considerably from year to year. Thus commercial catches are taken in different areas from year to year within the region. Occasional commercial catches taken along the seaward coast of Fraser Island, and near Tin Can Bay confirm this variability in distribution. Zinsmeister and Emerson (1979) found "brief periods of atypical circulation play an important role in the distribution of marine life". The short larval duration, of two weeks in *A. balloti*, is also likely to limit larval distribution to other suitable habitats, such as east of Fraser Island unless current and wind systems are favourable.

Trawlers searching for scallops offshore have not found scallops in deep waters. The short larval period, landforms, wind and eddy current patterns may act to keep scallops within shallow waters. Shallow waters appear necessary for growth and survival. Thus the changing conditions affecting distribution patterns also affect commercial scallop catches. Commercial concentrations of scallops are limited to the north and south by the lack of eddy systems and coastal prominences which could keep plankton larvae within suitable shallow water habitats.

5.2 Specific Environmental and Biological Influences

Scallop fluctuations, including scallop fishing fluctuations, appear to be caused by variable annual settlements of larvae. This is a phenomenon common to many species of scallop in other areas (Sanders and Beinssen 1975; Miller, Allen and Costello 1981; Mottet 1979). The causes of variable settlement appears to be related to a complex array of variable environmental conditions. Physical parameters which appear to have the most significant effects on number concentration and mortality of larval scallops are wind, current, temperature and winter rainfall.

Winds during the major spawning season in spring are highly variable and extremely localised thereby enhancing the dispersal of scallop larvae throughout the area. The winds change from prevailing southeasterlies to variable and northerly winds. The frequency of variability in these winds from year to year may determine the amount of larval dispersal within the area, as inshore areas are shallow and water movement is under the influence of winds.

Currents are viewed as one way corridors of dispersal and dictate distributional patterns of larvae through passive transport. If currents are not flowing in the right direction, larvae may not find suitable settlement areas. Thus brief periods of atypical circulation probably play a significant role in scallop larval distribution and survival. Wind in association with currents may also severely restrict the scallop population by allowing larvae to be carried seaward into deep waters where they perish.

Temperature is a prime mechanism affecting the rate of gonad and egg development. Rising August temperatures stimulate scallops to spawn. However temperatures vary annually and thus the period of a major spawning season can vary from year to year. Considering that wind and currents also vary from year to year, a late spawning because of a delayed rise in temperature may have a completely different effect on the distribution and dispersal of scallop larvae.

Rainfall above 50mm during the August spawning period has been directly correlated with the reduction of scallop catches in the proceeding year. Rainfall outside the spawning period is not correlated with decreases in catches. Thus it would appear that low salinity causes high mortality in larvae during their planktonic life.

Inference determined from rainfall data and not from experimental study.

5.3 Problem Discussion

The influence of varying factors on scallop catches leads to the possibility of using predictive models. Rainfall, wind and temperature data are readily available from state and federal meteorological agencies. These data along with catch data could possibly be combined into a computer model assessing the influence of environmental factors on scallop catches. This could lead to a predictive model of catches in the next season. One major problem may be the limited current data available for the model. The model could assist fishermen in years of high dispersal and heavy rainfall, not necessarily by assisting them in increasing catches but by allowing them to predict their catch. Thus fishermen could better plan their next year's fishing activities.

For economic reasons scallop fishermen only fish grounds while catching scallops at a certain rate. Once catches decline to below 2 baskets/hr fishermen start searching elsewhere for heavier concentrations of scallops. It is possible in years when scallops are widely dispersed that catch rates will be low, even though the actual stock of scallops has not declined. Often searching is mainly within areas where previous good catches were recorded. The variable settlement of scallop patches from year to year may mean fishermen miss new areas of concentration. Better co-operation between fishermen in relaying catch information to each other is necessary.

Enhancement of the fishery appears to be a distinct possibility utilising a scallop seeding program. Catch records and substrate data show scallop settlement, growth and survival is possible in most of the study area. Many other areas along the coast of Queensland support adult populations in years following larval settlement. Thus many areas are only devoid of scallops due to the distributional restriction of larvae. A successful hatchery could provide seed for many areas besides the Bundaberg-Yeppoon area.

Seeding those areas in close proximity to local ports could greatly reduce searching time and fuel costs. Fishermen could work a greater number of days as poor weather conditions would have less influence on their operations. The need for expensive refrigeration equipment and large storage holds could also be reduced.

Natural scallop production could also be enhanced by seeding. Over a 5-8 year period, the Japanese have more than quadrupled their natural stocks using seeding methods and have increased their total scallop catch from 10,000 to over 100,000 tonnes (Mottet 1979). Successful seeding techniques have been reported in the USA and France in increasing scallop production and in stabilising scallop industries (Miller, Allen and Costello 1981).

5.4 Study Limitations

A criticism of the original FIRTA proposal as submitted by the author is the broad nature of the study, and considering the limited funds available the few personnel involved and the time allocated for the study. The original proposal did not consider the funds or staff necessary to set up a new laboratory, an algal producing unit, or the laying of a pipeline to gain access to clean seawater. A recirculating seawater system also had to be designed and constructed for the holding of prespawning adults and for the rearing of scallop larvae. The limited data on scallop catches was another problem as too was the limited local physical knowledge of the area. The time originally allocated for the gathering of biological information and for laboratory studies was therefore severely reduced.

Conclusions and recommendations should therefore be regarded as being preliminary, although very good indicators as to where future efforts in research and management should be directed, with respect to assisting and expanding the Queensland scallop industry.

6.0 Conclusions

The annual scallop resource is unpredictable at present. It is more common for environmental conditions to be sub-optimal for larval settlement and concentration. The large fluctuations in annual catch experienced by scallop fishermen will always prevail. Thus it is difficult for fishermen and processors to guarantee a continuous supply of scallops to the market place.

Current reversals offshore in some years during spawning seasons greatly enhance the chance of greater numbers of larvae being retained within the Hervey Bay-Yeppoon area. Annual wind patterns and eddy systematics determine the dispersal of larvae. Bustard Heads is the most consistent area for successful larval settlement.

Heavy rainfall during the spawning season in August is detrimental to larval survival in inshore areas. Rainfall records show if rainfall is above 50mm in August that catches decline the following year.

Substrate does not appear to be a limiting factor for settlement of scallops over most of the region. Scallops are found on sandy substrates to depths of 60m; below this depth commercial scallop catches are scarce.

7.0 Recommendations

A practical approach to predicting good settlement years lies in monitoring rainfall, wind speed and direction, and any obvious general current changes within the area. If a predictive model can be developed it may enable alternate planning for the next season by fishermen and processors.

Co-operation between fishermen in reporting catch rates to one another should be greatly encouraged since areas of concentration differ from year to year. This should reduce searching time and fuel costs for the fleet, but not reduce total overall catches for individual fishermen.

Given the natural variability in annual scallop catches, one method of improving catch yields would be to establish a hatchery to produce seedling scallops for distribution on the fishing grounds and outside these known grounds.

The successful establishment of a scallop hatchery producing *Amusium* spat requires further research into larval rearing techniques. A successful pilot hatchery would be necessary before proceeding to full scale.

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