# AN INVESTIGATION INTO THE INFLUENCE OF THE ENVIRONMENT ON SPAWNING AGGREGATIONS AND JIG CATCHES OF CHOKKA SQUID *LOLIGO VULGARIS REYNAUDII* OFF THE SOUTH COAST OF SOUTH AFRICA

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# ABSTRACT

Erratic and highly variable catches in the South African chokka squid *Loligo vulgaris reynaudii* fishery, cause socio-economic hardship for the industry and uncertainty for resource managers. Catch forecasting can reduce this problem as it is believed that catch variability is strongly influenced by environmental factors.

In this study, data were collected at varying temporal and spatial scales. Data for the hourly time-scale study were collected from 1996-1998, aboard commercial vessels, whilst for the longer time-scales, data were extracted for Kromme Bay (a single fishing area) from existing databases (1991-1998) that were comprised of compulsory catch returns and oceanographic data. The environment-catch relationship for chokka squid on the inshore spawning grounds was then investigated using multiple correlation and regression analysis, analysis of variance, contingency table analysis and cross-correlation statistical techniques.

This simple, direct, 'black box' statistical approach was relatively successful in developing a predictive capability. On a short time-scale (hourly), the regression model accounted for 32% of the variability in catch, with turbidity the main determinant (13%). On a daily-monthly time-scale, the best prediction model was on a monthly scale, accounting for 40% of the variability in catch. The principal determinant, bottom temperature anomaly (11%), was found to lag one month forward.

Seasonal and diel catch variations induced changes in the relative importance of turbidity, water temperature and wind direction on catches. A strong, positive relationship was found between easterly winds (which cause upwelling) and catch, particularly in summer. Catch rates, however, decreased with an increase in turbidity. The correlation between temperature and catch was generally negative, however, higher catches were associated with a temperature range of 13-18°C. Highest catch rates were associated with easterly winds, zero turbidity conditions and sea surface temperatures from 15.0-16.9°C. Selected case studies (*in* *situ* observations) suggested that upwelling and turbidity events act as environmental triggers for the initiation or termination of the spawning process, respectively.

A holistic approach is required to improve predictive capability of chokka squid abundance. Although short-term predictability remains essential (i.e. hourly-scale), future research should concentrate on long-term prediction models (e.g., monthly time-scales) involving greater spatial variation, which are the most important for management.

***Vir my ouers,***

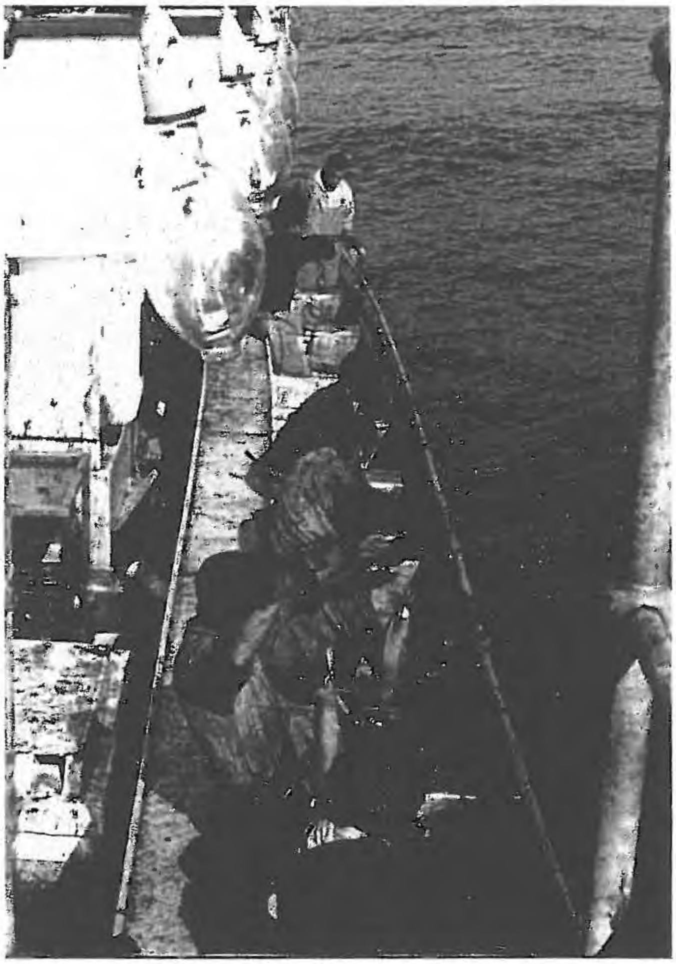
***JAN EN MARIÉ SCHÖN***

***dankie vir al die liefde, ondersteuning en inspirasie***

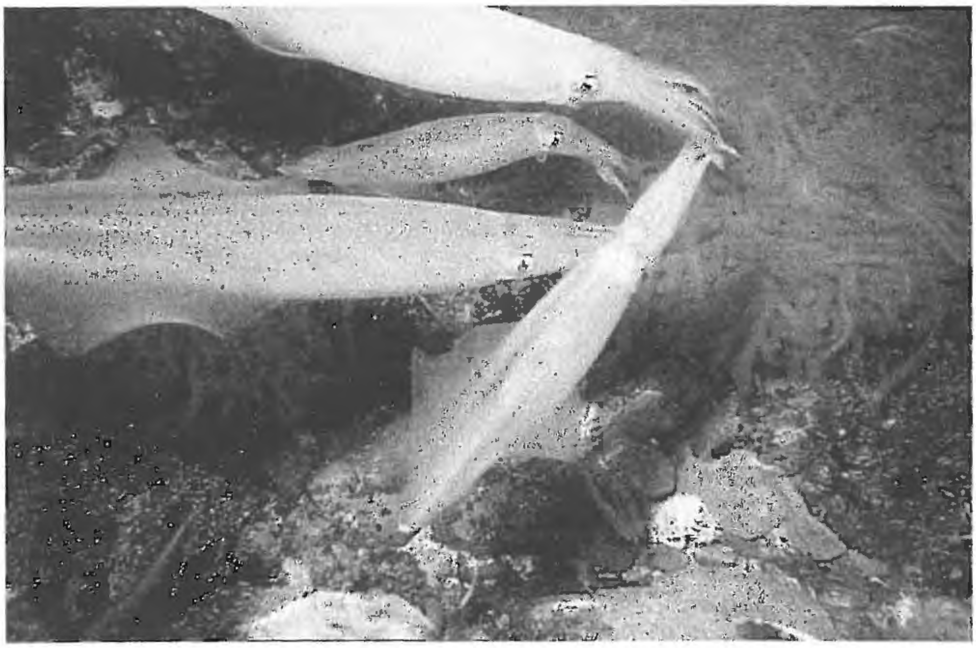
*To my parents,*

*JAN AND MARIÉ SCHÖN*

*for their love, support and inspiration*



Commercial chokka jig fishermen



Spawning chokka squid *Loligo vulgaris reynaudii*

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**All models are wrong;**

**some, though, are more useful than others and we should seek those.**

**At the same time we must recognise that eternal truth is not within our grasp.**

(P. McCullagh and J.A. Nelder)

# CHAPTER 1

# INTRODUCTION

## 1.1 GENERAL

Cephalopods are currently the third most valuable species group in the global marine harvest, following shrimp and tuna (FAO 1992). World-wide cephalopod catches peaked in 1987 at 2.3 million ton, of which approximately 80 percent were squid species (Roper and Rathjen 1991), and catches are probably still increasing. Since there are approximately 288 species of squid (Nesis 1987), while the world's major cephalopod fisheries are based on only a few large species found in relatively large numbers (O'Dor 1992), squid are still regarded as one of the most under-utilised marine resources.

The cephalopods show a high degree of speciation and variability ranging from genera such as *Octopus* and *Sepia*, each comprising more than a hundred species, to the genus *Onychoteuthis*, comprised of one species with circum-global distribution (O'Dor 1988a). About 120 cephalopod species are currently known in southern African waters, consisting of 66 teuthoids (squids), 29 sepioids (spirulids, bobtails and cuttlefish) and 25 octopods (octopuses) (Augustyn and Smale 1995). Cephalopods of commercial interest are the octopods *Octopus vulgaris* (common octopus) and *Octopus dofleini* (giant octopus), and the teuthoids *Todaropsis eblanae* (lesser flying squid), *Todarodes angolensis* (Angola flying squid) and *Loligo vulgaris reynaudii* (chokka squid) (Augustyn and Smale 1995). The feasibility of directed exploitation of *Loligo duvaucelii* (Indian Ocean squid) on a commercial scale (W. Sauer, Rhodes University, pers. comm.) and the expansion of the *O. vulgaris* fishery is currently being assessed (A. Oosthuizen, Port Elizabeth Museum, pers. comm.). Two squid species are caught as a trawl by-catch: *Todaropsis eblanae* along the west and south coast and *Todarodes angolensis* along the west coast (Augustyn and Smale 1995). *Loligo vulgaris reynaudii* d'Orbigny, commonly known as "chokka", is the only squid directly targeted at present, as well as the only cephalopod of major commercial importance in the South African fishing industry (Augustyn 1986). In 1995 the squid jig fishery was the fifth most important fishery in terms of mass caught, contributing 1.2% of the total landings in South Africa, but in terms of value (at 5.9% of the total landings) was rated fourth most important (Stuttaford 1997).

## 1.2 RATIONALE AND OBJECTIVES

The South African chokka squid fishery is comprised of mainly small and medium-sized enterprises and the involvement of big business is limited. The fishery is renowned for erratic fluctuations in catches, especially on a monthly basis (Augustyn 1989). These catch fluctuations and the associated uncertainties could have devastating economic consequences to many fishermen, families and people associated with the industry, especially during periods of low catches, and can also impact the management of the resource (Augustyn and Roel 1998). Although little can be done to stabilise catches, catch forecasting may alleviate certain problems by making the industry more robust to catch variability. Forecasting would not only benefit the management of this resource, but would also enable fishery participants to minimise risk and secure a livelihood (Roberts in prep.).

The cause of erratic fluctuations in chokka squid catches is unknown. In the opinion of fishermen, the 'weather' is the usual reason offered for an unsuccessful fishing trip or low catches. There is little doubt among fisheries scientists that physical factors are prime determinants of biological events, and that abiotic factors tend to dominate marine ecosystem function (Mann 1992). All phases of the chokka squid life cycle are likely to be influenced by environmental conditions, e.g. distribution, abundance, growth, behaviour, survival and recruitment (Roberts and Sauer 1994).

To date, research on *L. v. reynaudii* has concentrated mainly on biology and life cycle, while relatively little is known on the influence of the environment on chokka squid. Various authors (Augustyn 1991, Sauer *et al.* 1991, Boyd *et al.* 1992, Augustyn *et al.* 1994, Roberts and Sauer 1994, Sauer 1995a) have attempted to correlate environmental parameters to chokka squid abundance and catches, both for jig and trawl fisheries. Augustyn (1989) was the first to suggest that prevailing environmental conditions could be a major factor influencing squid abundance or availability on the spawning grounds. Sauer *et al.* (1991) attempted to correlate surface water temperatures with squid catches at St Francis Bay and, as a result, proposed a model relating temperature and wind condition with catch. While their analysis was preliminary, the results nevertheless hinted that catches increase when water temperatures decrease, mainly during the summer upwelling season. From this work a hypothesis was proposed stating that cold-water events caused increases in chokka squid catches. Roberts and Sauer (1994) added further support to this notion after they noticed a link between the total annual chokka catch and years of increased coastal upwelling. By examining diving and vessel log records Roberts and Sauer (1994) also proposed that high levels of benthic turbidity may account for periods of poor chokka catches, a hypothesis that was supported by Augustyn *et al.* (1994).

Such introductory work led to the initiation, in 1994, of a multi-disciplinary research programme, ambitiously referred to as The South African Climate Change and Squid Programme (SACC&SP), under the auspices of Marine and Coastal Management (formally the Sea Fisheries Research Institute). The goal of the SACC&SP is to develop environmental-driven predictive capability for chokka squid. The work presented in this thesis forms part of that goal.

The objectives of this study are to:

- synthesise available information on the South African *Loligo vulgaris reynaudii* jig fishery, as well as conditions of the physical environment along the south coast;
- assess the current catch trends of the chokka squid fishery;
- identify possible causal relationships between physical environmental parameters and the abundance and availability of squid on the inshore spawning areas, on the shortest possible time-scale, i.e., hours; and on a longer time-scale, i.e., days-weeks-months (associated with high degree of database inaccuracy); and
- quantify relationships between physical environmental parameters and catch per unit effort (CPUE).

Collection of real-time CPUE and environmental data necessitates having an observer on board the commercial vessels. Since funding did not allow for paid observers, data collection aboard commercial vessels was made by the author; such a task was often dependant on extraneous factors, including a good relationship with the skipper and the availability of space on the vessel.

## 1.3 THESIS OUTLINE

The formation of effective predictive models of biological processes or properties must involve correct assessment of current physical events (Mann 1992). Chapter 2 presents a literature review regarding both the fishery and the oceanographic regime along the south coast of South Africa. A brief history of the fishery is given, followed by a review of the development of fishing technologies and harvesting strategies. Long-term catch data extracted from a database housed at the Department of Marine and Coastal Management, and catch data collected on board commercial fishing vessels (over a two-year sampling period) were analysed to assess current catch trends within the fishery, as well as general fishery characteristics, such as quality of data, boat activities, catch trends and catch distribution. The climate and inshore oceanography of the south coast are described. Oceanographic data collected during the study period are also presented to illustrate typical temperature and turbidity profiles. Chapters 3 and 4 explore possible environmental-catch relationships in the inshore jig fishery for *L. v. reynaudii*. Chapter 3 reports an *in situ* study, based on catch and environmental data collected on a short time-scale from commercial fishing vessels, with a large spatial variation. A time-series study in a single location, is presented in Chapter 4; these data were extracted from long-term databases and were investigated on a daily, weekly and monthly time-scales. Management implications are addressed in Chapter 5.

# CHAPTER 2

# BACKGROUND

## 2.1 THE SOUTH AFRICAN CHOKKA SQUID FISHERY

### 2.1.1 General

Chokka squid, *Loligo vulgaris reynaudii*, has long been caught by line fishermen along the southern Cape coast for use as bait (Augustyn 1989, Augustyn and Smale 1995). Until the early 1980s all commercial squid catches were trawled, mostly as a bycatch of the hake and sole fisheries (Augustyn 1989, 1991). A proportionately large catch was also taken by fleets from other nations (Augustyn *et al.* 1992). Commercial jig fishermen in South Africa have exploited squid on the spawning grounds since 1984. Since then, handline jigging for chokka has displaced bottom trawling as the most successful harvesting method. The fishery has developed rapidly from 1985 onwards (Augustyn *et al.* 1992, Sauer 1993) and effort and pressure on the resource has dramatically increased. More than 90% of the total squid catch is currently caught by jig (Boonstra 1997). With the recognition of squid as a seafood delicacy, and, moreover, stimulated by the decline of the rand on the foreign exchange markets, the export of squid has become a lucrative industry. For example, in 1989 the wholesale value of jigged squid reached a record R108 million compared to R8 million for trawled squid (Augustyn 1989). Currently almost all South African caught chokka squid is exported freshly frozen to European and Asian markets where it commands a high price.

### 2.1.2 Management history and current trends

Initial development of the fishery was chaotic, when a large number of small boats, many without commercial fishing licences, converged on the coastline between Jeffrey's Bay and Oyster Bay to exploit "white gold" (Sauer 1993). At the time, legislation governing squid exploitation was lacking. Towards the end of 1986, a six-week closed season was introduced to limit effort as the first measure of control. However, this applied only to vessels not registered in the designated fishing area (Augustyn *et al.* 1992, Sauer 1993). A public bag limit of 20 squid$\cdot$person$^{-1}\cdot$day$^{-1}$ was also introduced to sustain a high quality product for marketing and to restrain the unlicensed selling of squid (Augustyn *et al.* 1992). Later, an effort-controlled management plan for the fishery was introduced, with the issuing of a limited amount of squid licences, based on historic performance. This regulation reduced the number of boats from a total of 560 to approximately 240 over the 1986/87 and 1987/88 seasons (Augustyn *et al.* 1992). A three-year moratorium on licence transfers was also applied (Sauer 1993). In 1988, a comprehensive one-month closed season during the peak spawning season (in November) was introduced. Thereafter, the duration was flexible however, and varied according to performance of the commercial fleet and fluctuations in the abundance index from trawl surveys (Augustyn *et al.* 1992). Initially, the closed season was applicable to commercial fishing and not to the public fishing of 20 squid$\cdot$person$^{-1}\cdot$day$^{-1}$. In 1998, the regulations were refined and the closed season was set to four weeks from 25 October to 22 November, applicable to both commercial and public fishing efforts. A conservation component complementing the management measures prohibited chokka squid fishing in the Tsitsikamma National Marine Park, situated within the main spawning area (Sauer 1995b). The reserve serves as a protective breeding area for the species (Sauer 1995b) and, ultimately, may minimise the loss of selected genetic characteristics, important to a faster recovery time in the event of a possible collapse of the fishery (O'Dor 1992).

During the initial developmental stages of the fishery, local Eastern Cape fishermen voiced concern about the future of the squid stock and the need for management measures (Sauer 1993). Consequently, in order to represent their interests, the South African Squid Management Industrial Association (SASMIA) was formed in 1991 by members of the squid fishery and the South African Squid and Linefish Industrial Association (SASLIA) (Sauer 1993). The organisation consists of factory owners, boat owners, fishermen and scientists. The objectives are: "To represent the squid fishery as an industrial body or interest group; to furnish information, to advocate and protect the interest of the squid industry, and make representations to government, the minister of Environmental Affairs, the chief directorate of Sea Fisheries (now the Department of Marine and Coastal Management) about any matter which concerns the squid industry; and to constitute a forum for discussion of all matters pertaining to the entire spectrum of the squid industry" (Stuttaford 1997). Recently the South African government adopted a policy aimed at the restructuring and redistribution of local marine fisheries. A proportion of licences were removed from existing licence holders and were reallocated to fishermen from disadvantaged backgrounds. At present, SASMIA plays an important role in assisting the government towards reaching its goal, as well as continuing collaboration and funding of research projects of interest to the squid fishery.

### 2.1.3 Evolution of fishing technology and harvesting strategies

As a result of increased interest in the potential of cephalopod fisheries, directed fishing methods for cephalopods have evolved from methods traditionally used in the finfish, crustacean and mollusc (other than cephalopods) fisheries (Rathjen 1991). A wide variety of fishing methods, including trawls, gillnets, seines, lift nets, trap nets, trolling, lights, tidal traps pumps and jigs (Rathjen 1984), have been used to harvest cephalopods stocks. No single method has been found to be adequate for all cephalopods due to the high diversity in behaviour, form and habitat among species (Rathjen 1991). Jigging, however, is the single most important fishing method currently employed (Rathjen 1991) and accounts for 40% of the world cephalopod catch (Rathjen 1989). Initially only Japanese squid jigs were used in the chokka squid fishery, but due to different local conditions, new types appeared on the market. Most jigs used today are manufactured in South Africa. Jigs are either baited or unbaited, but the latter is more common.

The development of technologies and harvesting strategies was mainly driven by pressure from export markets that demanded a better quality product and increased competition in the fleet, which strove towards higher fishing efficiency of vessels. Developments include an increase in boat size, improved light attraction methods and processing capabilities (grading, packing and blast-freezing) out at sea. Added to these are the technological advancements of fish-finding devices and boat navigational equipment. Although attempts have been made to use mechanical jigging and scoop-netting, these have not proved cost-effective (Augustyn and Smale 1995).

The South African hand jig fishery began with the use of ski-boats (6-8m) which operated only during the day, but this harvesting method limited the capacity of the fishery (Sauer 1995a). Since 1992, there has been an increase in the number of deckboats, or vessels with onboard packing and freezing capabilities. Deckboats range in length from 12 to 21 m, with a crew capacity of 12 to 28, and so far have proved to be most effective. Since 1997, the chokka squid fleet has been comprised of mainly large deckboats with few ski-boats remaining in commercial operation. The increase in vessel size is also evident in the gradual decrease in the number of boats; to purchase larger boats, the boat licences of smaller boats must be amalgamated, allowing an increase in the number of crew (Table 2.1).

Table 2.1: Summary of fleet characteristics recorded and calculated from raw catch statistics on the Marine and Coastal Management Linefish database (No. boats = total number of boats that submitted chokka squid catch data; Average no. of crew calculated from maximum number of crew submitted per boat).

| Year | No. boats | Average no. crew/boat | Average catch in ton/boat | Median catch in ton/boat |
|---|---|---|---|---|
| 1985 | 227 | 10.1 | 11.57 | 3.63 |
| 1986 | 562 | 10.0 | 6.21 | 1.41 |
| 1987 | 365 | 9.3 | 7.67 | 2.11 |
| 1988 | 335 | 10.1 | 14.54 | 7.32 |
| 1989 | 342 | 10.1 | 28.57 | 13.33 |
| 1990 | 311 | 11.3 | 10.57 | 5.21 |
| 1991 | 278 | 12.7 | 24.08 | 15.58 |
| 1992 | 292 | 13.3 | 8.88 | 4.30 |
| 1993 | 297 | 13.8 | 21.51 | 9.83 |
| 1994 | 285 | 15.0 | 23.14 | 8.16 |
| 1995 | 295 | 16.2 | 23.29 | 9.05 |
| 1996 | 285 | 17.9 | 25.36 | 11.16 |
| 1997 | 239 | 19.0 | 16.16 | 5.53 |

Since 1997, the exploitation of squid on the deeper spawning grounds (Roberts *et al.* in prep. a) has led to a dramatic increase in the light power of vessels through the introduction of Korean-type hanging light bulbs. On average, a 15-m vessel will have 6 to 24 bulbs of 2-kW strength compared to 6-9 1-kW spotlights (Sauer 1993) as previously used. The use of parachutes as sea drogues has also become common practice. These are used to reduce wind drift over the deeper spawning areas. These modifications enable vessels to leave the traditional, shallow fishing grounds (<60m) for the deeper areas, approximately up to 150 m (pers. obs.). The brighter lights are used to attract squid present in the upper water column (0-60 m) where the use of handlines is effective. This method of harvesting is most common during winter. A decrease in the efficiency of handlines at depths greater than 60 m has recently prompted a reassessment of mechanical jigging machines. A large (30m) Korean squid vessel with immense light power (approximately 200 X 2-kW light bulbs) and mechanical jiggers is currently operating in South African waters.

These developments in fishing technology have resulted in an increased capacity as seen by the increasing trend in the annual catch per boat and the median annual catch per boat (Table 2.1). The median catch gives a better indication of increased capacity, since the effects of the fishing skill and experience of the skippers and the amount of annual effort per boat are partly eliminated. The median is also less likely to be less driven by the large catches of a few boats, thus being a better measure of central tendency. Roel (1998) attempted to investigate the influence of vessel efficiency on catch rates using a Generalised Linear Model. Using the model, the catch rate of a particular vessel was found to be a function of the product of squid abundance in a particular year, and the efficiency of the vessel (represented by vessel attributes). The results were inconclusive but suggest that there is little gain in including vessel attributes in the model, and imply that the development of fishing technology in the chokka squid fishery plays a minor role in terms of increased catch rates and thus vessel efficiency. However, the time period examined in the study by Roel (1998) was relatively short (2 years), while technological advances are a continuous, long-term development process. Furthermore, the units representing an estimate of catch rate and abundance ($kg \cdot man^{-1} \cdot h^{-1}$) may have been too refined, considering the database used. The validation of this database (i.e., the compulsory catch returns) and, in particular, the problem of inaccuracy regarding the usage of a short time-scale CPUE estimate is addressed in Section 2.2.1.1.

### 2.1.4 Research

Research on commercially exploited squid started with joint Japanese-South African surveys, conducted from 1980 to 1982, which investigated the abundance and population structure of squid along the south coast, in depths between 75 to 220m (Uozumi *et al.* 1984, Uozumi *et al.* 1985). Three species were considered the most important by the industry, i.e., *Todaropsis eblanae*, *Todarodes angolensis* and *Loligo vulgaris reynaudii*. At that time, *L. v. reynaudii* was caught by demersal trawlers and was the most common cephalopod species in the catch.

*Loligo vulgaris reynaudii* is found over most of the continental shelf off the west and south coast of South Africa. The distribution of chokka squid is generally continuous from Port Alfred in the east to the Cape Peninsula in the west. Their occurrence becomes sporadic between Cape Columbine and the Orange River (Augustyn 1991) (Fig. 2.1). The extreme limits of the chokka squid distribution on both coasts has not been well defined (Augustyn 1986). Chokka squid are found throughout the water column, but the depth distribution varies between the west and south coasts. Squid are found up to 350 m along the west coast (Cape Agulhas to the Orange River), whereas on the south coast (continental shelf between Cape Agulhas and Port Alfred, including the Agulhas Bank) only a small percentage of the biomass occurs deeper than 200 m (Augustyn 1991, Augustyn *et al.* 1994). Biomass estimates for the south coast are higher than for the west coast (Augustyn 1991). In part, this may be due to the high biomass found on the Bank itself, where *L. v. reynaudii* is the dominant cephalopod species (Smale *et al.* 1993).

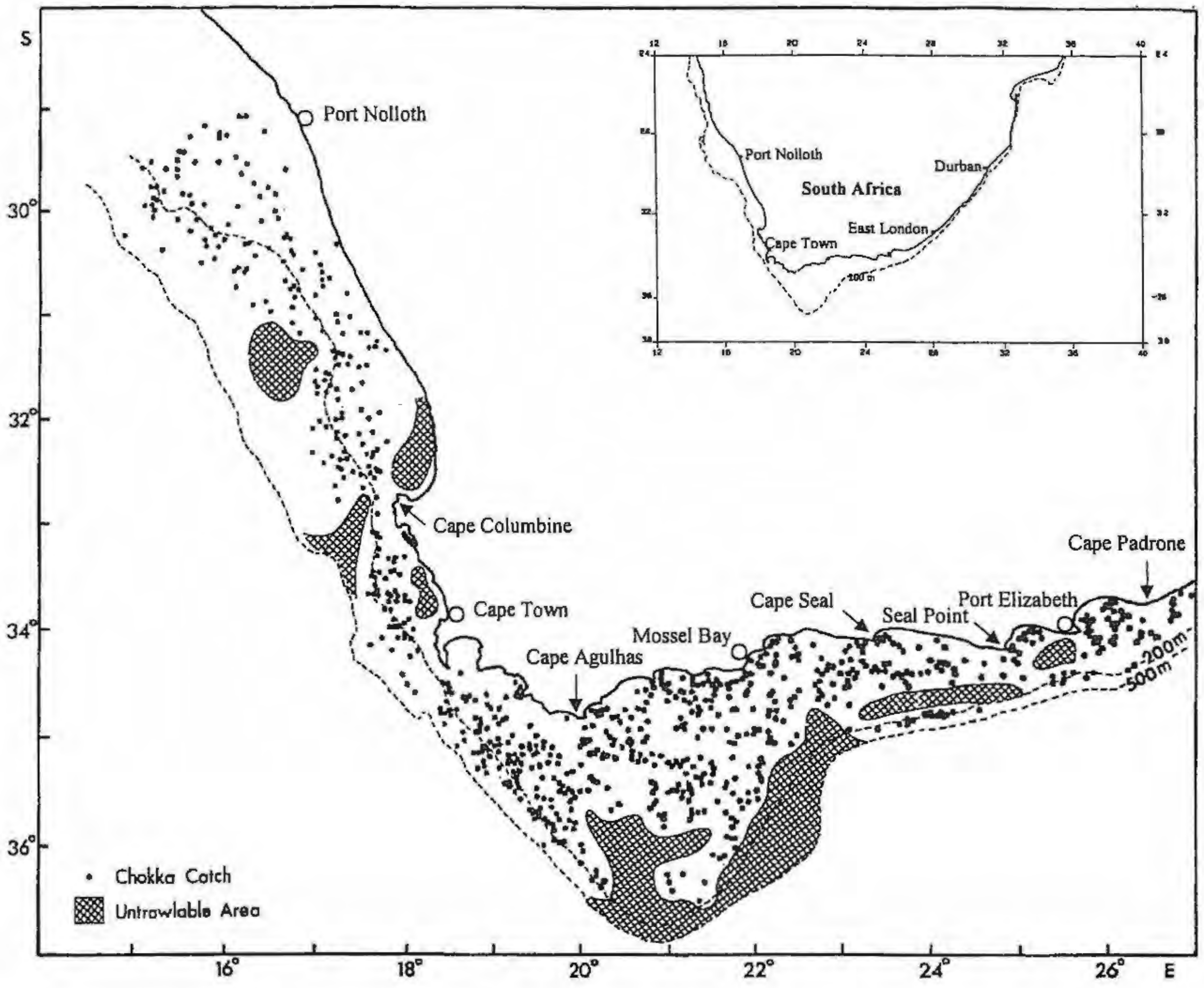

Fig. 2.1: Distribution map of *Loligo vulgaris reynaudii* along the South African west and south coast composed from trawl surveys conducted by Chief Directorate: Marine and Coastal Management (from Roberts and Sauer 1994)

The directed exploitation of chokka squid began on a large scale in 1985. To develop a management strategy for the resource, extensive research was required. Initially it was important to clarify the taxonomic position of *L. v. reynaudii* in order that biological studies could be established. The differences between *Loligo reynaudii* and its European and north-west African counterpart *Loligo vulgaris*, were originally considered to be of specific nature (Augustyn 1989). However, based on biochemical and morphological systematics, the differences were found to be of a sub-specific nature, resulting in the subspecies designations *L. v. reynaudii* and *L. v. vulgaris* (Augustyn and Grant 1988). Research subsequently focused on life cycle, fisheries potential along the southern and western Cape coasts (Augustyn 1989), feeding (Lipinski 1987, 1990, Augustyn 1990) and reproductive biology (Augustyn 1990, Sauer and Lipinski 1990) of the species. Later research emphasis shifted to studies of the spawning grounds on the south coast.

#### 2.1.4.1 Research on the inshore spawning grounds of *Loligo vulgaris reynaudii*

The majority of chokka squid are caught on and around the spawning grounds; a good understanding of the spawning behaviour and movement of squid in these inshore areas is considered essential.

Like most loliginids, *L. v. reynaudii* generally move inshore to spawn. Research has shown that spawning occurs off the coast of South Africa, between Robben Island in the west (Augustyn 1990) and East London in the east (Augustyn 1990, Sauer 1991, Augustyn *et al.* 1993, Sauer and Smale 1993), at water depths ranging from 10 m to approximately 120 m (Augustyn 1990). The main spawning grounds are located along the Eastern Cape coast, from Plettenberg Bay to Port Alfred (Augustyn 1990, Sauer *et al.* 1992, Sauer and Smale 1993), above the 60 m isobath (Roberts *et al.* in prep. a). The preference for this region suggests that the species has specific environmental requirements during spawning. Roberts and Van den Berg (in prep. b) investigated the position of the main spawning grounds in relation to alongshore spatio-oceanographic gradients. They found that spawning of chokka squid occurs in a distinct region along the South African coast which best suits egg development, since that portion of the life cycle is strongly influenced by temperature and oxygen gradients. Although the region is not optimal with respect to food and survival of paralarvae, the surface current distribution fields of the region may mitigate those limitations (Roberts and Van den Berg in prep. b).

Sauer (1991) reported on the population structure, abundance, spawning characteristics and reproductive biology of *L. v. reynaudii* from the inshore spawning grounds along the Eastern Cape coast between 1988 and 1990. This was followed by extensive research of the spawning grounds, summarised in Table 2.2, which addressed various biological and fishery aspects.

The existence of mass post-spawning mortality, a characteristic of *L. opalescens* (Arnold and Williams-Arnold 1977), has never been observed in *L. v. reynaudii*. Evidence that chokka squid die after spawning is provided by a transformation in the size distribution from summer to winter (Augustyn and Smale 1995). It appears that mass mortality events do not occur because post-spawning mortality is probably extended in time and space (Augustyn 1990).

Table 2.2: Summary of studies that focused on the inshore spawning grounds of *Loligo vulgaris reynaudii*.

| Reference | Subject |
|---|---|
| Sauer *et al.* (1991) | Preliminary environment-catch relationship |
| Sauer and Lipinski (1991) | Feeding on spawning grounds |
| Sauer and Smale (1991) | Predation on spawning grounds |
| Augustyn *et al.* (1992) | Management review and life-cycle summary |
| Sauer *et al.* (1992) | Location of spawning grounds, spawning and schooling behaviour |
| Augustyn *et al.* (1993) | Stock assessment methods |
| Sauer (1993) | Ecology of spawning squid |
| Sauer *et al.* (1993) | Egg distribution and abundance |
| Sauer and Smale (1993) | Spawning behaviour |
| Augustyn *et al.* (1994) | Overview of life history and ecology |
| Hanlon *et al.* (1994) | Body patterns and spawning behaviour, underwater video |
| Lipinski (1994) | Biological parameters comparison for different sampling methods on the spawning grounds, selectivity of methods |
| Roberts and Sauer (1994) | Environmental influences on life cycle – West Coast and spawning grounds |
| De Wet (1995) | Gonad histology, fecundity and reproductive behaviour |
| Lipinski and Underhill (1995) | Sexual maturity (stages and patterns) |
| Sauer (1995a) | Impact of fishing on spawning aggregations |
| Sauer (1995b) | Effectiveness of a marine reserve within the inshore spawning grounds |
| Smale *et al.* (1995) | Predation on spawning squid |
| O'Dor *et al.* (1996) | Spawning aggregation dynamics |
| Durholtz *et al.* (1997) | Ageing methods and techniques (nuclear microprobe mapping) |
| Sauer *et al.* (1997) | Diel migration patterns of spawning squid, reproductive behaviour |
| Augustyn and Roel (1998) | An overview of fisheries biology, stock assessment and management |
| Blackburn *et al.* (1998) | Embryonic development |
| Lipinski *et al.* (1998) | Daily migration patterns on spawning grounds |
| Melo and Sauer (1998) | Ovarian atresia |
| Roberts (1998a) | Environmental influence on spawning aggregations and the incorporation of biological components |
| Roberts (1998b) | El Niño, squid catches |
| Roel (1998) | Stock assessment |
| Roel *et al.* (1998) | Effect of different effort levels and the closed season on the jig fishery |
| Durholtz (1999) | Biomineralisation in statocysts and statolith based ageing |
| Melo and Sauer (1999) | Question of serial spawning |
| Oosthuizen (1999) | Effect of temperature on embryonic development and hatching success |
| Sauer *et al.* (1999) | Fecundity |
| Sauer *et al.* (in press) | Migration patterns on inshore spawning grounds |

Chokka squid are serial spawners (Melo and Sauer 1999) and spawning occurs throughout the year. Discrete modes in the size composition of offshore squid (Augustyn 1989), however, confirm the occurrence of seasonal peak spawning periods (Augustyn 1990, Augustyn *et al.* 1994). These peak periods occur sporadically; the major in spring to early summer (September to December) in most years, and the minor in autumn to winter in some years (Augustyn *et al.* 1994). With the exception of *L. vulgaris*, which has one major spring spawning with further spawning episodes throughout the year (Worms 1983), two or more spawning peaks per year seem to be a characteristic of most loliginid species, e.g., *L. opalescens* (Fields 1965), *L. pealeii* (Summers 1971), *L. forbesi* (Holme 1974) and *L. gahi* (Hatfield *et al.* 1990).

Length frequency analysis has indicated that *L. v. reynaudii* sporadically migrate onto the inshore spawning grounds primarily as a discrete population group (Augustyn 1990). Several factors suggest this: (i) the absence of any modal size progression to indicate growth, (ii) the majority are mature, (iii) a proportion of females are spent (Melo and Sauer 1999), and (iv) the reduced level of feeding on the spawning grounds and the thinner mantle walls as compared to offshore squid (Augustyn 1990). Both sexes differ in their size and body patterning, and tend to migrate in discrete schools in the vicinity of the spawning sites (Sauer *et al.* 1992). These schools only mix during spawning (Sauer *et al.* 1992). The sudden appearance of shoals of large, mature, squid on the inshore region, may vary from small aggregations of squid a few metres wide to large shoals hundreds of metres across. Fishermen target these aggregations of chokka squid particularly when mating and egg laying take place (Sauer *et al.* 1992). The sex ratio in commercial catches is often heavily biased in favour of males (Augustyn 1990, Augustyn and Smale 1995). The greater abundance of males on the inshore spawning grounds was confirmed by Lipinski (1994) who found the overall sex ratio to be 1:2.5, females to males. This could be indicative of a number of factors such as differential inshore migration, greater longevity in males than in females, greater abundance of males (Augustyn 1990) or the more aggressive behaviour of males (more likely to attack jigs) (Augustyn and Smale 1995).

Current and ongoing research on *L. v. reynaudii* include studies that addresses the position of the spawning grounds in relation to spatio-oceanographic gradients around South Africa (Roberts and Van den Berg in prep. b), behavioural strategies during spawning and tactics against predators (Smale *et al.* in prep.), the deep spawning grounds of *L. v. reynaudii* (Roberts *et al.* in prep. a), the role of benthic turbidity events in regard to deep spawning (Roberts *et al.* in prep. b), the need to forecast catches from a fishery and management perspective (Roberts in prep.), and means to estimate batch fecundity for this species (Melo and Sauer in prep.).

## 2.2 AN ASSESSMENT OF EXISTING CATCH DATA, TRENDS AND CHARACTERISTICS OF THE FISHERY

### 2.2.1 Data source and validation

An analysis of catch data was divided into two parts. Firstly, a general overview and description of the fishery was undertaken using catch data extracted from the Marine and Coastal Management Linefish database. No extraction criteria were used in order to avoid errors occurring with the extraction process. The raw catch records were thus extracted and the catch trends presented in this chapter were calculated from raw data. Secondly, to assess the fishery on a shorter time-scale, sampling trips were conducted on commercial chokka squid vessels over a two-year period (May 1996 – May 1998). Catches and other boat activities were monitored on an hourly to daily scale, during a total of 154 days at sea, of which 146 were fishing days. The geometric mean, calculated according to the formula given in Chapter 3 (Section 3.2.1), was used to determine the average catch rates. The distribution of chokka squid catch rate data, on hourly to monthly time-scales, is strongly skewed towards lower values. The geometric mean (which is less than the arithmetic mean) was thus considered to be a better measure of central tendency. Furthermore, the effect of outliers, in light of the modelling exercises (Chapter 3 and 4), will be reduced.

Data on distribution were obtained from records of fishing positions during sampling trips on commercial vessels. Additional positions, recorded since the inception of the fishery, were obtained from various commercial chokka skippers. The annual geographical distribution of the fleet was derived from the Marine and Coastal Management Linefish database.

#### 2.2.1.1 Database validation

Compulsory submissions of daily chokka squid jig catch statistics are required of all licensed fishermen and fishing companies, and are captured in the database. Catch statistics for chokka squid have only been separated from those of other squid species since 1983 (Augustyn 1989). Returns were not always accurate or regularly submitted during the initial stages of the jig fishery; however, this improved with the introduction of licences in 1988 (Augustyn 1989).

Commercial returns were validated by comparing statistics recorded during 146 sampling days (17 trips), spent on four different commercial chokka squid vessels, over a period of two years. Submission of data did not appear to be influenced by the presence of an observer on board, as there existed a lack of enforcement regarding submission of accurate catch returns. Submitted returns include date, catch location (common place name), number of fishing crew, number of hours fished and weight of the catch. These were compared on a daily basis to the submitted entries and the percentage of inaccurate submissions was calculated for each factor (Table 2.3).

Table 2.3: Comparison of observed values with the chokka squid catch statistics submitted and retained in the Marine and Coastal Management Linefish database.

| Factor | Percentage inaccurate submissions | t-value (paired) | Significance ($\alpha=0.05$) |
|---|---|---|---|
| Date | 41 | | |
| Location | 50 | | |
| # Crew | 82 | 12.595 | $p<0.0001$ |
| # Hours | 93 | 9.840 | $p<0.0001$ |
| Weight | 31 | 1.754 | $p=0.0819$ |

Inaccurate date submissions were mostly one or two days before or after the observed date. Where the catch location was inaccurate, 23% of the submitted locations were close to the actual vicinity (approximately less than 5 nautical miles) and 27% were further away (>5 nautical miles). A large percentage of the submitted data on number of crew and number of hours fished were recorded as the maximum number, i.e., total number of crew on the vessel (63%) and a 24-hour fishing period (30%). A further 53% of the 'number of hours' values were missing altogether. Observer data regarding number of crew and number of hours fished were significantly different from submitted values ($p<0.0001$, Table 2.3). However, the weight values only differed at a 10% level of significance. Weight values were considered inaccurate when they differed by more than 10% from the observed weights caught. A total of 32 197 kg squid were caught during the observation period of which 26 672 kg was submitted to the database (83%). No data were submitted for three entire fishing trips, a total of 19 days during, which 5 176 kg was caught according to the observer.

The observer survey clearly illustrated that a large degree of inaccuracy, especially on a daily basis, exists in the catch statistics. The use of vessel data can however still be considered adequate for general description purposes and the examination of long-term trends. However, these data should be viewed with caution when used for short time-scale analyses, for isolating catches from a specific catch location, or for catch per unit effort (CPUE) calculations.

### 2.2.1.2 CPUE as an index of abundance

In most fishery assessments, commercial catch and effort data are the major source of information about stock size. Catch per unit effort (CPUE) is thus the most commonly and routinely used index of abundance in fishery studies (King 1995). Throughout this thesis, the use of CPUE as a proxy for squid abundance was considered standard practice. One of the expected key changes in circumstances affecting fishery stock assessment in the next 50 years is that commercial CPUE will not be accepted as a default index of abundance, and interpretations will be based on a range of possible relationships between fish abundance and CPUE (Sainsbury 1998).

Many problems do, however, persist in the interpretation of catch rates and their use in estimating abundance indices of exploited marine resources (Hilborn and Walters 1992). These problems include the low precision and/or inaccuracy of these data (illustrated above for the chokka squid fishery), inadequate data coverage of the spatial extent of the stock, and the more issues of whether data from a commercial fishery, which attempt to maintain a high catch rate, truly reflects stock abundance (Campbell 1998). The inability to correct such data has been a significant factor in some assessment failures (Sainsbury 1998).

A problem that is particularly applicable to the chokka squid fishery, is use of spatial aggregated data. Fishermen actively target spawning aggregations, thus supplying local indices of abundance, which make the use of CPUE as an index for abundance more difficult. CPUE is strongly influenced by the experience of fishermen, changes in fishing strategies and fishing efficiency, and various environmental and behavioural factors. Variations in CPUE do thus not necessarily reflect changes in abundance and obscures the comparison of catch rates to abundance on both temporal and spatial scales.

## 2.2.2 Boat activities

Boat activities were observed and recorded during a total of 154 sampling days on commercial chokka squid vessels. Boat activities include fishing (both squid and fish), squid processing (weigh-in, packing, glazing), searching for squid, travelling, sheltering from adverse weather, mooring outside harbours due to minor breakdown or for loading additional supplies, and unproductive periods where the crew rest or sleep while on the fishing grounds. The different activities are listed and expressed as a percentage of the total time in Figure 2.2.

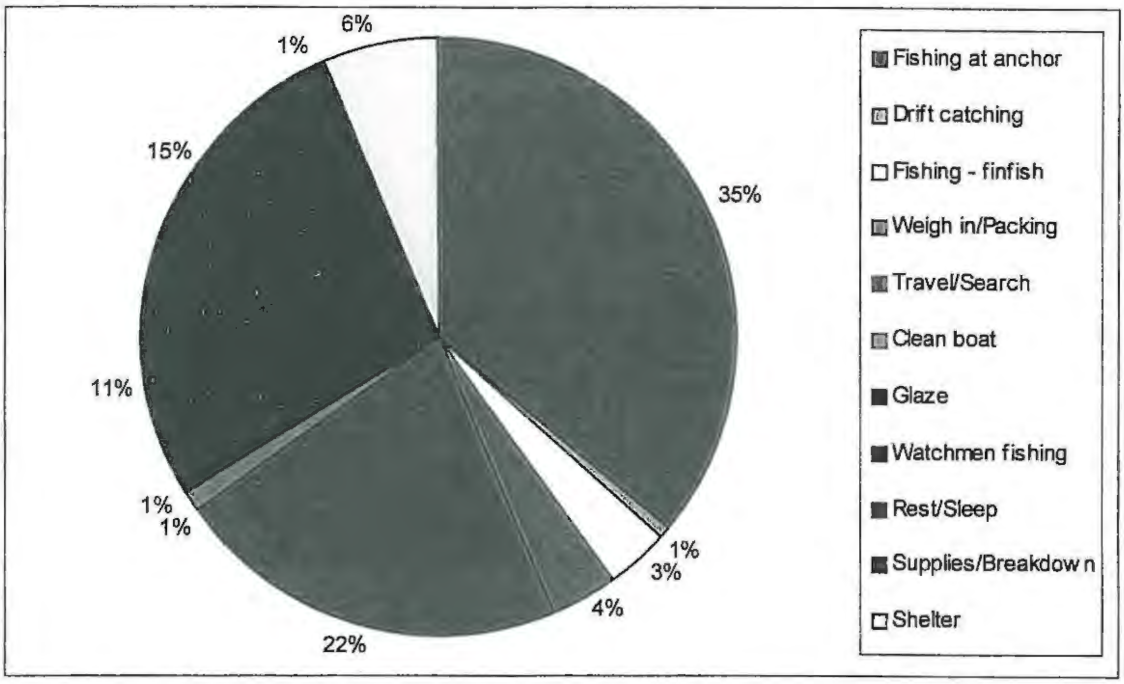

Fig 2.2: Different boat activities expressed as a percentage of total time at sea (154 days).

Fishing for chokka squid was categorised as 'fishing at anchor', 'drift catching' or 'watchmen fishing'. Drift catching applies to fishing during the day on the inshore fishing grounds and not to night fishing or fishing that used parachutes. During unproductive fishing periods at night, two crew members remain on watch for safety reasons. Fishing while on watch, termed watchman fishing, cannot be grouped with productive fishing times. Chokka squid fishing constitutes 47% of the total time, but only 36% if watchmen fishing is excluded. 'Fishing on anchor' remains the most important activity, followed by 'travel' and 'searching' for squid.

### 2.2.3 Catch fluctuations and seasonality

The most prominent characteristic of the South African *L. v. reynaudii* jig fishery is the erratic fluctuations in catches on hourly, monthly and annual time-scales. There are highly significant differences in catches ($p=0.0001$, Kruskal-Wallis Test Statistic, $H = 38.180$) and CPUE ($p<0.0001$, $H = 62.064$) between years (Fig. 2.3). The average annual catch from 1985 to 1997 is approximately 5200 ton with a range from 2600 to 9800 ton. The annual effort (number of fishing days) fluctuates similarly over the same period, ranging from 5000 to more than 20 000 fishing days, with an average of 13 600 days. The CPUE follows a trend similar to the total annual catch and effort, averaging 366 $kg \cdot boat^{-1} \cdot day^{-1}$. However, CPUE estimates should be interpreted with caution as factors such as the continuous change in boat sizes and "over-crewing" have not been taken into account. The high CPUE values in the initial stages of the fishery could be related to effects of non-linearity between CPUE and abundance.

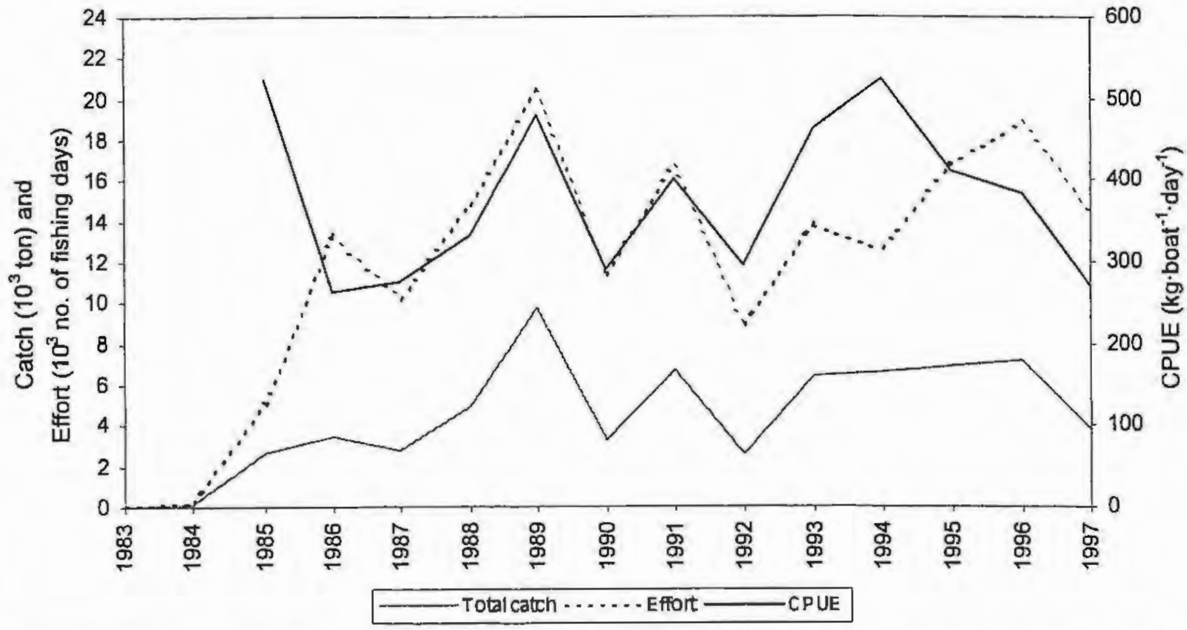

Fig. 2.3: Annual jig catches, effort and catch per unit effort of the *Loligo vulgaris reynaudii* fishery in South Africa, 1983-1997 (calculated from the Marine and Coastal Management Linefish database).

Catches during summer (April-October) are generally higher than during winter (May-September) (Fig. 2.4a). Anomalies, where winter catch exceeded summer catch, occurred during 1986 and are associated with the starting phase of the jig fishery, and 1989, a year of exceptionally high catch. A similar seasonal trend can be observed in the average CPUE over the same period (Fig. 2.4b). This trend is a reflection of the fact that summer is the peak spawning season for chokka squid and that the jig fishery tends to target spawning aggregations which yield high CPUE values.

Fishing occurs both during the day and night throughout the year. Daytime fishing is more common during the summer, whereas night-time fishing under lights is dominant during the winter months. Although there is a distinct change in the pattern of fishing activities between seasons, it is a continuous process with no obvious transition point. Due to characteristic fishing patterns between different seasons, the summer months are considered throughout this study to be between October and April.

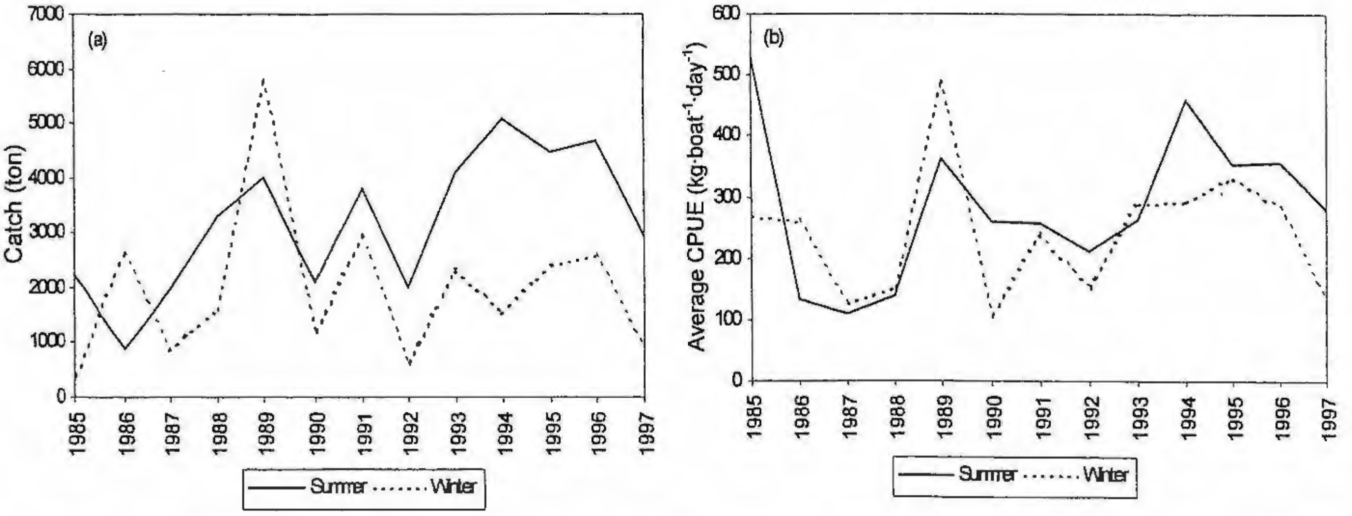

Fig. 2.4: (a) Seasonal catches of chokka squid in the jig fishery (summer – October to April; winter – May to September); (b) Average seasonal catch per unit effort (calculated from the Marine and Coastal Management database).

Figure 2.5 illustrates the fluctuation of the mean CPUE value at hourly intervals over a 24-hour period. During the day the fleet target squid on the inshore spawning area. This occurs throughout the year. The generally higher observed daytime CPUE values during summer reflect the higher abundance of squid on the inshore spawning grounds during peak spawning. At night most of the fleet moves further offshore and attracts squid using lights. The more offshore night fishing concurs with the general known behaviour patterns associated with squid spawning wherein most squid move offshore at dusk (O'Dor *et al.* 1996, Sauer *et al.* 1997). Dispersion of squid away from the spawning site results in lower night-time CPUE values; CPUE rises again when squid return at dawn.

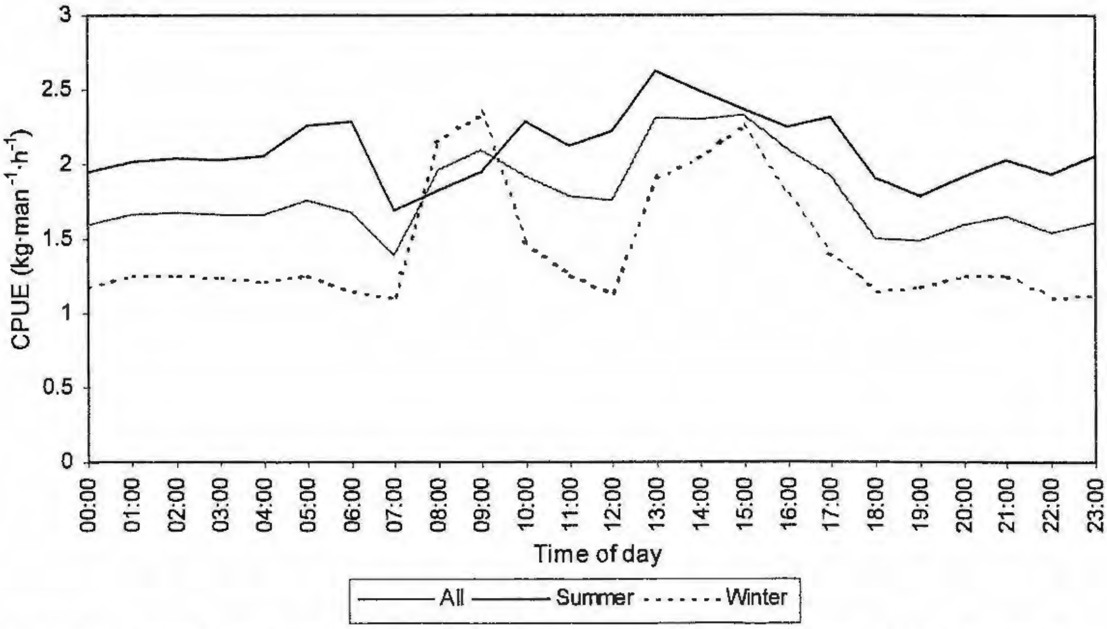

Fig. 2.5: Mean of jigged catch (kg·man$^{-1}$·h$^{-1}$) of *Loligo vulgaris reynaudii* over 145 fishing days in hourly intervals during summer, winter and both seasons combined.

The only available data for comparison to the observed diel jig catch fluctuation, although not directly, are that for trawled chokka squid. The relationship between time of day and observed catches for trawled *L. v. reynaudii* along the west coast of South Africa (05:00-20:00) (Augustyn 1991), the summer trawl catches along the south coast (Augustyn 1989) and the trawl catches of *L. v. vulgaris* in shallow waters (<110 m) off Northwest Africa (Porebski 1970), all show similar trends. In these studies catches were found to be best at 07:00 to 10:00 in the morning, less in the afternoon from 14:00 to 18:00, and poor at midday. The winter pattern reported in this study (Fig. 2.5) matches the pattern observed in the studies cited above, but the summer pattern shows very little similarity to other authors' results with the absence of poor midday catches and the presence of a distinct decrease in catches after sunrise (06:00 to 07:00). Furthermore, an early morning increase in catches (04:00 to 06:00 in summer, 07:00 to 09:00 in winter) is evident and is a phenomenon that has also been recognised by chokka squid fishermen as the "morning rush".

The poor resemblance of the data to that of other studies might be attributed to the expected prominent affect spawning behaviour can have on the diel patterns of jig catches. Sauer *et al.* (1997) monitored the diel patterns of squid visitations to an egg bed during summer spawning and recorded the ratio of hours present to hours monitored. The observed summer CPUE pattern correlated slightly to these migrations (r=0.28) and marginally better with the movements of male squid (r=0.31). The inadvertent selectivity of the fishery for large males (Sauer *et al.* 1997) might be related to this. However, these low correlations highlight the complexity of such relationships and indicate the existence of additional influencing factors such as gear selectivity. To fully explain these fluctuations in hourly catch rates, the effect of fishing methods and fishing pressure on aggregating squid should, in future, be considered. The necessity for more accurate hourly catch rate data concurrent with detailed behavioural observations was highlighted.

### 2.2.4 Catch distribution

Chokka squid are hand-jigged mainly on the spawning grounds (Augustyn 1990) (Fig. 2.6). Small catches are occasionally recorded towards more extreme easterly and westerly locations, i.e., on the south coast of Kwazulu-Natal and Port Nolloth on the west coast.

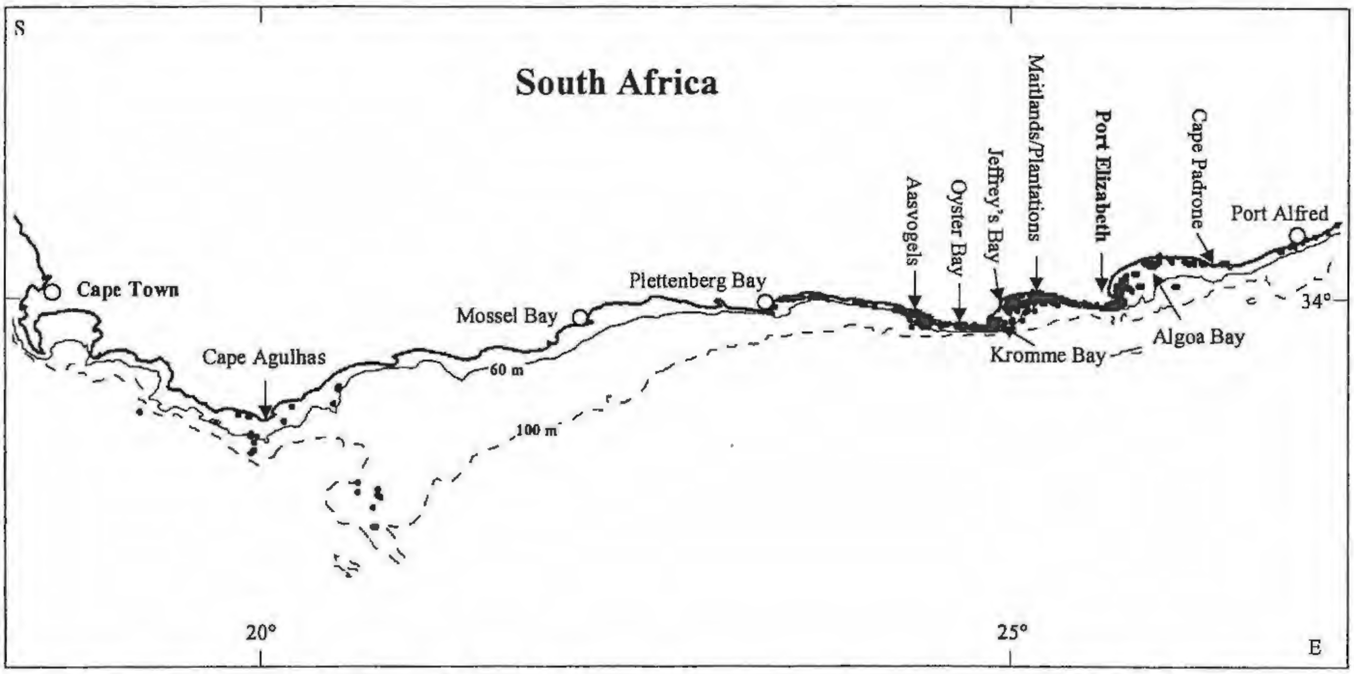

Fig. 2.6: Map of the South African south coast displaying the main fishing areas and daytime fishing locations that are associated with the inshore spawning grounds of *Loligo vulgaris reynaudii*.

Traditionally, the jig fishery was based close inshore (<50 m) near river and beach launch sites. The most utilised fishing grounds were Kromme Bay, Jeffrey's Bay, Oyster Bay and Maitlands (Table 2.4).

Table 2.4: The best catch locations throughout the year in terms of total number of fishing days spent in the area and the total yearly catch in the area (from Marine and Coastal Management Linefish database).

| Year | Most important location in terms of effort (no. of fishing days) | | Most important location in terms of catch (ton) | |
|---|---|---|---|---|
| 1985 | Kromme Bay | 1225 | Kromme Bay | 570 |
| 1986 | Oyster Bay | 2403 | Oyster Bay | 842 |
| 1987 | Kromme Bay | 1736 | Oyster Bay | 594 |
| 1988 | Kromme Bay | 2716 | Maitlands/Plantations | 986 |
| 1989 | Maitlands/Plantations | 4520 | Maitlands/Plantations | 2721 |
| 1990 | Maitlands/Plantations | 2452 | Maitlands/Plantations | 783 |
| 1991 | Jeffrey's Bay | 3609 | Jeffrey's Bay | 1025 |
| 1992 | Oyster Bay | 1259 | Oyster Bay | 402 |
| 1993 | Jeffrey's Bay | 2284 | Jeffrey's Bay | 952 |
| 1994 | Jeffrey's Bay | 2369 | Aasvogels | 898 |
| 1995 | Jeffrey's Bay | 3534 | Jeffrey's Bay | 1124 |
| 1996 | Jeffrey's Bay | 2338 | Aasvogels | 1280 |
| 1997 | Maitlands/Plantations | 1689 | Port Alfred | 477 |

The move to larger deckboats has led to increased exploitation in areas further west (e.g., Aasvogels) and east (e.g., Algoa Bay) (Fig. 2.6). A decrease in effort and catch in the main fishing area, with a concomitant increase in other areas, can be observed since 1992, when the use of deckboats increasingly became the norm (Fig. 2.7). Areas west of the main area (i.e., west of Aasvogels) became less utilised as the fishery developed, possibly due to lower productivity.

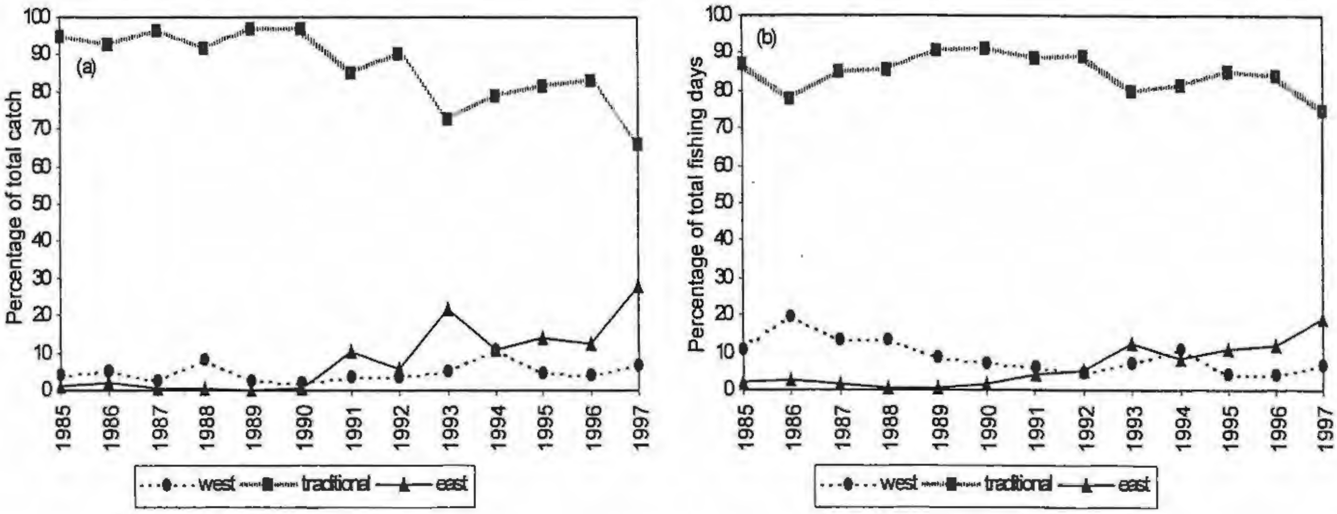

Fig. 2.7: Importance of three fishing regions in terms of (a) catch, the weight caught in the region per year expressed as a percentage of the total annual catch; and (b) effort, no. fishing days spent in the region per year expressed as a percentage of total annual no. of fishing days. The regions are: west of Aasvogels (west); between Aasvogels and Algoa Bay (traditional); and east of Algoa Bay (east) (calculated from the Marine and Coastal Management database).

High competition among boats and possibly the poor catches during 1997, forced boats to search and explore areas outside the traditional fishing area. This led to a marked increase in effort and catches in these extreme locations. However, this tendency was not as pronounced in the western areas, although the Cape Agulhas area experienced a notable increase in effort. It should be kept in mind that the western area is smaller than areas eastwards, and is characterised by difficult fishing conditions and accessibility. The tendency to explore areas outside the traditional fishing area was, however, very prominent for the eastern areas (east of Algoa Bay), mainly around Port Alfred (Table 2.4). In 1997, the eastern areas produced 28% of the total chokka squid caught in South Africa compared to a 13% contribution in 1996 (121% increase) (Fig. 2.7a). Effort in the eastern areas also increased from 12% to 19% of the total (62% increase) over the same period (Fig. 2.7b). Higher exploitation rates in areas both east and west of the main traditional fishing area continued during the 1998 fishing season (pers. obs.).

The lower exploitation levels in areas outside of the traditional fishing area were previously considered to serve as protective or "reservoir" areas. An increase in fishing in these areas, including the exploitation of squid over the deeper spawning areas, has increased the pressure on the chokka squid resource.

## 2.3 CLIMATIC AND INSHORE OCEANOGRAPHIC CONDITIONS ON THE CAPE SOUTH COAST

### 2.3.1 General

The oceanographic conditions around southern Africa are amongst the most varied in the world. Two major boundary current systems sweep the coast of southern Africa, i.e., the Agulhas Current flowing southwards on the east coast and the Benguela Current flowing northwards on the west coast. The tip of the continent (36°S) is far enough south to deflect part of the Antarctic Circumpolar Current, which travels from west to east in the subantarctic Southern Ocean, up the west coast to form the cold Benguela Current (Ross 1988). The warm Agulhas Current forms part of the Southern Indian Ocean current gyre (Ross 1988) and is one of the largest western boundary currents in the world (Van Ballegooyen *et al.* 1991). The Agulhas Current closely follows the edge of the continental shelf along the east coast until it reaches Cape Padrone (Fig. 2.1). West of this, the Current moves progressively away from the coast as the shelf widens (Lutjeharms 1998). At about 40°S, the Current turns eastwards and is referred to as the Agulhas Return Current (Ross 1988). The Agulhas Current has an important effect on the coastal waters of the eastern and southern Cape coasts, through boundary phenomena such as eddies, plumes and filaments (Lutjeharms 1998). The hydrography of the coastal waters between the Agulhas Current and the coastline is complex and is influenced by the proximity of the Agulhas Current. Since chokka squid spawn in this area, it is necessary in the context of this study to gain an understanding of the hydrographic conditions.

### 2.3.2 Climate on the south coast

Prevailing weather has a pronounced influence on oceanographic conditions, since the large scale movement of water in the oceans, sea temperatures, as well as the local occurrences of currents and waves are weather related phenomena (Schumann 1989, Stone *et al.* 1998).

The weather patterns over southern Africa are dominated by two semi-permanent high pressure systems found over the South Atlantic and south-west Indian Oceans, respectively (Hunter 1987). The latitudinal movement of the centres of these anticyclone systems, from summer to winter, results in markedly different seasonal wind regimes. In summer, the high pressure systems are situated further south than in winter and deflect frontal systems to the southern part of the continent. In winter, the frontal systems often pass over the continent and are frequently preceded by a shallow low pressure system (coastal lows).

The principal influence on the weather of the south coast and Eastern Cape region comes from the west (Schumann 1989). Although subject to large scale climatic events, many variations in temperature, rainfall and wind occur over very short distances in the region (Stone 1988, Stone *et al.* 1998), resulting in a large degree of climate variation within a relatively small area.

Longshore winds dominate in the region (Schumann 1989). Westerly winds prevail both during summer and winter (Stone *et al.* 1998). It has been shown that at most sites along the coastal boundary of the Agulhas Bank, easterly winds predominate over westerly winds in summer, whereas in winter the situation is reversed (Schumann 1992). The easterly wind stress drives coastal upwelling, particularly at the major south coast headlands of Cape Seal, Cape St. Francis and Cape Recife (Schumann *et al.* 1982, 1988), and has important implications for local sea conditions.

### 2.3.3 Oceanography of the south coast

#### 2.3.3.1 Bathymetry

Coastal and bottom topography strongly influence ocean current and temperature structures in local regions (Schumann and Beekman 1984, Schumann *et al.* 1988). The south coast is characterised by a rugged, steep coastline, broken by log-spiral shaped embayments associated with headlands or capes (Birch 1981). The profile of the sea floor along this region exhibits a well defined continental shelf (200 m isobath). Further to the east, off Cape Padrone, the shelf is steep and narrow, at approximately 30 km (Lutjeharms 1998). West of Cape Padrone the shelf widens and the continental slope is more gentle (Lutjeharms 1998). Further west, directly south of Cape Agulhas, the shelf break is 270 km from the coast (Schumann *et al.* 1988, Goschen and Schumann 1990). Along the south coast, 32% of the inshore region is less than 100 m and there is very little outer shelf between 201-400 m (13%), as compared to the west coast of South Africa with 10% and 49%, respectively

(Roberts and Van den Berg in prep. b). In terms of sediment texture, the shelf region off the south coast is comprised mainly of sand (47%) and gravelly sand (20%), as compared with primarily dominant muddy sand (79%) along the west coast (Roberts and Van den Berg in prep. b).

#### 2.3.3.2 Currents

The Agulhas Current has a varying influence on the shelf waters depending on the shelf width and coastline shape (Lutjeharms 1981). Although the Current is the dominant ocean-scale feature off the east coast of South Africa (Goschen and Schumann 1990), it has a less pronounced influence on the coastal waters off the south coast, as it diverges away from the coast following the edge of the continental shelf. This is evident by the increase in distance of the average inshore boundary of the Agulhas Current (defined as the position of the inshore thermal front), at 44 km off Cape Padrone and 60 km off Cape Recife (Goschen 1988).

Despite the diversion from the coastline along the southeast coast, the Agulhas Current water occasionally penetrates onto the shelf in the form of short-term warm surface plumes attached to shear-edge eddies and the longer term Natal Pulses (Goschen and Schumann 1990). According to these authors, a so-called Natal Pulse occurs on average about twice a year and is defined as "an extensive meander in the core of the Agulhas Current, flowing around an inshore cold-water eddy, propagating as a solitary feature or in series with others, that appears to originate in the Natal Bight and can be traced southward along the whole southeast coastline".

Studies have shown that warm surface waters from the inshore, leading edge of large meanders in the Agulhas Current occasionally circulate as a thin surface layer into the log-spiral shaped bays along the south coast, viz. Algoa and St Francis Bay (Goschen and Schumann 1988, 1990). Goschen and Schumann (1988) have indicated that wind-forcing is likely to play a major role in this circulation of warm water. During a south-westerly wind, the resulting Ekman transport in the surface layers can force a plume attached to a shear-edge eddy to move further onshore, causing a rise in sea surface temperature (SST) (Goschen and Schumann 1990). Otherwise, there is little direct influence of the Agulhas Current on the south coast (Schumann *et al.* 1982).

By comparison, the inshore waters are influenced and governed by short-term events on smaller spatial scales, resulting in more complex hydrography and water movements. The influence of wind-forcing on water movements is important on the south coast (Schumann *et* *al.* 1982, Goschen and Schumann 1988). For example, winds can generate local currents, which are important for mixing inshore waters.

In contrast to the strong flow of the Agulhas Current, flow on the mid and inner shelf region of the south coast is weak and variable (Goschen and Schumann 1988, Boyd *et al.* 1992). Current speeds exceeding 1 $m{\cdot}s^{-1}$ do, however, occur at times on the inner shelf (Schumann and Beekman 1984). The inshore currents are dominantly barotropic (with little variation in current speed and direction with depth, where reference to water movement includes the whole water column) along the whole south coast (Goschen and Schumann 1988, Boyd *et al.* 1992). However, Roberts and Van den Berg (in prep. a) found an increase in frequency of baroclinic currents (large variation in current speed and direction with depth) during the summer months along the south coast. Such currents were reported to coincide with periods during which vertical stratification was most intense. The net direction of the flow near the coast mainly reflects wind-forcing (Goschen and Schumann 1988, Whittle 1996) and swell angle, and is modified by topography and coastline shape (Goschen and Schumann 1988). As westerly winds form the greatest portion of the total wind force, the overall effect may be an eastward advection of the inshore waters (Schumann *et al.* 1982, Whittle 1996). However, available evidence indicates that there are frequent current reversals (towards the west) interspersed with slack periods (Ross 1988).

#### 2.3.3.3 Upwelling

Coastal upwelling strongly influences the inshore coastal waters along the south coast. Alongshore wind stress is the driving force behind this process (Bakun 1990). Easterly wind stress along the south coast causes upwelling to occur at the major capes (Schumann *et al.* 1982, 1988, Beckley 1983, Boyd and Shillington 1994). The greatest frequency of upwelling occurs in summer and autumn, during which easterly winds are dominant (Schumann *et al.* 1982, Beckley 1983, Schumann and Martin 1991).

The mechanism for coastal upwelling involves winds blowing parallel to the coast. Momentum is transferred to the surface layer by friction. Coriolis force acts at right angles to the direction of motion causing the surface water to move left (southern hemisphere) of the direction of the wind (Ekman drift). When surface water is forced offshore by wind, it is replaced by the vertical transport of colder, nutrient-enriched bottom water. The thermocline (layer where there is a sharp decrease in temperature with depth) moves upwards and may reach the surface causing a well-defined surface frontal zone with colder inshore water and warmer water offshore. The cold, upwelled water is then available to flood the adjacent coastal embayments (Boyd and Shillington 1994, Goschen and Schumann 1995).

The duration of wind-induced upwelling depends on local conditions such as ocean structure, bottom topography and past history (Schumann *et al.* 1982). With the onset of a suitably strong easterly wind, large displacements of the thermocline can occur within one to 12 hours (Oosthuizen 1999). These gradients of upwelling occur mostly at a rate of 0.1-1.9 $°C{\cdot}h^{-1}$, and temperature changes range between 3-10°C (Oosthuizen 1999). Such wind-induced upwelling is generally of short duration, but may still take several days to dissipate after the wind stops blowing (Schumann *et al.* 1982, 1988). Westerly winds, through wave action, cause vertical mixing and therefore enhance the breakdown of the thermocline (Beckley 1983, Schumann and Beekman 1984). These winds also disperse cold surface water (Goschen and Schumann 1995). The offshore extent of coastal upwelling is generally confined to a few kilometres (Schumann *et al.* 1982).

To the east of Cape Padrone upwelling occurs on a larger scale. The driving force is believed to be due to the divergence of the Agulhas Current from the coast (Schumann *et al.* 1988). Deeper, cooler, water from below the tropical surface water is lifted onto the shelf between East London and Cape Padrone to form a bottom layer on the eastern Agulhas Bank. Persistent north-easterly winds force warmer surface water (to a depth of 50 m) offshore and cause upwelling of the bottom layer adjacent to the coast. Schumann *et al.* (1988) proposed that this divergent upwelling has an important influence on waters in Algoa Bay. The time-scales associated with divergent upwelling are in sharp contrast to wind-induced upwelling events. Cold water has been observed to penetrate into Algoa Bay and persist for several weeks, probably continuously fed by cold water from the east (Schumann *et al.* 1988).

Plankton production is stimulated by upwelling which can influence the population dynamics of various fish species (Field *et al.* 1980, Mann 1992). Although upwelling along the south coast does not have the same economic significance as it does on the fishery of the west coast of South Africa (Schumann *et al.* 1982), it still provides productive environments.

#### 2.3.3.4 Temperature structures

Various papers have described the temperature structure over the Agulhas Bank (see Zoutendyk 1973, Schumann and Beekman 1984, Carter *et al.* 1987, Boyd *et al.* 1992, Largier *et al.* 1992, Boyd and Shillington 1994) and trends in SST along the South African coast (see Christensen 1980, Beckley 1983); with the exception of Algoa Bay (Beckley 1988, Goschen and Schumann 1988, Schumann *et al.* 1988) and Kromme Bay (Oosthuizen 1999), the inshore areas of the south coast are not well represented.

The shelf waters over the Agulhas Bank are characterised by strong, shallow thermoclines (Carter *et al.* 1987) that show marked seasonal variation in structure along the south coast. An intense thermocline forms during summer and weakens during winter (Schumann and Beekman 1984). The temperature structure of the inshore area along the Cape south coast is characterised by strong seasonality as well as spatial and temporal variability, especially during summer months (Schumann *et al.* 1982, Beckley 1983, 1988, Oosthuizen 1999). The change in temperature can be ascribed to various factors such as heat exchange between sea and atmosphere, mixing by wave action, convective stirring, or advection by currents and wind stress (Perry and Walker 1977) and is therefore mostly a function of local winds, local coastal configuration and the prevailing temperatures of the water masses in the vicinity (Lutjeharms 1998). Generally, along the south coast, temperature decreases during easterly winds due to upwelling, but increases as warmer water is forced towards the coast by westerly winds.

With different factors influencing the coastal waters, and because of the different origins of the water, substantially different temperature records and their associated means can be expected on a spatial scale along the coast. For example, near Port Elizabeth waters are influenced to a larger extent by seasonal changes as compared to those near East London; this is illustrated by a difference in the seasonal mean temperature changes in the areas, of 5 °C and 2 °C, respectively (Lutjeharms 1998). This difference has been attributed to a more steady influence of the Agulhas Current near East London. Spatial differences are also evident on a smaller scale, where marked temperature fluctuations occur on the seaward side of a cape as compared to inside Algoa Bay (Beckley 1983). Besides the strong influence of upwelling on the water temperature in the vicinity of a cape, the bays along the south coast are shallower and generally expected to have well mixed waters (Goschen and Schumann 1988).

Temperature data collected during this study (154 random CTD dips, from 1996-1998) indicate that four types of vertical temperature structures generally occur in the coastal waters. These are depicted in Figure 2.8; they include: a continuous decrease in temperature with depth, but no well developed thermocline (Fig. 2.8a), slight and strong thermoclines (Fig. 2.8b, c), and isothermal conditions (Fig. 2.8d). A sequence of temperature profiles associated with an upwelling event are illustrated by Figures 2.8b, c, d. Figure 2.8b illustrates the movement of cold water towards the shore and along the bottom with the onset of an easterly wind of adequate strength. The established thermocline moves towards the surface (Fig. 2.8c) where it forms either a thermal front or is dissipated into a relatively isothermal profile (Fig. 2.8d).

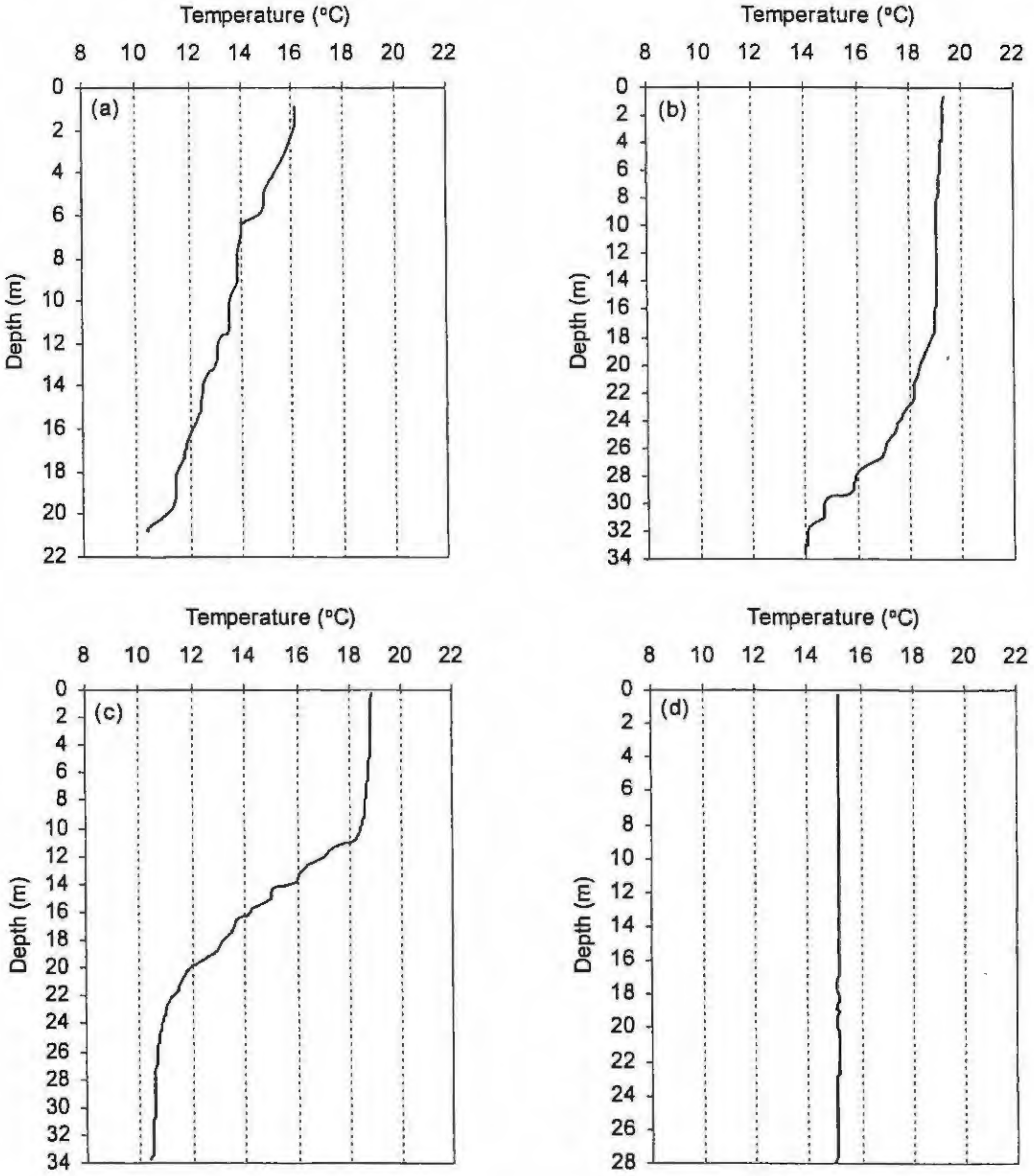

Fig. 2.8: Examples of different temperature profiles in the water column of the inshore water along the Cape south coast.

Oosthuizen (1999) found that temperature gradients ranged from 0.08 to 8.47°C. Similarly, in this study, temperature gradients were categorised into either isothermal (<3°C), minor (3-5°C) or major events (>5°C). The frequency of occurrence of these gradients is illustrated in Figure 2.9. The results indicate generally stable temperature regimes along the south coast (55% isothermal conditions). The distinct seasonal pattern of a stable winter and a variable summer (Schumann *et al.* 1982, Beckley 1983, 1988, Oosthuizen 1999) was supported by the results of this study.

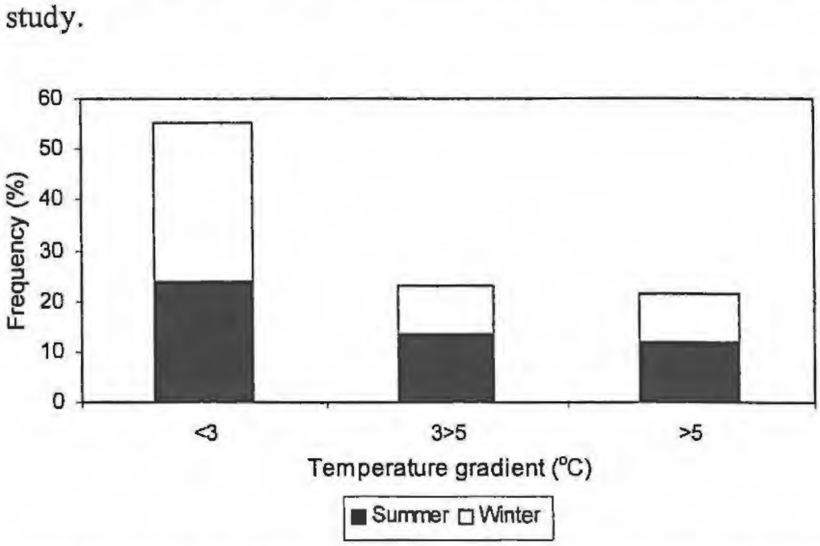

Fig. 2.9: The frequency of occurrence and seasonality of three categories of temperature gradients measured inshore along the Cape south coast.

### 2.3.3.5 Turbidity

The widespread occurrence of a high benthic turbidity or nepheloid layer (in an oceanographic context, bottom water of unusual turbidity) along the south coast, was first noticed by Zoutendyk (1973). The nepheloid water is composed of an inorganic and an organic fraction (Zoutendyk and Duvenhage 1989). The inorganic fraction is derived from the mud belts which are located parallel to the coast on the inner shelf, and the organic fraction is variously derived from the defecation and death of plankton, and the abrasion of macrophytes from reefs (Zoutendyk and Duvenhage 1989).

The turbidity profile types observed and recorded during this study (Figure 2.10) are similar to those observed by Zoutendyk and Duvenhage (1989). Similar to Zoutendyk (1973) and Zoutendyk and Duvenhage (1989), the nepheloid layer was found to be between one and 10 m thick. This layer is located below the thermocline where there is a marked drop in light transmission, from 50-70% at the surface to zero near the bottom (Zoutendyk 1973).

Turbid waters were always found to be associated with the bottom, and most turbidity (73%) confined to the bottom 1-2 meters (Fig. 2.10b). Low turbidity was usually found higher up in the water column (Fig. 2.10c), and is probably associated with turbulent mixing within the water column breaking up the nepheloid layer. Turbidity was never observed in the top half of the water column.

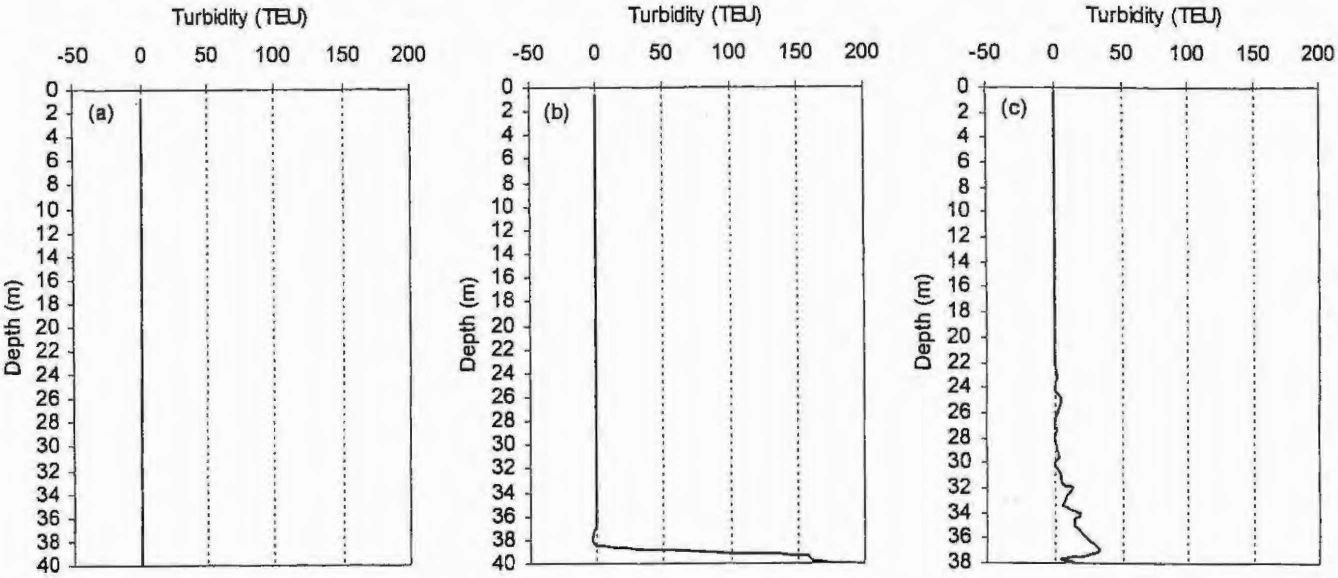

Fig. 2.10: Examples of different turbidity profiles (from 154 random CTD dips) found in the water columns of the inshore waters along the Cape south coast. TEU – turbidity engineering units (see Fig. 3.3).

The frequency of occurrence and seasonality of turbidity events is illustrated in Figure 2.11. In general, turbidity events are not considered to be common and were found to exist in 30% of the CTD deployments analysed. In the remaining 70% of the turbidity profiles sampled along the south coast, clear water or zero turbidity, was found throughout the water column (Fig. 2.10a). Most of the turbidity events observed were of moderate levels, with only 6% found towards extreme levels (>200 TEU). The highest level of benthic turbidity measured during this study was 3895 turbidity engineering units (TEU) or 47 nephelometric turbidity units (NTU) (see Fig. 3.3, Chapter 3). The occurrence of turbidity events was found to be slightly higher during winter (54% occurrence) than summer.

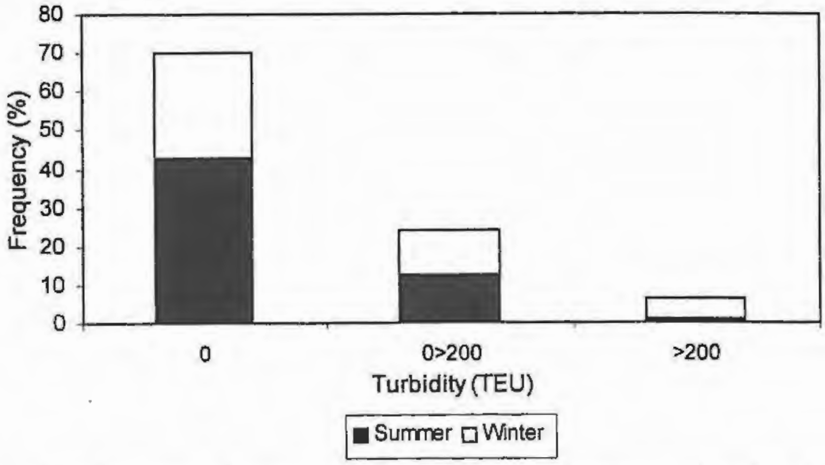

Fig. 2.11: The frequency of occurrence and seasonality of three categories of turbidity events (average of bottom meter TEU) measured inshore along the Cape south coast

In contrast to the clarity of upwelled water found on the west coast of South Africa, Zoutendyk (1973) found the upwelled water along the south coast to be of lower clarity. In this study, upwelling (considered as the presence of a vertical temperature gradient greater than 3°C) was normally associated (66% frequency) with zero turbidity. Turbidity events seemed to have a higher frequency (63%) and longer duration within the shallow bays (e.g., Kromme and Algoa Bay) as compared with the seaward side of the capes.

# CHAPTER 3

# ENVIRONMENTAL INFLUENCES ON CHOKKA SQUID CATCHES: AN *IN-SITU* STUDY

## 3.1 INTRODUCTION

Oceanographic features and environmental conditions have a significant effect on fish and other marine life. Even subtle changes in the physical environment may cause profound changes in the abundance and distribution patterns of populations (Kareiva 1995). The distinct characteristics and short life cycle of cephalopods, squid in particular, make cephalopod stocks particularly susceptible to environmental conditions and changes (Pierce 1995, Roberts *et al.* 1998).

Both fishermen and scientists strongly believe that the unusually high variability in *Loligo vulgaris reynaudii* catches is strongly linked to the diverse and highly variable marine environment around South Africa. An understanding of the relationship between squid catches and the environment might lead to the ability to forecast these fluctuations, to the advantage of the fishing industry and the resource managers (Roberts in prep.). Environmental research on squid, however, has received little attention globally and represents only a very small portion of the total published literature on squid (Roberts *et al.* 1998).

The species which support the largest squid fisheries, in particular the shelf slope species *Illex illecebrosus* and *Todarodes pacificus*, have received the most attention in terms of environmental research, with *L. v. reynaudii* being the most studied neritic species (Roberts *et al.* 1998). Examples of such studies include the relationship, influence or effect of physical oceanographic features and processes on squid distributions (e.g. O'Dor 1988a, Nakamura and Siriraksophon 1992, Rodhouse *et al.* 1992, Trites 1983, Fedulov and Arkhipkin 1986, Murata 1989, Roberts and Van den Berg in prep. b), the spawning process (e.g. Trites 1983, Roberts 1998a) and embryonic development (e.g. O'Dor *et al.* 1982, Oosthuizen 1999). The relationship between the environment and squid abundance or catch has received the most attention (e.g. Serchuk and Rathjen 1974, McInnis and Broenkow 1978, Roberts 1983, Coelho and Rosenberg 1984, Fukada *et al.* 1991, Sauer *et al.* 1991, Roberts and Sauer 1994).

These studies have been primarily descriptive, but some empirical relationships have been reported for some species.

The majority of the empirical models relating environmental parameters to abundance were based upon a "black box" statistical approach (i.e., no need for knowledge of the underlying dynamics of the processes involved (Roberts *et al.* 1998)), where an attempt was made to find simple, direct statistical correlations between environmental parameters and squid catches using correlation and regression analyses. Correlations were successfully found for *I. illecebrosus* (Coelho and Rosenberg 1984, Dawe *et al.* 1998) and *Loligo forbesi* (Pierce 1995), and demonstrated that readily measurable environmental parameters such as temperature and salinity can be useful predictors of abundance.

Initially, environmentally linked research on *Loligo vulgaris reynaudii* considered experimental jig catches in False Bay (Augustyn 1989) and trawled catches along the west coast (Augustyn 1991). Temperature, wind direction and low oxygen concentrations on the west coast were identified as possible factors influencing catch. The environment-catch relationship becomes more complex on the inshore fishing grounds, with the commercial catches probably reflecting the influx of squid into shallow water to spawn (Augustyn 1990, Sauer *et al.* 1991). Spawning chokka squid are mostly caught above egg masses, and sustain the jig fishery. The greatest potential for the influence of the physical environment arises during the spawning, egg incubation and larval phases of the chokka squid life cycle (Augustyn *et al.* 1994). Previous studies on the inshore spawning grounds (Sauer *et al.* 1991, Roberts and Sauer 1994) suggested an environment-catch relationship, but were not conclusive. This study takes a step towards finding a quantifiable relationship using the "black box" approach, i.e., locating simple statistical correlations between environmental parameters and inshore chokka squid catches on a short time-scale (hours to days).

Catch rates are used to represent abundance, and the two terms are used interchangeably, throughout this study. In this regard, a number of assumptions had to be made when considering the catch records. Firstly, the inshore presence of squid is directly related to spawning activity (Sauer *et al.* 1991); therefore catch rates are assumed to be directly proportional to spawning intensity (i.e., good catch values imply an increase in spawning activity). Secondly, it has been assumed that chokka squid are homogeneously distributed within a spawning or fishing area. The third assumption implies that squid are always available in the area. Lastly, although experienced fishermen target spawning aggregations while inexperienced fishermen rather search for boat aggregations, this study assumes that all skippers have the same fishing skills and ability to locate spawning squid.

## 3.2 MATERIALS AND METHODS

### 3.2.1 Sampling strategy

Eighteen sampling trips, averaging 8.6 days per trip, were conducted on board five commercial chokka squid jigging vessels between May 1996 and May 1998. Initially monthly trips for at least 10 consecutive days at sea were intended, but factors such as the weather, equipment breakdown and irregular sailing dates limited the frequency and duration of trips. Sampling stations during this period were distributed throughout the main spawning area between Plettenberg Bay and Port Alfred (Augustyn 1990, Sauer *et al.* 1992, Sauer and Smale 1993) (Fig. 3.1).

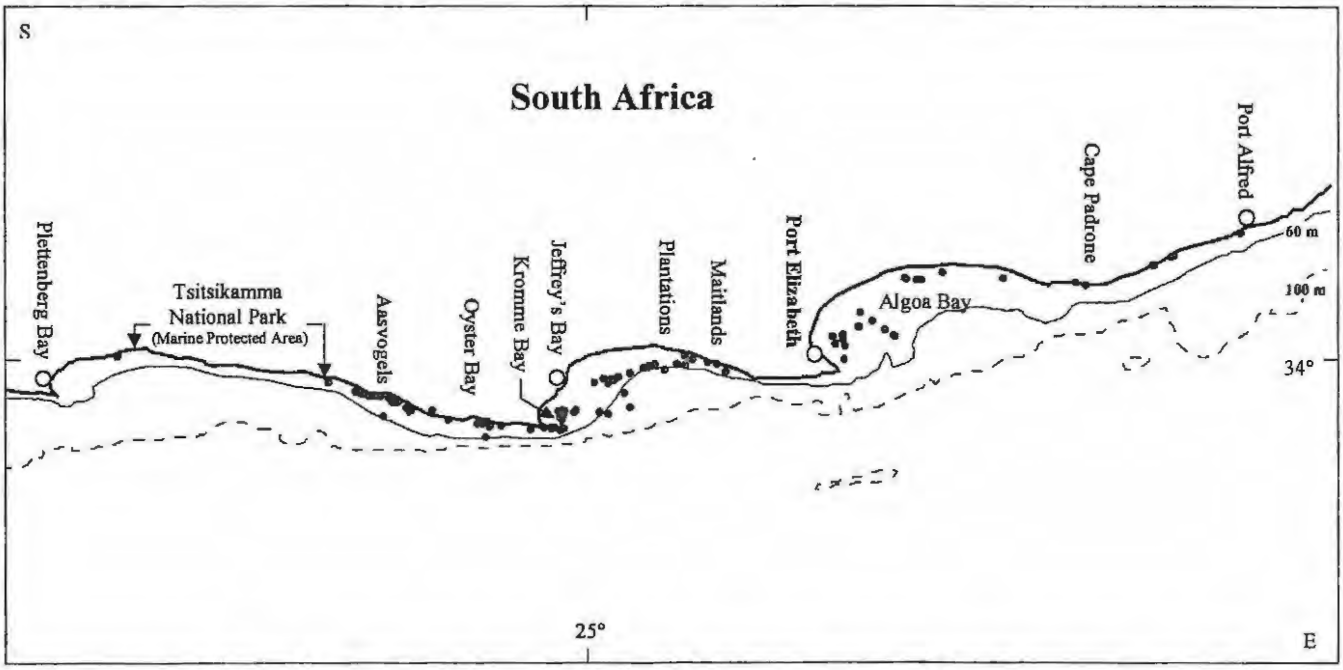

Fig. 3.1: Map of the South African south coast displaying sampling stations along the main inshore spawning area of *Loligo vulgaris reynaudii* between Plettenberg Bay and Port Alfred.

Table 3.1 summarises the sampling trips in terms of days and hours spent at sea. Equipment failure or breakdown, delay in the set-up of the sampling equipment and time spent assisting with the boat activities led to a reduced time available for gathering data. Effective sampling days were reduced from 157 to 130.5. This non-sampling period is defined as 'days lost' in Table 3.1.

Table 3.1: Summary of sampling trips on commercial squid jigging vessels.

| Date | # days | # hours | # CTD dips | # days lost | (hours lost) |
|---|---|---|---|---|---|
| May 1996 | 8 | 163 | 16 | 0 | |
| Jul 1996 | 9 | 191 | 12 | 0.5 | (12) |
| Aug 1996 | 8 | 169 | 9 | 0 | |
| Sept 1996 | 5 | 100 | 5 | 0.7 | (16) |
| Oct 1996 | 10 | 214 | 16 | 3 | (71.4) |
| Jan 1997 | 15 | 330 | 20 | 0.6 | (15) |
| Feb 1998 | 3 | 53 | 0 | 3 | (53) |
| Apr 1997 | 5 | 105 | 3 | 1 | (23.5) |
| May 1997 | 10 | 212 | 10 | 0 | |
| Jun 1997 | 7 | 139 | 4 | 2 | (46.8) |
| Jul 1997 | 5 | 89 | 2 | 1.4 | (33) |
| Aug 1997 | 5 | 90 | 2 | 1.7 | (40.9) |
| Sept 1997 | 8 | 160 | 10 | 1.1 | (26.5) |
| Oct 1997 | 10 | 211 | 6 | 4.9 | (118.3) |
| Nov 1997 | 10 | 220 | 11 | 0 | |
| Dec 1997 | 5 | 99 | 2 | 1.7 | (41) |
| Feb 1998 | 15 | 325 | 13 | 3.1 | (75.5) |
| Apr 1998 | 5 | 92 | 2 | 0.6 | (13.8) |
| Apr/May 1998 | 14 | 310 | 21 | 1.2 | (28.8) |
| Total: | 157 | 3272 | 164 | 26.5 | 615.5 |

Effort data (man·hour) were collected by noting the number of men fishing for a given time period and ranged from 10 minutes to one hour, depending on the fishing conditions (rate of catches) and time of day. Man hours fished were calculated for every recorded interval to the nearest minute. Although the number of men fishing continuously changed, these intervals appeared to be most practical and enough to give a clear representation of hourly effort over a fishing period.

Catch records (kilograms) were noted at irregular intervals and depended on weigh-in times selected by the skippers between fishing periods. Hourly CPUE values ($kg \cdot man^{-1} \cdot h^{-1}$) were calculated using catch (kg) and total effort (man·hour) over the fishing period. The geometric mean was used to determine average catch rates. As the catch rate data contain zeros and are skewed towards lower values, they were transformed to natural logarithm ($\ell n(CPUE+1)$). The average CPUE was calculated using a formula modified from Rogers (1992):

$$\text{Average CPUE} = (\text{antilog}\ \{\Sigma\ \ell n(CPUE+1)/n\})-1$$

The environmental and oceanographic parameters measured during this study were selected and prioritised on the basis of results from previous studies (Augustyn 1989, 1991, Sauer *et al.* 1991, Roberts and Sauer 1994, Roberts 1998a, Roberts and Van den Berg in prep. b). The oceanographic and environmental parameters measured were: water temperature, turbidity, salinity, water depth, wind velocity, wind direction, swell height, nature of the seabed (bottom structure), current speed and current direction.

An *Ocean Sensor Model OS200* CTD (conductivity, temperature and depth) (Fig. 3.2) was used to measure salinity, temperature and water depth. Data in engineering units were transmitted every second to a notebook computer on the surface via a 100 m cable. These data were then converted into real temperature, depth and salinity values by means of a software programme (written by P. Claassens, Marine and Coastal Management). An *OBS-3* turbidity sensor was attached to the CTD frame (Fig. 3.2) and functioned through the same system and software programme. Turbidity values were recorded in engineering units (mV), referred to in this study as turbidity engineering units (TEU) (see Fig. 3.3). The CTD was calibrated prior to the start of the study, and recalibrated by the manufacturers in March 1997.

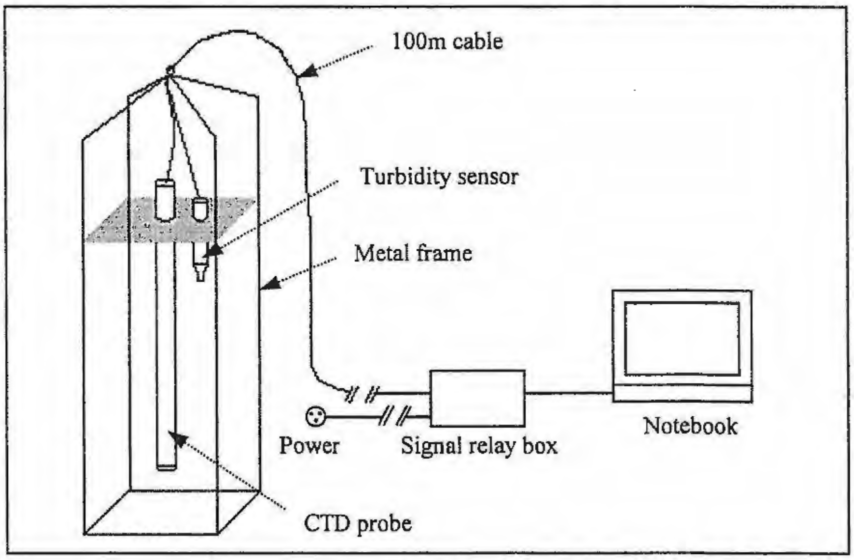

Fig. 3.2: Schematic diagram of the CTD probe, turbidity sensor and data recording sampling set-up.

Water temperature was measured in degrees Celsius (accuracy of ±0.01°C). Determining the depth of the thermocline was problematic due to the observed diverse range of temperature profiles. Temperature gradient (the difference between sea surface temperature (SST) and bottom temperature (BT)) functioned as an alternative indicator of the presence or absence of a thermocline. Water depth was transformed from pressure units (accuracy of ±0.5%), recorded in meters and compared to the depth measurement of the echo-sounder on the fishing vessel. Only maximum depth was used in analysis. Salinity values were calculated from CTD measurements in practical salinity units (PSU) (accuracy of ±0.03 PSU).

The general relationship between the measured turbidity engineering units (TEU) output by the CTD and nephelometric turbidity units (NTU) is shown in Figure 3.3 (data supplied by K. Dorfler, University of Port Elizabeth). TEUs measured in this study need to be divided by a factor of 1.6 to be compatible to that used in the graph. A table which will relate TEUs, NTUs and actual horizontal underwater visibility is currently being assembled (Dorfler, University of Port Elizabeth). In this study, engineering units were used to maintain the high resolution of the measurements. Since turbidity events were found to be associated with the bottom (Chapter 2), and because this is where spawning takes place, an average of the values for the bottom meter were considered an appropriate indicator of water turbidity. Turbidity values can be substantially enhanced by the CTD unit stirring up sediment when touching the seabed, especially on sandy bottoms. Such incidents were clear on the turbidity profiles and were discarded. The use of the average value also eliminated the possible use of less obvious unrepresentative values.

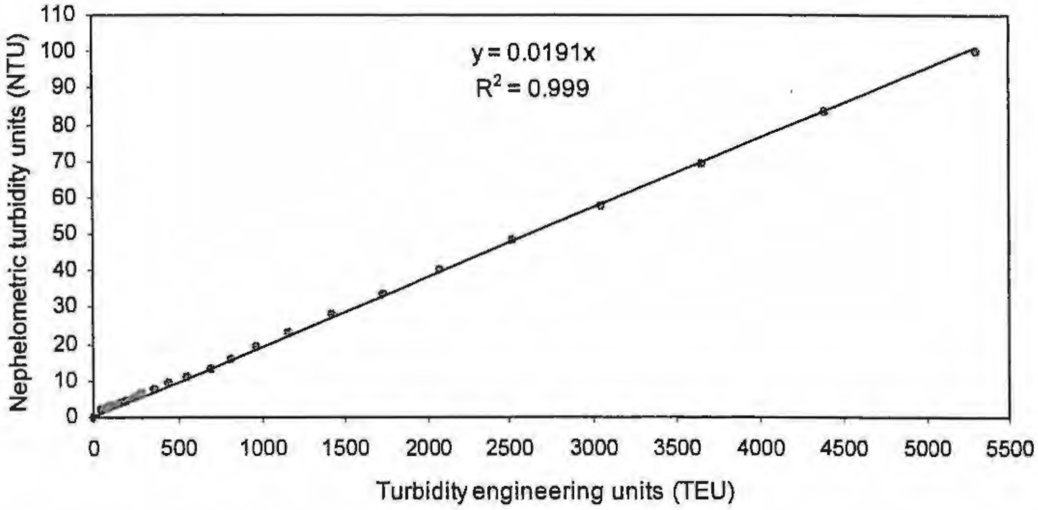

Fig. 3.3: Relationship between turbidity engineering units (TEU) and nephelometric turbidity units (NTU).

Wind velocity and direction were measured using a portable *Davis Weather Wizard III* anemometer and direction sensor. Wind velocity was recorded in kilometres per hour (accuracy of ±5%). The wind direction was measured in degrees (accuracy of ±7°) according to meteorological convention. Later, this was converted to the 16 compass rose points system (nearest 22.5° direction increment). Wind velocity and direction were recorded at 30-minute to one-hour intervals.

Several parameters, such as swell height, bottom structure, current speed and current direction, could not be measured accurately from a commercial squid fishing vessel. This was mainly because of the shortage of space for the required additional instrumentation. Measurements were rather conducted by indirect methods.

Swell height was obtained by calculating the deviation in water depth displayed on the echo-sounder. It was estimated that the error using this method would be approximately 0.25 m (of the average swell height). The nature of the sea bottom (bottom structure) was divided into three broad categories, viz. sand, reef/sand and flat reef. The different bottom structures were distinguishable based on the strength of echo (50 and 200 MHz). Biological material snagged on the fishing jigs also provided information on the nature of the sea bottom. For example, substances such as *Gorgonia* and feather stars that are associated with reefs indicated either reef or reef/sand.

Surface current speed was recorded in four broad categories depending on the angle of the cable to the water surface when the CTD was on the seabed (i.e., the angle caused by the resistance of the cable to the current throughout the water column). The four categories are: light, moderate, strong, and very strong, and represent cable angles of approximately <10°, 10-20°, 20-30° and >30°, respectively. By comparing the direction of the CTD cable to the vessel navigational equipment, corrected to true north, the current direction was recorded in 8 compass rose points (45° wind direction categories).

For each set of oceanographic and environmental measurements, the date and time of day were recorded and the position within the lunar cycle was calculated from SA Navy Tide Tables (SAN 1991-1998).

The time and regularity of the CTD deployments were dependent on boat activity and were restricted to weigh-in times when no fishing occurred, to avoid interference. At least one full set of oceanographic and environmental data was assured during a fishing period, which could be later related to the corresponding CPUE value.

## 3.2.2 Data analysis

### 3.2.2.1 General

Two statistical approaches were followed (Fig. 3.4), a correlation and multiple regression analysis, which resulted in simple empirical models, and a less quantitative but relatively holistic contingency table approach. The important explanatory variables from the multiple correlation and regression analysis were additionally subjected to analyses of variance by categorising the data. Additionally, summer data were treated separately. Case studies were used to illustrate the distinct causal relationships revealed by the statistical analyses. These studies relied on the vessel being among the first to find a newly formed spawning aggregation. The probability of this was obviously low, when considering competition among fishing vessels.

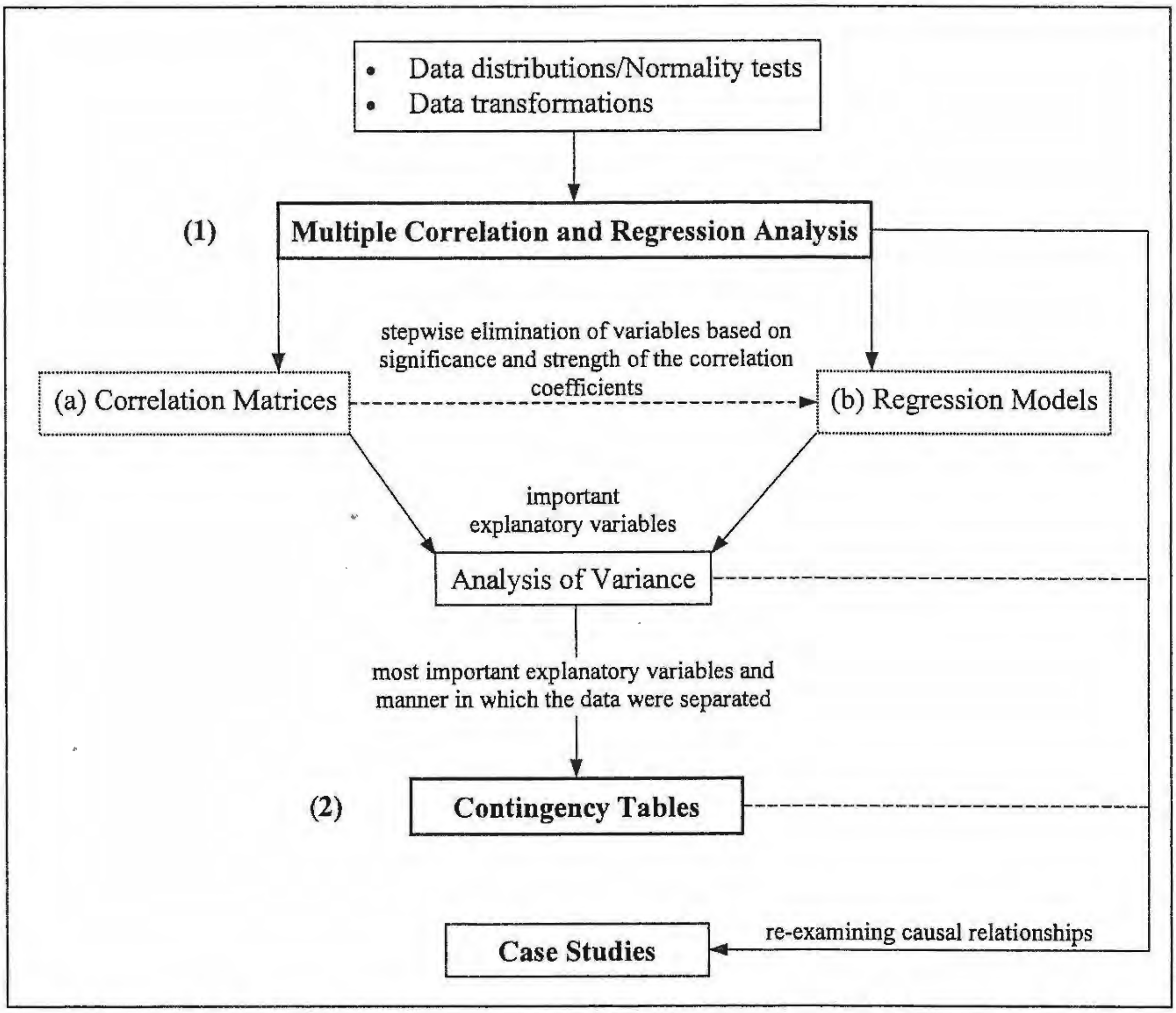

Fig. 3.4: Diagram illustrating the sequence and techniques for the statistical approach.

Normality of the variables was assessed using the Shapiro-Wilk W test because of its strong power properties compared to a range of alternative tests (Shapiro *et al.* 1968). Various transformations were assessed to improve the data distributions. The only meaningful transformation was the log-transformation of the abundance variable $\ell n(\text{CPUE} + 0.05)$. Log-transforming removes zeros from the data set and attempts to normalise the distribution. Although a normal distribution might result, the log-transformation of the zeros has a negative spike, the magnitude of which, depends on the number of zeros. However, this should be balanced by the benefits of normalised data. Due to the low magnitude of the catch rates values, a smaller constant (<1) for the transformation formula, was assessed. Using a constant of 0.05, instead of one, slightly improved the regressions.

For the multiple correlation analysis, the Spearman correlation coefficient was used because it is less sensitive to outliers and non-normality than the standard Pearson estimate. This method assumes that the variables under consideration were measured on an ordinal scale, i.e. the individual observations can be ranked into two ordered series. Therefore, using the ordinal scale of measurement, the relationship between values can be identified, but not quantified. The magnitude and significance of the resulting correlation coefficients aids selection of the environmental indices to be used in the modelling exercise. Multiple and forward stepwise regressions were carried out with the abundance variable (CPUE) as the dependent or response variable and the environmental parameters as independent or predictor variables. The analysis initially included all possible independent variables, after which non-significant terms were progressively eliminated (at the $p=0.05$ probability level) in a stepwise fashion.

All statistical analyses were carried out on STATISTICA Version 5 (StatSoft, Inc.) and S-PLUS Version 4.0 (Mathsoft, Inc.).

### 3.2.2.2 Analysis of circular and periodic variables

In circular variables, not only is any designation of high or low values arbitrary, but there is no true zero, although there is usually an arbitrary zero, e.g., the 0° designated to the north direction on a compass rose, or midnight as the zero or starting point of the time of day (Zar 1984). This feature creates behaviours in calculations that are different from linear variables.

Techniques similar to Bell *et al.* (1995), promulgated by Batschelet (1981) and Zar (1984), were used to evaluate whether circular and periodic factors (wind and current direction, lunar cycle) could explain variation in the dependent variable (CPUE).

Wind direction was measured according to the azimuthal circular co-ordinate system, in which an angle $\alpha$ is measured clockwise from the positive Y-axis, corresponding to North on a compass rose. Magnetic directions were corrected for by subtracting the variation (25°W) so that the positive Y-axis indicates true north. The fact that wind directions are reported as the direction from which the wind is blowing, whereas current directions are recorded as the direction the current is moving, would need to be accounted for in the data analysis.

Wind and current directions were transformed into an angular measure, i.e., radians (R), a prerequisite for computer calculations, by multiplying the angle $\alpha$ by $2\pi/360$. The lunar cycle (29.5306 days), considering new moon as the nominal zero of the cycle, were transformed into circular variables by multiplying day-since-new moon by $2\pi/29.5306$ to obtain an equivalent radian measure. The sine and cosine of these independent variables were then calculated. The x-variables are therefore angular transforms of the original x-axes and both are required to convert the angular measurement to a co-ordinate system. Using the azimuthal circular co-ordinate system, the sine of the radian measures of the independent variable are used as the X component (i.e., the east-west component in the case of wind direction, and the new moon-full moon component in the lunar cycle) and the cosine as the Y component (i.e., north-south and first quarter-last quarter component). Batschelet (1981) shows that a Y variable over a cycle can be expressed as:

$$Y = M + \beta_1 \sin RX + \beta_2 \cos RX$$

where $\beta_1$ and $\beta_2$ are coefficients and M is the predicted mean level, formally equivalent to an intercept in a non-periodic regression. The equation can then be solved directly using sinRX and cosRX as new variables. Circular variables were therefore treated using both the sine and cosine transforms of the independent variable in regressions and correlations.

## 3.3 RESULTS

### 3.3.1 Description of data

A wide range of data distributions, mostly erratic, were evident for the majority of the variables measured (Appendix A1). With the exception of surface salinity, all the environmental indices and the dependent variable (CPUE) were non-normally distributed (Appendix A2). No obvious qualitative pattern could be observed from individual scatter diagrams, i.e., plotting the different environmental variables against CPUE.

The significance of differences between day/night and summer/winter catches (Fig. 3.5), due to the distinct changes in diel and seasonal fishing techniques, and approaches of the jig fishermen (Chapter 2), was assessed. In both cases the difference was significant with p-values of 0.02 and 0.002 respectively. Seasonal and diel cycles were, therefore, treated as discrete variables as opposed to periodic variables. Moreover, in the case of seasonal influences, the sampling trips were too irregularly spaced to override catch fluctuations influenced by short-term conditions, and which would have lead to a comparison on different time-scales.

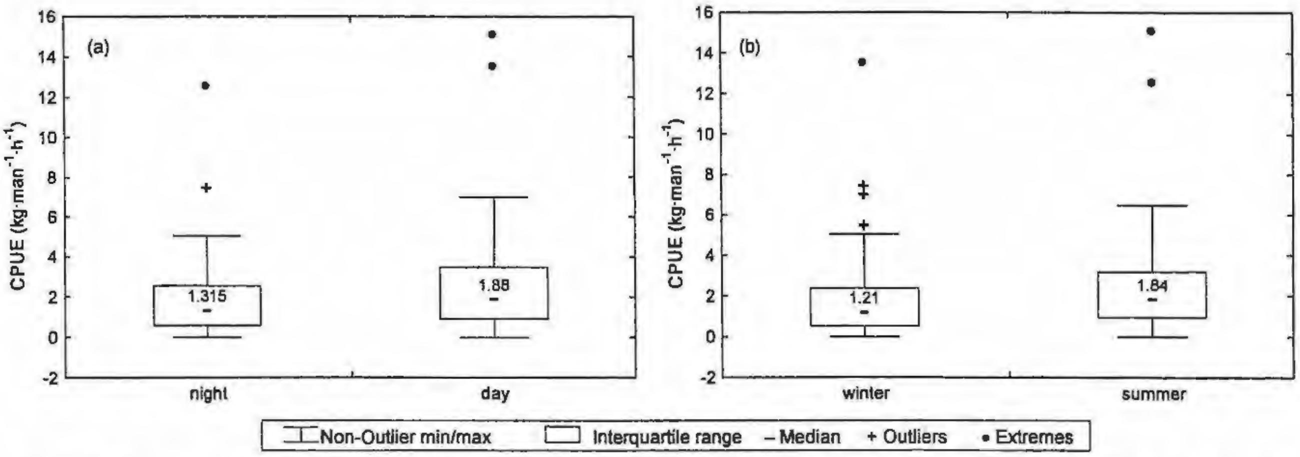

Fig. 3.5: Box and whisker plots illustrating the characteristic (a) diel and (b) seasonal catch per unit effort distribution for the South African *L. v. reynaudii* fishery, calculated from data collected during sampling trips from 1996-1998.

## 3.3.2 Multiple correlation and regression approach

### 3.3.2.1 Multiple correlation analysis

Of the 19 predictor variables considered, eight were significantly correlated with abundance, viz. season, depth, lunar cycle (both circular components), wind direction (E-W component), wind speed, SST and turbidity (Appendix B1). Other significant correlations among the different environmental indices themselves further supported some of the apparent relationships with abundance, or indicated general oceanographic and environmental characteristics. Although none of the correlations were particularly strong, some empirical relationships are indicated.

*Season and depth*

The positive correlation of season with abundance reflects the characteristic higher summer catches in the jig fishery (Fig. 3.5b). Negative correlation of depth with abundance is more likely a reflection of fishing tactics than the direct effect of the environment on catches. As it is less time consuming to catch spawning squid in relatively shallow water, a decline in catch rates can be expected when targeting spawning squid in deeper waters within the general inshore spawning area. The fleet generally moves slightly offshore with the dispersal of squid at night, using lights to attract squid into the upper water column in the vicinity of the vessel, and thus a relatively high catch rate is maintained. Since this relationship mirrors the alternating day or night fishing techniques and spawning movements, it may be considered to be indirectly indicative of diel catch fluctuations (Fig. 3.5a).

The relationship between season, depth and spawning behaviour, and the resulting shift in fishing approach to maximise on this, is also evident in the significant negative correlation of depth with season. This emphasises the tendency of fishermen to exploit squid mainly at shallow depths during summer.

*Lunar cycle*

The first-last-quarter component of the lunar cycle (sine of day since new moon) was found to be negatively correlated, and the new-full moon component (cosine of day since new moon) was positively correlated with abundance (Appendix B1). These results imply an increase in catch associated with the last quarter phase and the new moon.

*Wind direction and temperature*

The sine of wind direction was significantly and positively correlated with abundance (Appendix B1), implying an increase in catch during winds with an easterly component and consequent upwelling events. SST was significantly and negatively correlated with abundance; cold water inshore is a direct result of the upwelling process.

*Wind speed*

Wind speed was negatively correlated with abundance (Appendix B1). This may not, however, be indicative of an environmental effect on chokka squid abundance *per se*, since wind speed strongly affects the movement of the fishing fleet and fishing efficiency. Strong winds force boats to shelter, cause fishing lines to tangle and may induce stronger surface currents – as indicated by the positive correlation with current speed (Appendix B1). Wind was therefore not treated as a vector, and wind speed was considered separately as an influencing parameter.

Further effects and characteristics of wind speed are indicated with the significant correlations with swell height and the diel cycle. The positive correlation with swell reflects the common phenomenon of greater swell height during stronger winds, whereas the negative correlation with the diel cycle indicates the tendency of wind speed to reduce at night.

*Turbidity*

The correlation of turbidity with abundance was found to be significant and negative. The apparently higher frequency of turbidity events along the south coast during the winter is reflected by the negative correlation of turbidity with season (Appendix B1).

*Intercorrelations between environmental variables*

Other notable, or otherwise expected, significant correlations between environmental indices were: a positive correlation between SST and season (Appendix B1), with higher expected SSTs during summer, and the relationship between salinity and sea temperature.

### 3.3.2.2 Multiple regression analysis

The multiple regression analysis began with a full model: with abundance ($\ell n(CPUE + 0.05)$) as the dependent variable and all environmental indices (other than temperature gradient) as independent variables. The contribution of temperature gradient proved to be redundant to the regression, i.e., it was redundant with the contribution of other independent variables (presumably BT). The number of data points entered into the analysis was small (n=39) due to the exclusion of points with missing environmental variable values. Overall, the analysis proved to be highly insignificant ($p>0.2$). Turbidity was the sole predictor variable that was significant in the stepwise regression ($p=0.00003$).

Environmental variables were eliminated in a stepwise fashion based on the strength and significance of the individual Spearman's correlations with abundance. The full model was therefore reduced to a model where only WDIRCOS (cosine of wind direction) and the significantly correlated (simple correlation coefficients) environmental variables were regressed with abundance values (CPUE):

$$\ell n(CPUE + 0.05) = 21.13 - 0.20\,(SEASON) + 0.002\,(DEPTH) - 0.52\,(LUNARSIN) + 0.54\,(LUNARCOS) + 0.24\,(WDIRSIN) - 0.14\,(WDIRCOS) + 0.0053\,(WSPEED) - 0.048\,(SST) - 0.00072\,(TURBIDITY) + \varepsilon$$

This model accounted for 32% of the variability in abundance, with a highly significant relationship ($p< 0.00001$) between the dependent variable and the set of independent variables (Table 3.2). The probability plot of the residuals also showed a satisfactory normal distribution (Appendix B2). The comparison of the actual CPUE values with those predicted by the model highlights the shortcoming of the model in accounting for exceptionally high catch rates (Fig. 3.6).

Table 3.2: Results of the multiple regression analysis with CPUE ($kg \cdot man^{-1} \cdot h^{-1}$) as the dependent variable and SEASON (winter text value = 100; summer = 101), DEPTH (maximum meters), LUNARSIN (first-last-quarter component of the lunar cycle), LUNARCOS (new-full moon component), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), WSPEED (wind speed in $km \cdot h^{-1}$), SST (sea surface temperature in °C) and TURBIDITY (TEU) as independent variables. CPUE was transformed by the function CPUE = $\ell n$(CPUE + 0.05); significance ($p<0.05$) is marked in bold.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 6.095 | Intercept | 21.1307 | 23.5015 | 0.899 | 0.3704 |
| p-value | **p<0.00001** | SEASON | -0.2035 | 0.2339 | -0.870 | 0.3861 |
| Multiple R | 0.563 | DEPTH | 0.0020 | 0.0103 | 0.197 | 0.8442 |
| $R^2$ | 0.317 | LUNARSIN | -0.5152 | 0.1577 | -3.267 | **0.0014** |
| n | 128 | LUNARCOS | 0.5400 | 0.1861 | 2.902 | **0.0044** |
| df | 118 | WDIRSIN | 0.2383 | 0.1191 | 2.000 | **0.0478** |
| | | WDIRCOS | -0.1357 | 0.1673 | -0.811 | 0.4190 |
| | | WSPEED | 0.0053 | 0.0079 | 0.663 | 0.5085 |
| | | SST | -0.0476 | 0.0511 | -0.931 | 0.3537 |
| | | TURBIDITY | -0.0007 | 0.0002 | -3.026 | **0.0030** |

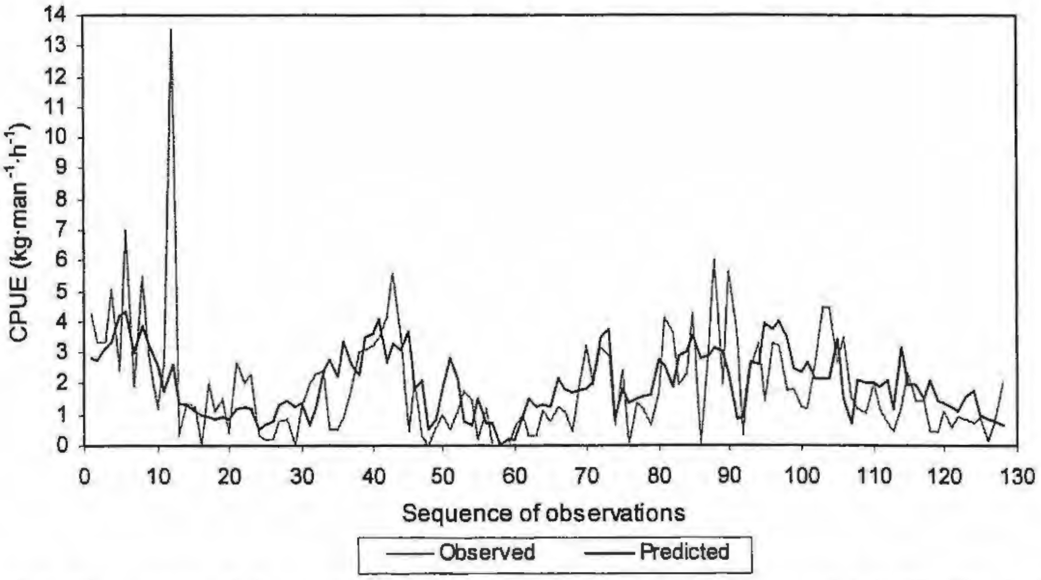

Fig. 3.6: Comparison of observed CPUE values with those predicted by the model: $\ell n(CPUE + 0.05) = 21.13 - 0.20 (Season) + 0.002 (Depth) - 0.52 (Lunarsin) + 0.54 (Lunarcos) + 0.24 (Wdirsin) - 0.14 (Wdircos) + 0.0053 (Wspeed) - 0.048 (SST) - 0.00072 (Turbidity) + \varepsilon$. Due to the irregular times that monthly sampling was conducted, the x-axis here indicates the sequence of the observations.

Four of the independent variables viz. LUNARSIN, LUNARCOS, WDIRSIN and TURBIDITY were significant ($p<0.05$). TURBIDITY and LUNARSIN were negatively correlated, and both WDIRSIN and LUNARCOS were positively correlated with CPUE. These four predictors were also selected by a stepwise regression analysis as the main determinants of abundance (Appendix B3). Turbidity proved to be the best predictor accounting for 13% of the variability in CPUE.

The remaining environmental predictors (SEASON, DEPTH, SST, WDIRCOS and WSPEED) were statistically non-significant in the regression, but were nevertheless chosen to be retained in the model. SEASON is an important factor considering the significant difference in seasonal catches (Fig 3.5b); the distinct spawning season of *L. v. reynaudii* occurs during summer, with associated high catch rates, and a recognisable change in fishing technique. DEPTH was retained in the model due to the distinguishable reduction in catch rate further offshore. Furthermore, DEPTH indirectly represents diel catch fluctuations. SST was retained due to its importance as an influencing oceanographic factor, as suggested by previous studies (Augustyn 1989, Sauer *et al.* 1991, Roberts and Sauer 1994), and because of the influence of temperature on egg development (Oosthuizen 1999). Wind as an environmental variable was separated into three indices due to the complex nature of its influence, and was also considered in the analyses. The separation of the sine and cosine components of a circular variable disguises actual degrees of freedom from the analysis which may result in a better, but unjustifiable probability value. Therefore, WDIRCOS and WSPEED were both retained in the final model.

The peak locations (phase angle, or point on the circular scale at which the linear variable is maximal) and amplitudes (minimum to maximum value of the linear variable) of the circular and periodic variables were calculated from their partial correlation coefficients. For the lunar cycle, the highest CPUE can be predicted to occur 26 days after new moon (or approximately 3.5 days before the next full moon, i.e., between the last-quarter phase and new moon) with an amplitude of 0.75. In the case of wind direction the highest CPUE is predicted at 120° and the amplitude 0.27.

### 3.3.2.3 Multiple correlation and regression analyses for the summer (peak spawning season) data set

Simple correlation analysis of the environmental indices with abundance for summer data only, resulted in the same significantly correlated variables as for the full data set, with the exception of the lunar cycle components and turbidity (Appendix B4). The magnitude of the correlation coefficients of DEPTH, WDIRSIN, WSPEED and SST with abundance all increased by at least 40%, and as much as almost 100% for SST. The insignificance of the lunar cycle indices and turbidity are probably due to the lesser importance of night fishing and the lower frequency of turbidity events during summer (Fig. 2.11). However, for the summer data (again, considering only the variables with significant Spearman's correlation coefficients), the multiple regression analysis was insignificant ($p<0.20$) (Appendix B5).

WDIRSIN was the best and only predictor variable that was individually significant in the stepwise regression.

### 3.3.3 Analysis of variance and data categorising

Variables showing importance in the multiple correlations analysis, with the exception of the circular variables and season, were individually subjected to analysis of variance. The variables were depth, wind speed, SST and turbidity, with the addition of BT and temperature gradient. BT was included because it more closely relates to the temperatures to which eggs are exposed, and temperature gradient because it is strongly related to upwelling.

The Kruskal-Wallis non-parametric test was used because of heterogeneous variances of categories, for all the variables considered. The categories for each variable, as well as the significance of the Kruskal-Wallis test values ($H_c$ = corrected for tied ranks), are presented in Appendix C1. Abundance was found to be significantly different for depth ($p<0.05$), turbidity ($p<0.05$) and BT ($p=0.10$). Although other variables showed insignificance, some general and seasonal trends are evident according to their graphic representation (Fig. 3.7-3.9).

Figure 3.7a shows average catch rates at 10-meter depth intervals. The difference in seasonal fishing strategy is well illustrated, wherein peak summer rates occur at shallow depths (<30 m) and decrease with depth, and the opposite trend occurring during winter. The results highlight the distinct diel catch fluctuations and the tendency of the fishing fleet to utilise the seasonal change in chokka squid behaviour to its advantage.

Figure 3.7b depicts a distinct, decreasing trend in CPUE with an increase in turbidity. A highly significant ($p<0.001$) difference was found between the catch rates at zero turbidity (i.e., TEU=0) and those greater than 200 TEU. This may indicate the ability of squid to tolerate moderate turbidity; catch rate dramatically decreases when turbidity values exceed a threshold value of 200 TEU (see Fig. 3.3). The generally higher catch rates at low turbidity during summer may also be a result of higher squid availability during peak spawning.

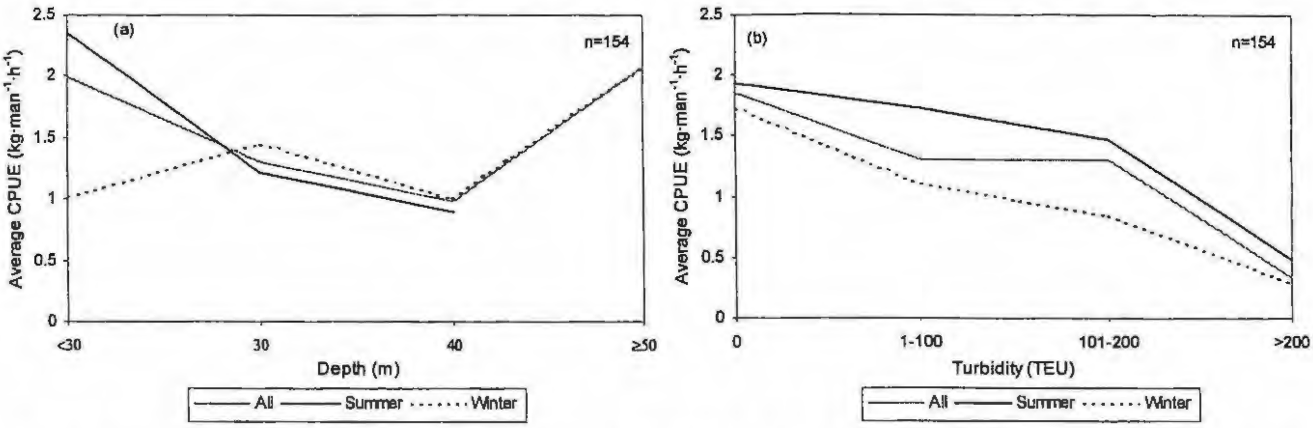

Fig. 3.7: Average catch rates of *Loligo vulgaris reynaudii* in (a) 10 m depth intervals and (b) 100 turbidity engineering units intervals during summer, winter and both seasons (all).

A general decreasing trend was observed in catch rates with increasing wind speed, where the highest catch was associated with winds less than 10 km·h$^{-1}$ (Fig. 3.8a). This phenomenon was most marked during summer. Wind speeds in excess of 40 km·h$^{-1}$ associated with an easterly component (causing upwelling) also led to a slight increase in CPUE values during summer. However, an increase in catch rates during periods of high wind speeds during summer may also be due to the fact that areas sheltered from the prominent summer easterly winds are largely within productive fishing areas. The change in the average catch rates over 1°C temperature gradient intervals (Fig. 3.8b) is associated with upwelling. The highest catch rates were associated with low (1-2°C) and high (5°C) temperature gradients, during both summer and winter. The temperature gradient is effectively indicative of the strength of the thermocline. Therefore, the high catch rates at low temperature gradients are associated with a dissipating or emerging thermocline, whereas the high catch rates with a strong thermocline are directly associated with upwelling.

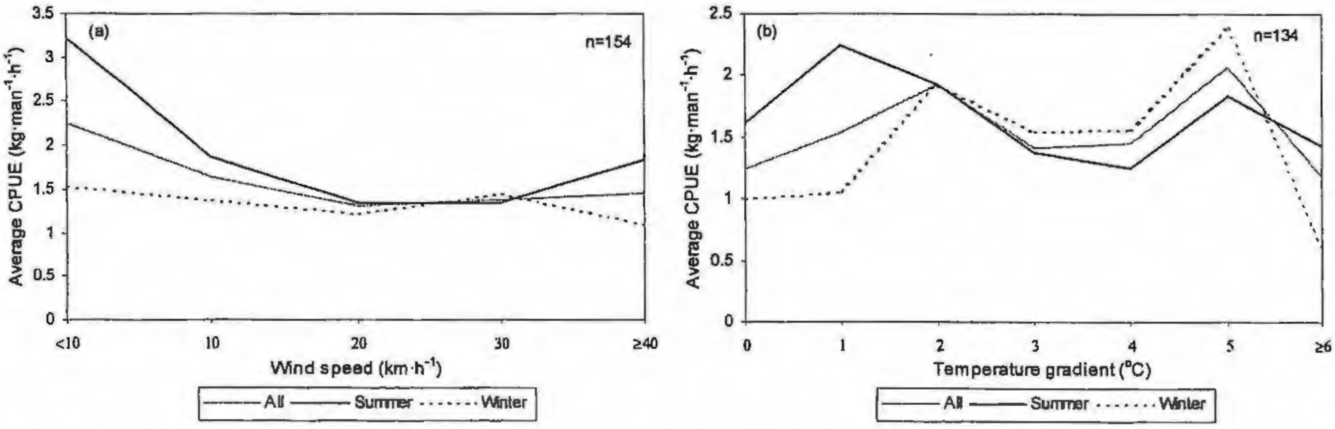

Fig. 3.8: Average catch rates of *Loligo vulgaris reynaudii* in (a) 10 km·h$^{-1}$ wind speed intervals and (b) one-degree temperature gradient intervals during summer, winter and both seasons (all).

Figure 3.9 shows average catches in 1°C BT and SST intervals. The average catch rates fluctuate erratically over the entire BT range (Fig. 3.9a), which is probably associated with the complex connection with temperature gradient. However, the peak in catch rates at a low BT can be connected to the peak associated with strong thermoclines. A distinct peak in summer catch rates can be observed at 15.0-16.9°C, and may also relate to the peak in average catch rates at low temperature gradients. Catches also tend to drop off with a high BT (>17°C). A trend in average catch rate with change in SST during summer was evident (Fig. 3.9b). Peak catches occurred at 15°C, but declined sharply towards both lower (13°C) and higher (18°C) SST extremes. Although less clear, the same phenomenon is observed regarding BT (Fig. 3.9a), where the peak summer catch falls within the same temperature range. The marked decrease in catch at 16°C to >17°C BT is probably exaggerated by the very low catch rates associated with the extreme warm temperatures (>19°C). Due to the low number of observations with high BT values, those observations were grouped as one category (>17°C). An increase in catch towards the extreme cold temperature values for both BT (<10°C) and SST (<13°C) was associated with an isolated anomaly: a strong upwelling event coincided with an already high abundance of spawning squid during February 1998. This may suggest a higher tolerance towards the lower spectrum of the temperature range compared to high temperatures.

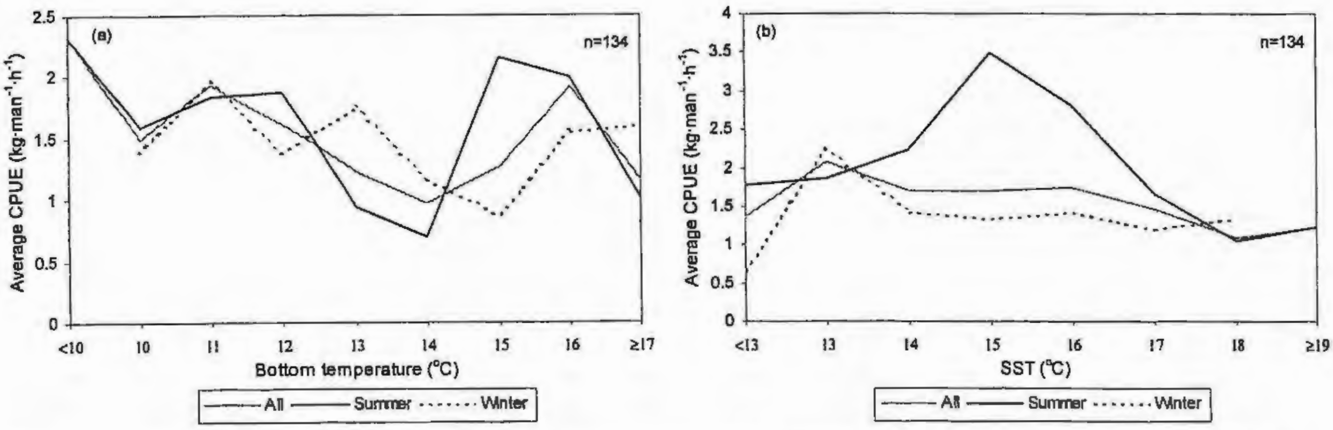

Fig. 3.9: Average catch rates of *Loligo vulgaris reynaudii* in one degree intervals for (a) bottom temperature and (b) sea surface temperature, during summer, winter and both seasons (all).

Due to the distinct trend in catch rates with a change in water temperature during the main spawning season, the summer data were alternatively subjected to an analysis of variance. The number of categories was reduced and the intervals were increased to 2°C for both BT and SST due to the reduction in the size of the data set. This enhanced the trends otherwise observed at the 1°C intervals. A one-way analysis of variance was performed due to homogeneity of variances for these data (Appendix C2). Variation among the catch rate means was significantly different for both BT ($F=3.28$, $p<0.05$) and SST ($F=3.74$, $p<0.01$). A Tukey-Kramer multiple comparison test revealed significant differences between the mean CPUE at 15.0-16.9°C SST, with both the 17.0-18.9°C ($p<0.01$) and ≥19°C ($p<0.05$) categories. The result further indicates the decreased tolerance of chokka squid for high water temperatures.

### 3.3.4 Contingency table approach

Based on the importance of variables from both qualitative and quantitative perspectives (see above analyses), the relationship between wind direction, turbidity, SST and abundance was subjected to a contingency table test. In view of the results and evident trends of previous analyses, the method in which frequencies were observed was different for each variable (Table 3.3).

Table 3.3: Summary of the manner in which the data for each variable were separated for the contingency table frequency counts and the different variable codes.

| Variable | Units | Code | |
|---|---|---|---|
| CPUE | $kg \cdot man^{-1} \cdot h^{-1}$ | CPUE L | below/equal to median |
| | | CPUE H | above median |
| Wind direction | degrees | Wind direction 0 | no easterly component (<45 or >135°) |
| | | Wind direction E | with easterly component (45-135°) |
| SST | °C | SST 0 | <15 or ≥17°C |
| | | SST 15 | 15.0-16.9°C |
| Turbidity | engineering units | Turbidity 0 | no turbidity (=0) |
| | | Turbidity H | turbidity >0 |

The 2-way frequency tables for testing the independence of CPUE with each of the environmental variables are summarised in Appendix D1. The results of the contingency table analysis for both the full data set and the summer data are summarised in Table 3.4. Due to the presence of some low observed frequencies, especially with the summer data set, the Yates chi-square statistic was calculated to achieve a more conservative estimate.

Table 3.4: Results of the contingency table analysis where the independence of CPUE was tested against wind direction, SST and turbidity. Significance ($p<0.05$) is marked in bold. ($\chi_c^2$ – Yates chi-square statistic).

| All data:<br>Frequency table (2x2) | $\chi_c^2$ | p-value | Summer:<br>$\chi_c^2$ | p-value |
|---|---|---|---|---|
| Wind direction x CPUE | 7.756 | **0.005** | 9.034 | **0.003** |
| SST x CPUE | 0.104 | 0.747 | 4.592 | **0.032** |
| Turbidity x CPUE | 4.646 | **0.031** | 0.044 | 0.833 |

CPUE was found to be dependent on wind direction for both the full data set and the summer data. For the full data set the chi-square statistic was insignificant ($p>0.5$) considering CPUE and SST, which implies a high agreement between the two variables. However, in summer, CPUE was found to be dependent on SST. This result is expected considering that the high catch rate trend in the 15.0-16.9°C temperature window was most pronounced during summer (Fig. 3.9b). CPUE also proved to be dependent on turbidity within the full data set. However, during summer, the dependence was insignificant ($p>0.5$) and may be due to the low frequency of turbidity events observed during summer.

The observed frequencies and the probability of CPUE being above or below the median catch rate were calculated for each set of possible environmental variable combinations (Table 3.5). Wind direction and turbidity are considered for the full data set, and SST and wind direction for the summer data set only.

Table 3.5: Observed frequency and probability of CPUE being below or above the median with different combinations of influencing variables. The median CPUE value for the entire data set (all data) was 1.57 kg·man$^{-1}$·h$^{-1}$ and 1.84 kg·man$^{-1}$·h$^{-1}$ for summer data. See Table 3.3 for variable codes used.

| All data:<br>Variable code<br>CPUE | <br><br>Wind direction | <br><br>Turbidity | <br>Frequency | <br>Probability (%) | Summer:<br>Variable code<br>CPUE | <br><br>Wind direction | <br><br>SST | <br>Frequency | <br>Probability (%) |
|---|---|---|---|---|---|---|---|---|---|
| L | 0 | 0 | 36 | 58 | L | 0 | 0 | 28 | 72 |
| L | 0 | H | 20 | 67 | L | 0 | 15 | 2 | 40 |
| L | E | 0 | 10 | 26 | L | E | 0 | 6 | 38 |
| L | E | H | 7 | 64 | L | E | 15 | 1 | 13 |
| H | 0 | 0 | 26 | 42 | H | 0 | 0 | 11 | 28 |
| H | 0 | H | 10 | 33 | H | 0 | 15 | 3 | 60 |
| H | E | 0 | 28 | 74 | H | E | 0 | 10 | 63 |
| H | E | H | 4 | 36 | H | E | 15 | 7 | 88 |

Considering the entire data set, the probability that catch rates will be above the median (1.57 kg·man$^{-1}$·h$^{-1}$) is highest at 74%, and is associated with easterly winds and zero turbidity conditions. The somewhat reversed environmental conditions indicate a high probability for catches to be equal to or below the median catch rates (67%). During summer the highest probability (88%) of CPUE being above the median (1.84 $kg \cdot man^{-1} \cdot h^{-1}$) is associated with SST from 15.0-16.9°C and winds from an easterly direction. Again, the highest probability (72%) for catch rates to be below the median was associated with the opposite environmental conditions.

Although the results of a contingency table approach are not as quantitative as multiple regression, they do however, confirm and support the findings from the previous analyses, wherein wind direction, turbidity and SST were found to be important environmental variables which influence CPUE. Furthermore, the results strengthen the validity of the 'cold water-good catch' and 'high turbidity-poor catch' hypotheses.

## 3.3.5 Case studies

### 3.3.5.1 Case study 1: 21-25 July 1996

Figure 3.10 depicts the CPUE and corresponding wind direction, wind speed, water temperature and turbidity over a 4-day period. On the first day the vessel was fishing amongst other vessels, where-after, it moved alone to a new area. The abundance of squid was, therefore, not effected by high fishing pressure.

The first peak in catch rate corresponded to arrival in the new area, and was also associated with a moderate north-westerly wind, an isotherm temperature profile and no turbidity (Fig. 3.10a). The initial peak in catch rate indicates that squid were already available in the area. Throughout the night, the wind direction changed to north-east, resulting in an upwelling event and formation of a strong thermocline (Figure 3.10b). Under these conditions, catch increased markedly the following morning and was sustained throughout the day. At dusk the catch rate decreased sharply with, presumably, the dissipation of the spawning aggregation associated with the known diel migration pattern (Sauer *et al.* 1997). During the night the easterly wind dropped and the thermocline weakened as the integrity of the surface layer cooled and diminished (Figure 3.10c). The wind conditions then changed to a moderate to strong north-westerly wind and, simultaneously, a turbidity event (Fig. 3.10d). By this time the full impact of the upwelling event had been established and the entire water column, with the exception of a small thermocline at 20 m of 2°C, had cooled. Dissipation of the spawning aggregation, as recorded by the disappearance of the echo-trace on the video echo-sounder,

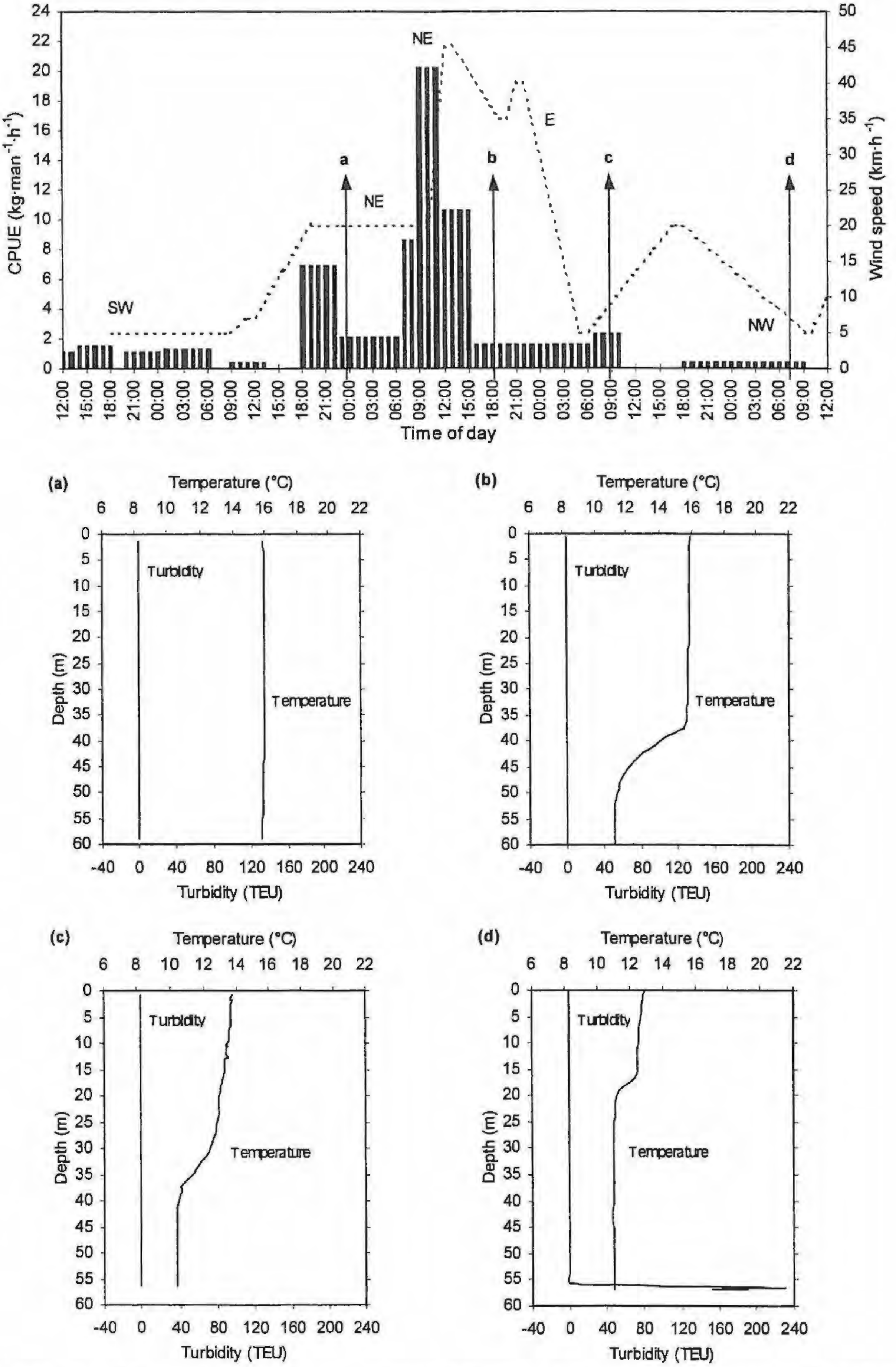

Fig. 3.10: The catch per unit effort and corresponding wind direction, wind speed, water temperature and turbidity over a four-day period, from 12:00 21 July – 12:00 25 July 1996. The times of four CTD deployments within this period are indicated and the resulting temperature and turbidity profiles are plotted (a-d).

coincided with the presence of turbidity and accounted for the extremely low, to no, observed catch rates thereafter.

Although the time of CTD deployments did not entirely coincide with the measured catch rates, they were always carried out just before or after the fishing period and in no instance was there a marked change in the weather conditions during a compared fishing period.

Evident from this case study is the initiation of high spawning activity (and resulting high catch rates) with the formation of a thermocline. It would appear that upwelling acts to trigger spawning and aggregation formation. The dissipation of the spawning aggregation with the onset of a turbidity event might also indicate that such events either prevent or act as a deterrent to the spawning process.

#### 3.3.5.2 Case study 2: 27-29 April 1998

In the second case study, over a 36-hour period in April 1998 (Fig. 3.11), the vessel was amongst other fishing vessels in the same area and catch rates were influenced not only by environmental factors, but also by fishing pressure.

Initial, poor catches were associated with a westerly wind, an isothermal temperature profile and no turbidity (Figure 3.11a). In the early morning, the area within which the aggregation had been formed was searched, but no squid seemed present, and the vessel explored other areas. Eventually, an aggregation was formed later in the morning and was located by other vessels. Arriving at the site, eight boats were already fishing and the catch rate decreased considerably within three hours of our arrival. Even though the catch rate was relatively high, the initial catch rate may have been underestimated (per. comm., skipper of first vessel on site).

In this instance, it again appears that the spawning process was initiated or triggered by upwelling. The upwelling and the associated formation of a thermocline (Fig. 3.11b) was a result of the wind turning north-east near midnight and prevailing throughout the next morning, when the good catches were experienced. Over the next few hours, no obvious change in the environment (Fig. 3.11c) was observed, with the thermocline still present, a north-easterly wind and zero turbidity conditions. Although natural predators may also have played a role, it is more likely that the decline in catch rates was caused by the intense fishing pressure.

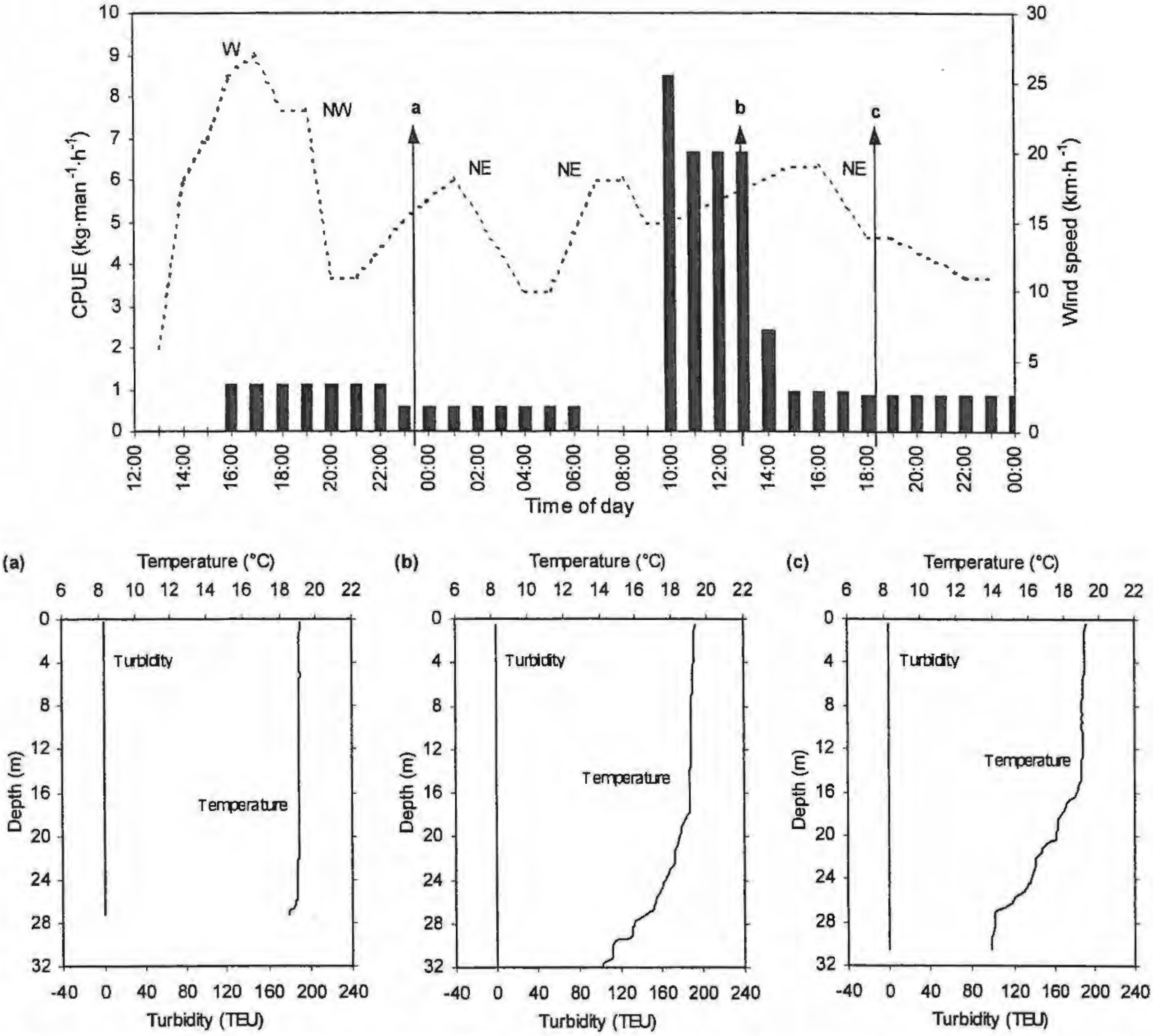

Fig. 3.11: The catch per unit effort and corresponding wind direction, wind speed, water temperature and turbidity over a 36-hour period, from 12:00 27 April – 00:00 29 April 1998. The times of three CTD deployments within this period are indicated and the resulting temperature and turbidity profiles are plotted (a-c).

## 3.4 DISCUSSION

### *Previous correlation studies and environment-catch models*

Several authors have investigated the relationship between the environment and squid distribution or catches (e.g. Serchuk and Rathjen 1974, McInnis and Broenkow 1978, Roberts 1983, Sauer *et al.* 1991, Nakamura and Siriraksophon 1992, Pierce 1995, Dawe *et al.* 1998), but only a few have managed to establish quantifiable relationships, with varying success (e.g. Sauer *et al.* 1991, Pierce 1995, Dawe *et al.* 1998). A statistical approach similar to that of the present study has been followed for studies of *Loligo forbesi* (Pierce 1995) and *Illex illecebrosus* (Coelho and Rosenberg 1984, Dawe *et al.* 1998). Despite the fact that those studies used bi-annual and annual data to investigate catch variations, the multiple correlation coefficients (reflecting the degree to which the environment influences squid catches) are considered comparable.

Pierce (1995) regressed catches of *L. forbesi* in different areas of UK waters against SST and salinity, and found multiple correlation coefficients ($R^2$) ranging from 0.28 to 0.91. Environmental indices (including large-scale oceanographic circulation pattern indices, sea temperature indices and shifts in the position of fronts within the Gulf Stream System) were significantly correlated with *I. illecebrosus* catches, with few exceptions (Dawe *et al.* 1998). The final environment-catch model of Dawe *et al.* (1998) accounted for 47% of the variability in *I. illecebrosus* catches (1973-1997). Coelho and Rosenberg (1984) considered a shorter time-series (1979-1981) and followed a simpler approach. They found that significant proportions of the variation in *I. illecebrosus* catch could be explained by only two independent variables, viz. month of year and average monthly SST. Their fitted model had a $R^2$ value of 0.91.

As in the *L. v. reynaudii* fishery, high variability in catch is characteristic of both the *L. forbesi* and *I. illecebrosus* fisheries. However, the better correlations obtained in those fisheries are perhaps due to the absence of intricate spawning behaviour. *L. forbesi* is caught primarily as a by-catch of demersal trawl and seine net fisheries (Pierce 1995). The major component of the catch data for the *I. illecebrosus* fishery was from an offshore trawl fishery that began in the early 1980s and targeted feeding and migratory squid (O'Dor 1983). Behavioural response to the presentation of jigs in the *L. v. reynaudii* fishery will have some influence on catchability, whereas the potential for such responses are absent with trawling. Furthermore, the above mentioned fisheries are not sustained by spawning squid, and the environment-catch models are consequently not affected by the complex behaviour associated with the spawning process as it is in the chokka squid fishery.

Sauer *et al.* (1991) generated a simple, linear catch prediction model for chokka squid, using SST and wind direction as predictor variables. The coefficient of determination from their model ($R^2$=0.63) is considerably higher than that determined from the present study ($R^2$=0.32). However, the authors pursued a somewhat opportunistic analysis and sampling strategy as concerned catch data and environmental measurements. By this it is meant that their sampling was conducted over a two-month sampling period known to concur with the peak summer spawning season, peak diel catches (wherein the fishery had not yet adopted a night-time fishing strategy, thus only daytime catches were recorded) and a peak upwelling period. Sampling was carried out with the knowledge of squid movements associated with north-easterly winds causing upwelling, and the resulting drop in sea temperatures within the sampling area, and catch measurements were restricted to a relatively small area within one of the major upwelling cells along the south coast (Schumann *et al.* 1982). The environmental sampling sites were not *in situ*. Furthermore, sampling locations involved irregular lag phased shifts in the SST plot in an attempt to link peak squid catches with marked temperature declines which are associated with probable upwelling periods further along the coast. The view, methodology, contribution to the understanding of the overall *L. v. reynaudii* environment-catch relationship, and the representative value of the results of the authors' study, can be best compared to the extracted case studies presented in Figures 3.10 and 3.11.

### *The current model (drawbacks)*

The empirical model for the present study accounted for a relatively low portion of the variability in abundance, rather highlighting the expected complexity of the relationship between environmental parameters and chokka squid abundance on their spawning grounds. The model, however, has several drawbacks that were not foreseen, but may partly explain the low explanatory value of the model here. The most influential drawbacks are the considerable irregularities associated with CPUE values.

#### *Factors influencing CPUE*

The absence of a fishing-pressure index as a variable in the regression model is a disadvantage and may be the major factor affecting the predictability potential of the model. Although fishing pressure has a direct and significant influence on chokka squid catch rates during some fishing periods, the effects can be masked and confounded by the impacts of environmental conditions and emigration patterns (see Lipinski *et al.* (1998) for daily emigration values).

An increase in fishing pressure on an aggregate of spawning chokka squid will ultimately lead to a decrease in spawning intensity, as numbers of squid are depleted, and therefore to a reduction in the catch rate. Sauer (1995a) proposed that a decrease in spawning intensity as a result of fishing pressure may be attributable to a certain threshold number of animals which is needed for continued spawning, or that a minimum number of egg pods are needed to attract further squid to the area. The attraction of female squid to eggs, both prior and during egg laying, has also been observed for *L. opalescens* (Hurley 1977). The removal of egg-laying females may perhaps reduce spawning intensity and immigration. This may be the case when fishing pressure is applied to a spawning aggregation during its initial formation. However, the effect of fishing pressure on an established spawning aggregation rather seems to be a case of reducing the threshold number of animals beyond that required to sustain the spawning process.

Variations in squid catches, as a measure of abundance on a large time-scale (i.e., monthly or annually), cannot necessarily be attributed to fishing pressure since even lightly exploited populations show similar patterns of variation (e.g. *Illex illecebrosus*: Coelho and Rosenberg 1984). However, on any scale, the effect of fishing pressure on abundance should not be ignored, but viewed in combination with other influencing factors.

Summer/winter and day/night catch rates were combined in the current model and also contribute to some irregularities within CPUE, and resulting in reduction of the predictability value. Catch rates differ significantly on a seasonal and diel scale (Fig. 3.5). Not only are catch rates associated with spawning, but also with otherwise more dispersed, feeding squid at night (Sauer and Lipinski 1991). Although a regression model based on the summer data was insignificant, the correlation coefficients between catch rates and several key environmental parameters substantially increased, as compared to those for the full data set.

Spawning behaviour (such as emigration and predator avoidance) and biological parameters (such as fecundity) are other aspects not accounted for in the model. Various behaviour patterns appear to be involved in the chokka squid spawning process (Sauer *et al.* 1992, 1993, Sauer and Smale 1993, Hanlon *et al.* 1994, Smale *et al.* 1995, Smale *et al.* in prep.). Diel migration (O'Dor *et al.* 1996, Sauer *et al.* 1997, Lipinski *et al.* 1998) and migration between aggregations are also evident (Lipinski *et al.* 1998, Sauer *et al.* in press). Such factors are known to influence spawning intensity and therefore catch rates. For example, Roberts (1998a) found indications that spawning termination is biologically driven rather than driven by environmental stimuli. In these cases it was suggested that the ovaries of female squid became partially or fully spent. The extent to which the absence of behaviour and biological elements influence the CPUE values is still speculative.

*Impact of the environment on catch*

In general, marine fauna will spawn in an environment that can provide sufficient food, predator protection and benign abiotic conditions for its offspring (Wootton 1990). Spawners seek environmental conditions that best suite egg development (Roberts and Van den Berg in prep. b), as well as food availability and protection from predators. Environmental influences are also a major factor affecting timing of the spawning process; chokka squid are serial spawners (Melo and Sauer 1999) and spawning takes place throughout the year (Sauer *et al.* 1991). Depending on the intensity of the spawning activity, the consistent availability of reproductively mature cohorts is assumed. Peak seasonal spawning periods do, however, occur sporadically (Augustyn *et al.* 1994). Seasonality of spawning intensity in species that spawn throughout the year is expected to be a function of a higher frequency in favourable abiotic conditions for spawning. The inshore influxes of chokka squid culminate in the formation of spawning aggregations at various sites along the south coast (Augustyn 1990, Sauer 1991) and although the environment appears to have a pronounced influence on high catch rates or high spawning intensity, it becomes less dominant in regard to lower catches. Thus, high catch rates of squid on the inshore spawning grounds is likely a function of favourable environment conditions (Augustyn and Smale 1995).

### *Environmental indices*

The results from the multiple correlation and regression analysis suggest that depth, the lunar cycle, turbidity, wind speed, wind direction and SST effect catch rates both directly and indirectly. Salinity, currents and swell height appear to be insignificant parameters but are briefly discussed.

#### *Salinity*

Certain physical parameters such as salinity, current speed, current direction and swell height, were statistically insignificant when correlated with abundance, and were excluded from further analyses. However, a relationship between squid catches and salinity has been found for other squid species, e.g., two *Nototodarus* species off New Zealand (Roberts 1983) and *Loligo forbesi* off Scotland (Pierce 1995). The absence of a relationship between chokka squid catches and salinity is not unexpected, as the salinity range found around South Africa is small (34 and 36 ‰) (Shannon 1995). The bottom salinity range recorded in this study on the inshore spawning ground was 34.6 to 35.7 ‰.

#### *Currents and swell*

Spawning squid need to maintain a certain degree of spatial stability above the egg bed (Roberts 1998a). Some squid species are capable of swimming speeds of 0.2-0.4 $m \cdot s^{-1}$, using only fin thrust (Webber and O'Dor 1986). Above this, more energetic and costly jet thrusting (O'Dor 1988a) becomes increasingly important (O'Dor 1988b). It is expected that strong inshore currents along the south coast which occasionally exceed 1 $m \cdot s^{-1}$ (Schumann and

Beekman 1984) may terminate spawning, particularly when bottom surge exceeds a certain threshold velocity (Roberts 1998a). Above the threshold, maintaining position above the egg beds would become too costly energetically.

Although current speed, current direction and swell height were expected to influence abundance to some extent, these proved to be insignificantly correlated. However, it is acknowledged that the method used to measure current represents surface currents or swell induced currents, rather than bottom surge. The fact that strong currents may also lead to a reduction in fishing efficiency may have masked the detection of a direct relationship between current speed and catch rate.

*Depth*

Species specific bathymetric distribution patterns for different life history stages (e.g. Serchuk and Rathjen 1974, Hatfield *et al.* 1990, Nakamura and Siriraksophon 1992) and distinct seasonal bathymetric distribution (Serchuk and Rathjen 1974) have been observed for various squid species. The spawning grounds of *L. v. reynaudii* are generally situated inshore in water depths of less than 50 m (Augustyn 1990). Deeper spawning grounds (to 120 m) are also known (Augustyn and Smale 1995). The amount of deep spawning and the extent to which inshore-offshore migration takes place are still unknown. The significant decrease in catch rates with depth is anticipated since handline fishing becomes more difficult in deeper waters and spawning intensity decreases with depth on the inshore spawning grounds, especially in summer. Night-time fishing, when the fleet moves to somewhat deeper water (50-70 m), is more prevalent during winter than summer, resulting in higher winter catch rates. However, depth cannot be used as a determinant to predict catches. Depth *per se* has no major direct influence on chokka squid catches, but rather the adapted fishing approach undertaken to best exploit inshore spawning is a function of depth, diel migration patterns and spawning seasonality.

*Lunar cycle*

Relationships between night catches and the lunar cycle have been observed for some squid species, i.e., *Illex illecebrosus* (Ichikawa and Sato 1976, Long and Rathjen 1980), *Onychoteuthis borealijaponicus* and *Ommastrephes bartrami* (Mercer and Bucy 1983). Studies of these species either found higher catches occurred near new moon or poor catches near the full moon. In contrast to the previous work by Augustyn (1989), a distinct relationship was observed during this study to exist between chokka squid catches and the lunar cycle. Lunar phase was found to be an important predictor variable in the regression model. An increase in chokka squid catches was associated with the last quarter phase approaching the new moon, with the highest catches occurring 3.5 days before new moon, and comparable with the findings for other squid species. The combination of day and night catch rates in this analysis obviously reduced the extent to which the lunar cycle could be associated with chokka squid catches. Yet, the influence of the lunar cycle was found to be pronounced during winter, when night-time fishing resulted in relatively good catches, otherwise indicated by an insignificant correlation between the lunar cycle and summer catch rates. It is possible that moon phase does not, however, directly influence catches, but rather that duration of moonshine during the night plays an important role (Nakamura and Siriraksophon 1992).

### *Turbidity*

Turbidity proved to be the most important predictor variable. High levels of benthic turbidity caused a distinct decrease in catch rates, and it would appear that strong turbidity events terminate spawning. It appears that an environmental window exists in which chokka squid can tolerate moderate levels of turbidity during spawning. Catch rates decreased dramatically below 200 TEU (200 TEU ≈ 2.4 NTU) but an extreme threshold limit that ultimately resulted in spawning termination was not apparent. The frequency of high turbidity events (TEU>200) was low (n=9) during this study, and more data are required to accurately define a threshold limit. The threshold may be slightly higher when a spawning aggregation is well established or during periods of high spawning intensity. Sauer and Smale (1993) suggested that visual signals are important in pair formation for *L. v. reynaudii*. The mechanisms behind the relationship between turbidity and catch rates may be directly related to the hindering effect high turbidity levels can have on spawning behaviour, in that turbidity will impede intraspecific chomatophoric communication (Sauer and Smale 1993) which plays an important role in chokka squid spawning (Hanlon *et al.* 1994).

### *Wind*

The effect of wind on squid catches seems to be more prominent with inshore species, e.g., *Illex illecebrosus* (Hurley 1980), than offshore species, e.g., *Nototodarus* species (Roberts 1983). *L. v. reynaudii* catches generally decreased with increasing wind speed. However, the higher catch rates associated with moderately strong winds (>40 $km \cdot h^{-1}$) during the summer months may imply an association with upwelling.

Wind direction appears to have a prominent influence on chokka squid catches. Catches were found to increase under easterly wind conditions. Since easterly winds are the main driving force behind upwelling in the study area (Schumann *et al.* 1982), the current results suggest an influential role played by upwelling on catches (Sauer *et al.* 1991). An association between squid catch, distribution and upwelling has been observed for other squid species such as *Nototodarus sloani* (Roberts 1983), *Ommastrephes bartrami* (Nakamura and Siriraksophon 1992) and *Loligo opalescens* (McInnis and Broenkow 1978).

### *Temperature and upwelling*

Many authors have identified temperature as a factor influencing squid larval distribution (e.g. Fedulov and Arkhipkin 1986, Rodhouse *et al.* 1992) and adult squid distribution or catch (e.g. Serchuk and Rathjen 1974, McInnis and Broenkow 1978, Roberts 1983, Coelho and Rosenberg 1984, Gong *et al.* 1990, Fukada *et al.* 1991, Sauer *et al.* 1991, Nakamura and Siriraksophon 1992, Pierce 1995, Dawe *et al.* 1998). From these studies, it has become increasingly clear that the temperatures to which squid responded were not always seasonal, but also associated with water masses (O'Dor 1992). Relationships between temperature and catch have been suggested for different squid species, but with variable success, diverse temperature ranges and directional correlation coefficients. Examples of such studies on loliginid species include *Loligo pealeii* (Serchuk and Rathjen 1974), *L. opalescens* (McInnis and Broenkow 1978) and *L. forbesi* (Pierce 1995).

The present study did not show a distinct relationship between temperature and catch, as the 'cold water-good catch' hypothesis (i.e. Augustyn 1989, Roberts and Sauer 1994) proposes. The lack of a distinct increase in catch rates with lower water temperature makes the simplicity of the 'cold water-good catch' hypothesis questionable and it may well be a temperature change, in either direction, that is more important.

Complex trends become apparent when categorising the observed catch rates within temperature intervals for each of the temperature indices considered. The relationship between catch and temperature gradient was statistically insignificant, but higher catch rates at high temperature gradients (i.e., presence of a relatively strong thermocline) hinted at the importance of upwelling. This result is by no means conclusive, however. During the summer months a very distinct trend in catch rates was observed with both the SST and BT ranges. Although clearer for SST, a significant increase in catches was observed within the 15-16°C range for both indices during the main spawning season. Results suggest that a higher catch, and thus higher spawning intensity of chokka squid, is associated with a preferred temperature range (13-18°C). Oosthuizen (1999) investigated the effect of temperature on the embryonic development of *L. v. reynaudii* in laboratory studies and found that the optimum hatching temperature is 12-15°C. Therefore, the temperature and catch relationship seems to be affected by ambient temperature on embryonic development, rather than on the spawning adults, but temperature could also contribute to the increased productivity that is associated with upwelling (and possibly an increase in food availability to the paralarvae) or else a decrease in predator abundance in colder water. During spawning, chokka squid appear to take advantage of the environmental window created by an upwelling event. Roberts and Sauer (1994) found, for example, that the annual chokka squid catch is higher in years of increased upwelling frequency. The selective advantages gained by spawning at this particular range of temperatures still require investigation.

In a direct sense, upwelling acts as an environmental trigger to the spawning process (see Fig. 3.10). Roberts (1998a) noted that an upwelling event coincided with the formation of a chokka squid spawning aggregation, lending further support to such a hypothesis. The relationship between squid catch *per se* and upwelling is indirect, and rather related to a change in water temperature.

### *Conclusion*

Wind direction, SST and turbidity are perhaps the most important environmental parameters influencing fishery abundance. This conclusion is supported by the contingency table approach. Simple probability relationships are not quantitative and are not regarded as being statistically "stringent", yet they may represent a more realistic view of the environment-catch relationship than quantitative, more stringent multiple regression models. High catch rates during this study were generally associated with easterly winds and zero turbidity conditions; and during summer, with easterly winds and SST from 15.0 to 16.9°C. The probability of high chokka squid catch rates under these conditions were 74 and 88%, respectively.

Although some distinct, direct correlations between environmental parameters and chokka squid abundance were found, simple empirical relationships are likely to have little predictive power. Only with a more comprehensive understanding of underlying dynamics, can one hope to anticipate the consequences of environmental perturbation on abundance (Kareiva 1995).

The simplicity of the model, wherein only the influential effects of environmental factors are considered, has obvious shortcomings. A multidisciplinary approach, where all abiotic, biotic and fishery parameters can be considered, is preferable.

## 3.5 CHAPTER SUMMARY

In this study the investigation into the relationship between environmental conditions and chokka squid catch rates were based on a simple, direct, "black box" statistical approach, using multiple correlation and regression analysis, analysis of variance and contingency table analysis (Fig. 3.4). The main results and conclusions include:

- Multiple correlation and regression analyses suggest that season, depth, the lunar cycle, turbidity, wind speed, wind direction and SST (sea surface temperature) effects chokka squid catch rates both directly and indirectly.
- The regression model accounted for 32% of the variability in catch, with turbidity the main determinant of catch (13%) (Appendix B3). Additionally, the lunar cycle (both components) and the sine of wind direction were significant parameters in the regression model.
- Wind direction, SST and turbidity appears to be the most important parameters influencing catch rates. Season and diel catch variations induced changes in the relative importance of these parameters on catch rates. High catch rates were generally associated with easterly winds (which cause upwelling), zero turbidity conditions and SST ranging from 15.0 to 16.9°C.

# CHAPTER 4

# ENVIRONMENTAL INFLUENCES ON CHOKKA SQUID CATCHES: A TIME-SERIES STUDY IN KROMME BAY

## 4.1 INTRODUCTION

Correlating environmental variations with biological ones poses various time-scale problems. Firstly, the observational window is limited by the length of the time-series at one end and by the interval between successive observations at the other (Legendre and Demers 1984). Secondly, different oceanographic or environmental processes and biological responses to these occur on different spatial and temporal scales, therefore these should determine the choice of the physical and biological parameters to be investigated (Legendre and Demers 1984).

A few authors have attempted to correlate environmental conditions with squid abundance or recruitment on a large time-scale or time-series, i.e., monthly or annually. For example, McInnis and Broenkow (1978) were able to demonstrate an 18-month lag between episodes of high temperature and subsequent spawning of *Loligo opalescens* in Monterey Bay, California. Dow (1979) correlated sea temperature cycles (1905-1975) with the abundance and availability of commercial marine and estuarine species off the Maine coast, including the squid *L. pealeii.* And Dawe *et al.* (1998) used a 73-year time-series to investigate the effect of environmental factors on the abundance of the short-finned squid *Illex illecebrosus.*

In this chapter the relationship between the environment and chokka squid abundance in Kromme Bay is investigated on different time-scales (i.e., daily, weekly and monthly) using a time-series data set. By investigating a single, specific location, the problem of spatial variability is partly eliminated. Increased complexity, however, is expected with the shift from a simple 'black box' approach using discrete time intervals (Chapter 3) to a longer, continuous time-scale.

*Loligo vulgaris reynaudii* are caught sporadically throughout the year at a number of sites in Kromme Bay (Fig. 4.1). The area was selected for this study based on the following attributes:

- the area is centrally situated within the main spawning area of chokka squid;

- relatively high importance as a fishing location (6-24% of total annual effort); producing 4-22% of the total annual jigged catch (1985-1997).
- total annual catch trends and catch seasonality are similar to that of the entire jig fishery;
- a long-term oceanographic mooring is situated in the bay.

The fluctuations of squid abundance in Kromme Bay was assumed to reflect the general trend for the fishery; also, that preference for the area as a spawning location, in terms of environmental suitability, played an insignificant role in the environment-catch relationship.

## 4.2 MATERIALS AND METHODS

### 4.2.1 Study area

Kromme Bay is situated in the western corner of the greater St. Francis Bay, a log-spiral shaped bay, located on the south-eastern coast of South Africa between Cape St. Francis in the west and Cape Recife (Port Elizabeth) in the east (Fig. 4.1). Kromme Bay is a shallow and relatively sheltered bay, situated north of Cape St. Francis and separated from the exposed southern coastline west of Seal Point. The oceanographic regime of the bay is complex, being influenced by prevailing oceanographic conditions within St. Francis Bay and the upwelling cell off Seal Point.

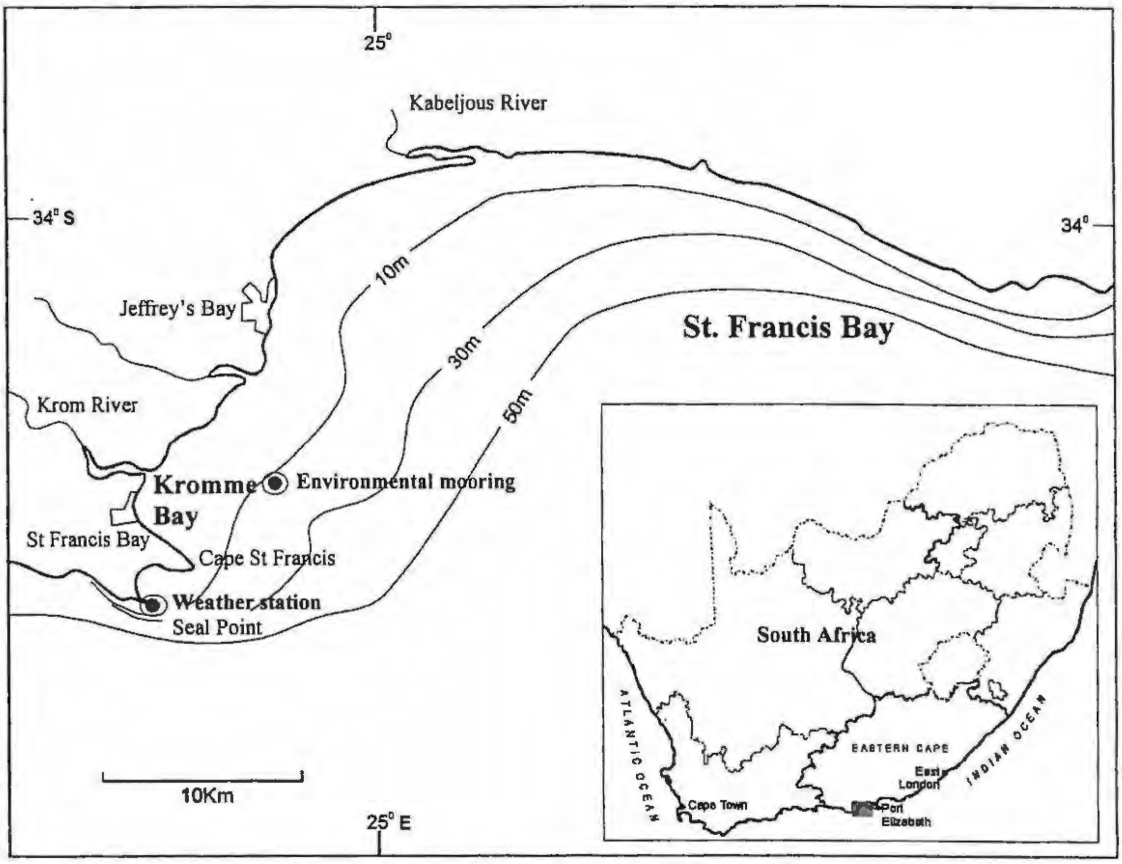

Fig. 4.1: Map of Kromme Bay, indicating the position of the bay in relation to the south coast of South Africa and the positions of the environmental mooring and weather station.

## 4.2.2 Data source and editing

The catch data for this study (01/1985-06/1998) were extracted from the National Marine Linefish database (Marine and Coastal Management). All calculations or summaries were calculated from the raw daily catch records of individual vessels. The validation of the database (Chapter 2, Section 2.2.1.1) suggested 50% inaccuracy for the recorded fishing locations.

In many instances only the weekly or total catch for the trip was recorded. These unrefined catch submissions were excluded. The percentage of data excluded as a result of editing was nevertheless relatively small: an average of 6% of the total annual catch and 7.5% of effort (no. of fishing days).

The weekly and monthly average CPUE ($kg \cdot boat^{-1} \cdot day^{-1}$) was calculated according to the formula presented in Chapter 3 (Section 3.2.1). As a popular fishing location, the bay is centrally positioned within the main fishing area and in the vicinity of a central harbour. Vessels were thus assumed to regularly search the bay for squid, and missing daily catch records implied no catches. Missing values were subsequently replaced by zeros, and catch records from the closed season were excluded from the analysis.

### 4.2.3 Environmental data

Environmental data collected include water temperature, turbidity, wind direction and wind speed. These were collected at a mooring site in Kromme Bay (shown in Fig. 4.2) and a permanent weather station situated at Seal Point (Fig. 4.1).

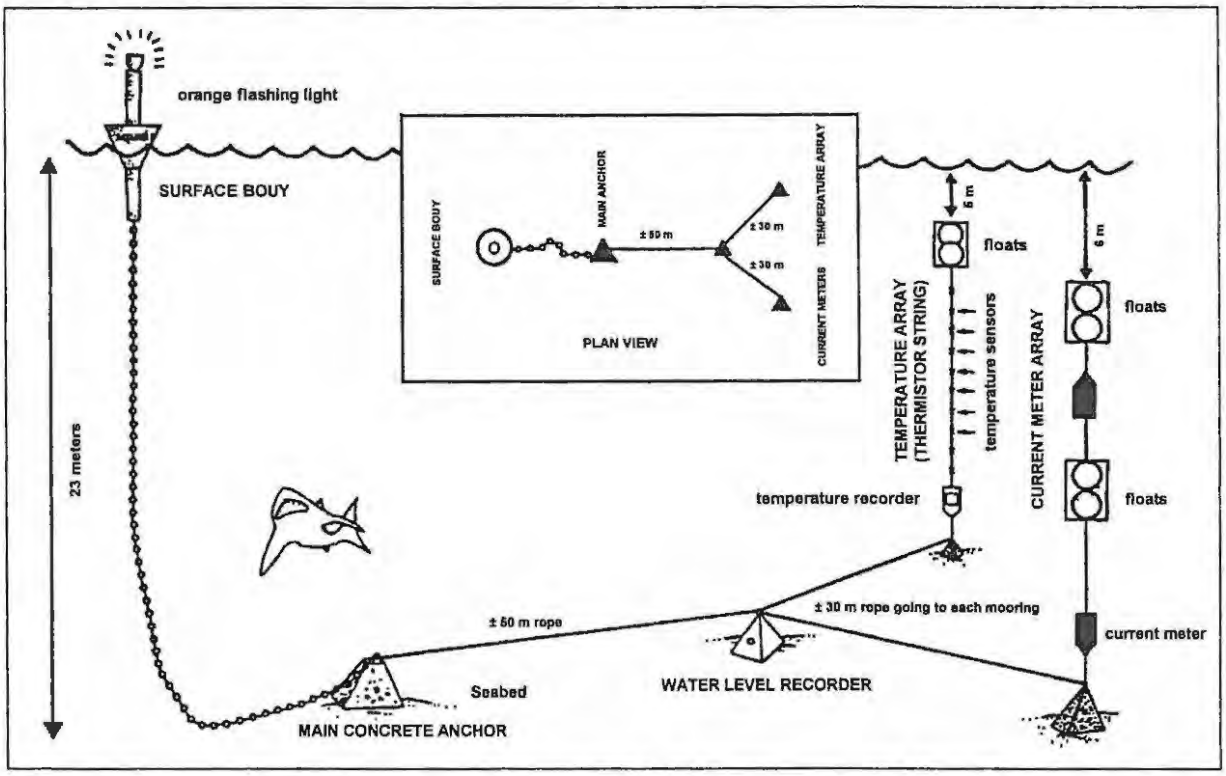

Fig. 4.2: Layout of environmental mooring in Kromme Bay.

Water temperature was measured in 60-minute sampling intervals by an *Aanderaa Temperature Profile Recorder Model 7* (accuracy of ±0.01°C). The temperature recorder consists of a 12-channel recording unit and a thermistor string employing 11 thermistors (temperature sensing elements), spaced throughout the water column (9-24 m). Only the top and bottom thermistors were used, representing sea surface temperature (SST) and bottom temperature (BT), respectively.

The temperature data, recorded from 18/10/1991 to 20/03/1998, were occasionally interrupted as a result of equipment servicing. The interruptions, however, were of short duration: on average 3 to 4 days, roughly every four months. An extended period of data loss occurred in 1992 (95 days), when the thermistor string broke loose from the mooring. This resulted in the data series being shorter whenever a continuous data series was required for analysis. In such a case, the temperature series was started at 01/01/93.

The daily, weekly and monthly mean SST, BT and temperature gradient (difference between SST and BT) were calculated from the hourly data. Mean values essentially 'smoothed out' short-term variability. Additionally, the daily temperature change in both SST and BT were calculated. In time-series data with strong seasonality, the annual harmonic tends to obscure the year-to-year variation. This effect was eliminated by computing the mean weekly and monthly temperature anomalies for the respective time-scales, as the difference between the monthly and weekly data and their respective 6-year means (1992-1997).

The turbidity data series used was short (02/04/95-24/06/95) and only used for daily analyses. Turbidity was measured with an *OBS-3 Suspended Solids & Turbidity Monitor* measuring at 60-minute intervals and recorded in engineering units (TEU). The sensor was attached to the thermistor string and situated 73 cm from the seabed, thus recording bottom turbidity.

The wind direction and speed data (22/01/93-31/03/1998) also experienced some interruptions. These include two extended periods of 56 and 39 days. As a result, the continuous wind data series extends only to the end of 1996. Wind direction was measured by an *Aanderaa Wind Direction Sensor 2053* in 60-minute intervals. Wind direction was recorded in magnetic degrees (accuracy of ±5%) according to the meteorological convention. Direction data were converted relative to true north by subtracting the variation (25°W). An *Aanderaa Wind Speed Sensor 2740* recorded wind speeds at 60-minute intervals. Wind speed was measured in $m \cdot s^{-1}$ (accuracy ±2%) and converted to $km \cdot h^{-1}$. This conversion was necessary for comparison to the wind speed measurements used in Chapter 3.

A number of additional variable sets were added to the data set. The position within the lunar cycle was calculated for individual catch records from the SA Navy Tide Tables (SAN 1991-1998). A variable for seasonal reference was added for each data set, such as the day of year (numbered 0-365), week of year (numbered 0-51) and month of year (numbered 0-11), coded DOY, WOY and MOY, respectively. A linear variable starting at zero at the start of the data series and increasing by one for each day (nDOY), week (nWOY) or month (nMOY) was also added to indicate longer-term change or trend over time.

## 4.2.4 Data analysis

### 4.2.4.1 General

A multiple correlation and regression analysis was performed, and used data over three different time-scales (daily, weekly and monthly). Cross-correlation analyses were attempted to identify possible response lags between series of variables. Since this method requires continuous time-series data, missing data were replaced by interpolation from adjacent values. Effectively, this proved relevant to the few short interruptions in the temperature data series. When computing the cross-correlation coefficients ($r_{xy}$) at 20 or more lags, a 0.01 level of significance was selected (McInnis and Broenkow 1978). Significant results from the cross-correlation analysis were incorporated into the multiple regression analysis, in order to increase the predictability of the regression model.

Normality of the variables was assessed using the Shapiro-Wilk W test (Appendix E1). Various variable transforma``tions were tested to obtain better normalised distributions. Log transformation of catch rate, by the function $\ell$n(CPUE + 1), proved to be the only meaningful transformation, and improved both the normality of the catch distribution and the regressions.

All statistical analyses were carried out on STATISTICA Version 5 (StatSoft, Inc.) and S-PLUS Version 4.0 (Mathsoft, Inc.).

### 4.2.4.2 Analysis of circular and periodic variables

The circular variables, i.e., lunar cycle, wind direction, day of year, week of year and month of year, were treated similar to that described in Chapter 3 (Section 3.2.2.2). The circular periods were 29.5306 days, 360 degrees, 365 days, 52 weeks and 12 months, respectively. The nominal zero for the lunar cycle was considered at new moon, at 0° or true north for wind direction and at the beginning of the calendar year for each of the annual cyclic variables.

Average daily, weekly and monthly wind directions were calculated from the hourly data, to avoid calculating a mean from means. The average weekly position within the lunar cycle (day since new moon) was also calculated from daily records. This involved a method whereby the sine and cosine of the angular measure (radian) of the particular value were calculated, similar to the transformation method used to include the variable in regression analysis (see Chapter 3). The arithmetic mean of the sine and cosine were calculated and represent the average of the circular variable for the particular greater time-scale. The mean value is obtained by dividing the mean of the angular sine values by the mean of the angular cosine values, then calculating the arctangent ($\tan^{-1}$) of the resulting number. The final value represents the average in angular measure or radians.

## 4.3 RESULTS

### 4.3.1 Daily analysis

#### 4.3.1.1 Daily data series: Multiple correlation analysis

Fourteen predictor variables were considered, of which six showed a significant relationship with the variable representing abundance (CPUE); these were: the linear variable (nDOY), the annual cyclic variables (both components), wind speed, SST and BT (Appendix F1). The results were weak, but suggest some empirical relationship between variables.

The positive relationship between catch rate and nDOY suggests a general increase in catch rates over the entire time span of the data series (approximately 6.5 years). Superimposed on this long-term catch trend is the seasonal trend, represented by the periodic components of the annual cycle. These relationships indicated an increase in catches around the peak spawning season, i.e., spring (DOYSIN) and summer (DOYCOS) (Augustyn *et al.* 1994). The correlation between abundance and turbidity was expected to show a strong negative relationship, but this correlation proved to be insignificant, as was the relationship with the lunar cycle.

SST and BT were negatively correlated with catch rates (Appendix F1), supporting the 'cold water-good catch' hypothesis. The relationship is to a large extent linked to upwelling, and thus a change in water temperature. However, no relationship was found with the sine of wind direction (east-west component), i.e., the winds which are the driving force behind upwelling. The two variables indicating the daily change in SST and BT also showed no significant relationship with squid catch. The lack of a relationship between easterly winds and water temperature, suggest a possible lag period between the onset of an easterly wind, causing upwelling at the headland, and cold water flooding into the adjacent embayment.

#### 4.3.1.2 Daily data series: Cross-correlation analysis

SST and BT were cross-correlated with the sine of wind direction. This relationship remains positive for SST, but weakened if lagged one day forwards (Figure 4.3a). The relationship with BT was significantly negative and its strength increased nearly 5-fold when lagged one day forward (Figure 4.3b). This confirms that there is a one- to two-day lag between the onset of an easterly wind/upwelling and the incursion of cold water into the bay. Multiple correlation analyses were repeated with the wind variables each lagged one day forward. This shift significantly increased the correlation coefficients between the sine of wind direction and the temperature variables. Easterly winds seem to have a stronger relationship with BT than SST.

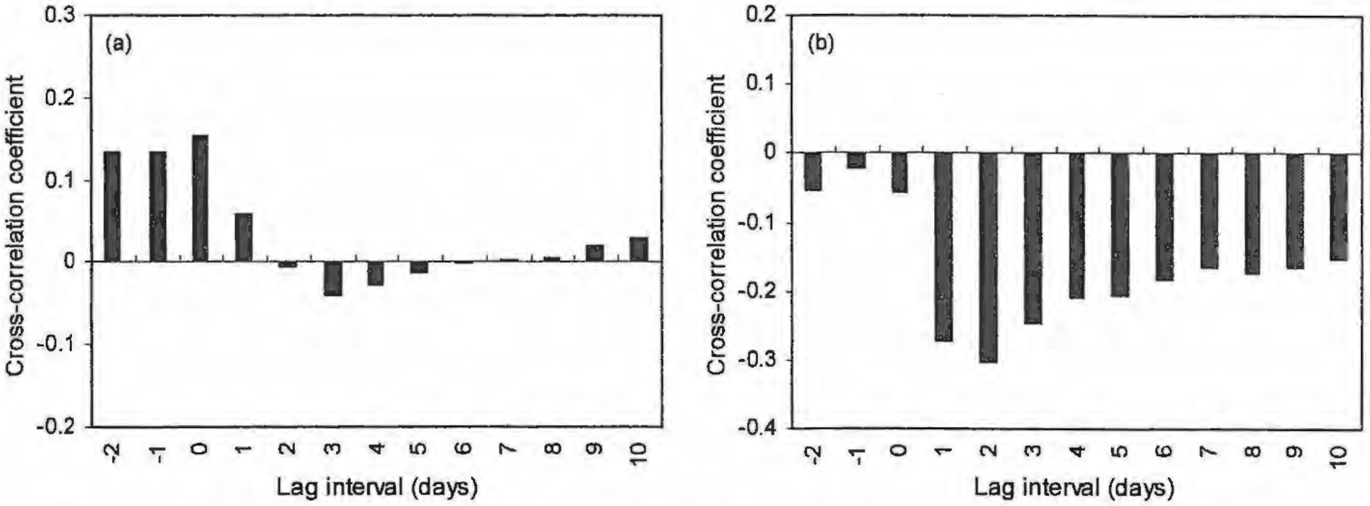

Fig. 4.3: Cross-correlation coefficients between WDIRSIN (east-west component of wind direction) and (a) sea surface temperature; and (b) bottom temperature. Significant correlations ($p<0.01$) are highlighted in blue.

As catch rates proved to be related to a decrease in water temperature, and considering the lag between wind direction and a decrease in temperature, a similar lag between wind direction and catches was expected. However, no significant relationship was found (Fig. 4.4a). Neither was a lag response in catch rate found with decreases in SST or BT (Appendix G1); however, the relationship may be expected to be direct considering the short time-scale applied.

Cross-correlation between turbidity and catch rate was performed. Catches appear to decrease two days before a turbidity increase (Fig. 4.4b). By lagging the relationship backwards, the correlation coefficient became negative and increased more than 70-fold.

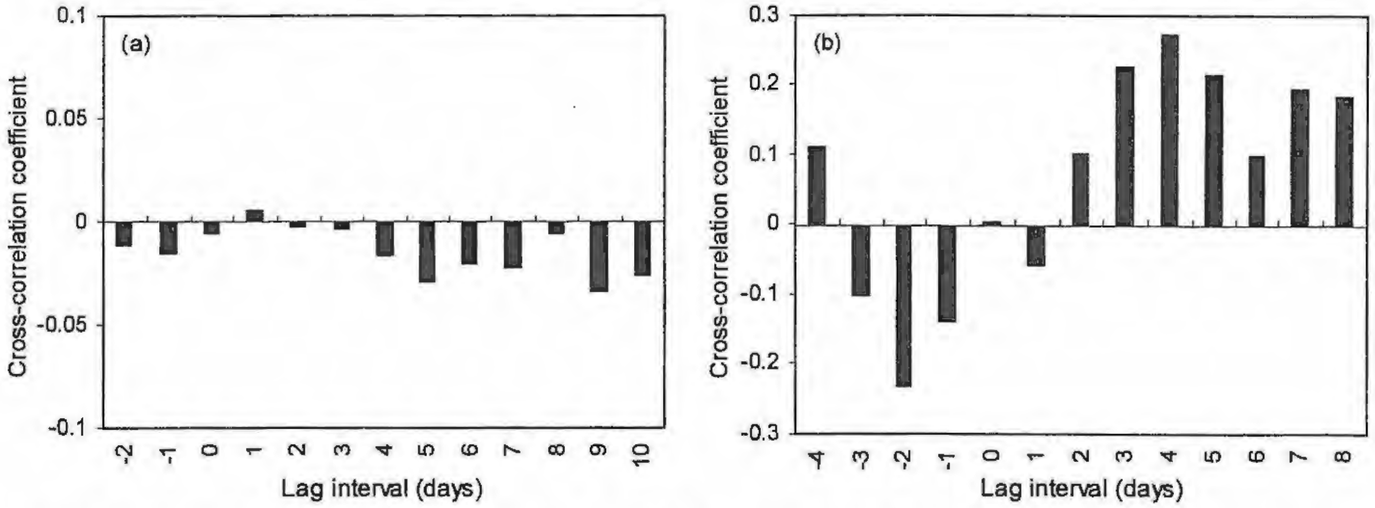

Fig. 4.4: Cross-correlation coefficients between CPUE and (a) WDIRSIN (sine of wind direction) and (b) turbidity. CPUE was transformed by the function $\ell n(\text{CPUE} + 1)$. Significant correlations ($p<0.01$) are highlighted in blue.

### 4.3.1.3 Daily data series: Multiple regression analysis

Two different daily data series were considered for multiple regression analysis: a short series (95 days) that included turbidity data (the turbidity data series) and the full data series. With respect to the turbidity data series, regression analysis began with a model ($n=84$) where 10 of the 14 environmental variables were included as independent variables. The results were significant ($p<0.03$) with a multiple regression coefficient of 0.23 (Appendix F2). The probability plot of the residuals was fairly normal (Appendix F3). The sine of the lunar cycle and the sine of the day of year showed importance as predictor variables.

The model was modified slightly to incorporate lag periods (that is, one day forward for the wind component variables and two days backward for the turbidity variable):

$$\ell n(\text{CPUE} + 1) = 12.42 - 4.62\,(\text{DOYSIN}) + 1.33\,(\text{DOYCOS}) + 0.83\,(\text{LUNARSIN}) + 0.68\,(\text{LUNARCOS}) - 0.034\,(\text{WSPEED}) - 0.79\,(\text{WDIRSIN}) + 0.93\,(\text{WDIRCOS}) + 0.03\,(\text{SST}) + 0.16\,(\text{BT}) - 0.0147\,(\text{TURBIDITY}) + \varepsilon$$

This model accounted for 36% of the variability in CPUE, with a highly significant relationship ($p<0.0002$) between the dependent variable and the set of independent variables (Table 4.1). The probability plot of the residuals showed an acceptable normal distribution (Appendix F3). LUNARSIN, SINDOY and turbidity were the main determinants of CPUE. The strongest predictor variables were SINDOY and turbidity, independently accounting for more than 8% of the variability in catch. The number of insignificant variables was high, but these were mostly components of periodic or circular variables and could, therefore, not be excluded from the model. The temperature variables were retained in the model based on the important influence water temperature is known to have on squid abundance (Chapter 3) and also due to the significance of the relationship to catch rate as determined by the correlation analysis.

Table 4.1: Results of the standard and stepwise multiple regression analysis using the daily turbidity data series. CPUE (kg·boat$^{-1}$·day$^{-1}$) is the dependent variable and DOYSIN (autumn-spring component of a year), DOYCOS (summer-winter component), LUNARSIN (first-last-quarter component of the lunar cycle), LUNARCOS (new-full moon component), WSPEED (wind speed), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), SST (sea surface temperature), BT (bottom temperature) and TURBIDITY (engineering units) as independent variables. The wind component variables (WDIRSIN, WDIRCOS and WSPEED) were lagged 1 day forward and TURBIDITY 2 days backward. CPUE was transformed by the function CPUE = $\ell n$(CPUE + 1); significance ($p<0.05$) is marked in bold type.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 3.9863 | Intercept | 12.4210 | 6.2554 | 1.986 | **0.0509** |
| p-value | **p<0.0002** | LUNARSIN | 0.8316 | 0.3329 | 2.498 | **0.0148** |
| Multiple R | 0.597 | DOYSIN | -4.6228 | 2.5498 | -1.813 | 0.0740 |
| R$^2$ | 0.356 | TURBIDITY | -0.0147 | 0.0047 | -3.163 | **0.0023** |
| n | 83 | WSPEED | -0.0342 | 0.0330 | -1.037 | 0.3033 |
| df | 72 | LUNARCOS | 0.6774 | 0.3653 | 1.854 | 0.0678 |
| | | BT | 0.1639 | 0.2276 | 0.720 | 0.4740 |
| | | WDIRCOS | 0.9342 | 0.7143 | 1.308 | 0.1951 |
| | | WDIRSIN | -0.7870 | 0.6249 | -1.259 | 0.2120 |
| | | DOYCOS | 1.3351 | 2.1054 | 0.634 | 0.5280 |
| | | SST | 0.0292 | 0.4077 | 0.072 | 0.9431 |

Stepwise regression:

| Variables | Multiple R | Multiple R$^2$ | R$^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| LUNARSIN | 0.2731 | 0.0746 | 0.0746 | 6.5286 | **0.0127** |
| DOYSIN | 0.4038 | 0.1630 | 0.0884 | 8.4520 | **0.0048** |
| TURBIDITY | 0.4957 | 0.2457 | 0.0827 | 8.6648 | **0.0044** |
| WSPEED | 0.5449 | 0.2969 | 0.0512 | 5.6794 | **0.0198** |
| LUNARCOS | 0.5692 | 0.3240 | 0.0271 | 3.0854 | 0.0833 |
| BT | 0.5814 | 0.3381 | 0.0140 | 1.6108 | 0.2085 |
| WDIRCOS | 0.5839 | 0.3409 | 0.0029 | 0.3287 | 0.5682 |
| WDIRSIN | 0.5939 | 0.3528 | 0.0118 | 1.3516 | 0.2488 |
| DOYCOS | 0.5969 | 0.3563 | 0.0035 | 0.4026 | 0.5278 |
| SST | 0.5970 | 0.3564 | 0.0000 | 0.0051 | 0.9431 |

For the analysis of the long daily time-series (Oct 1991 – March 1998), the linear variable (nDOY) was included and turbidity excluded. First, variables were regressed against CPUE (n=1481), assuming a direct relationship. The F-value was highly significant ($p<0.000001$) (Appendix F4), but R$^2$ was only 0.058. The probability plot of the residuals, however, indicates non-normality (Appendix F6), making the results questionable.

The independent variables considered in the previous model were again regressed against CPUE, but, this time with the wind component variables lagged one day forward. The analysis produced results similar to those above, but with some improvements (Appendix F5). The normal probability plot of the residuals did, however, not indicate a normal distribution (Appendix F6), and cautious interpretation of the results is suggested.

The peak locations and amplitudes of the periodic variables were similar for all the above models. The results imply that the highest CPUE can be predicted to occur during early summer (14-25 October), a few days (2.3-5.5 days) after new moon, and with winds blowing north-west to north (320 and 351°).

Results of the above analyses reached partial consensus with some general trends observed (Table 4.2). Contrary to expectations, water temperature and wind direction did not prove to be strong explanatory variables. Incorporating the apparent lag period between upwelling and the time when cold water appears in Kromme Bay into the regression analysis was relatively unsuccessful. The lag shifts also changed the sign of the relationship between temperature and catch rate to negative and generally increased the value of BT as a predictor variable. The importance of the lunar cycle was only highlighted by the multiple regression analyses. Generally, the seasonality of chokka squid catch rates was confirmed.

Table 4.2: Summary table of the significance of the environmental variables in relation to chokka squid catch rates for the different statistical tests, using the daily data series in Kromme Bay. Significance ($p<0.05$) and direction of Spearman's correlations and partial regression coefficients, and variables importance in the stepwise regressions are listed. Also listed are the significant multiple regression coefficients, the number of data points entered into the respective models, and the normality of the residual distribution. No listings imply that the variable was not considered for the specific analysis. Refer to Appendix F1 for a variable abbreviation key.

| Variable | $r_s$ | Turbidity data series: | | Full data series: | |
|---|---|---|---|---|---|
| | | $\beta$ | $\beta$ (include lagged relationships) | $\beta$ | $\beta$ (include lagged relationships) |
| NDOY | + | | | + (1) | + (1) |
| DOYSIN | - | ns (2) | ns (2) | - (2) | - (2) |
| DOYCOS | + | ns | ns | ns (4) | ns (5) |
| LUNARSIN | ns | + (1) | + (1) | ns | ns |
| LUNARCOS | ns | ns | ns | + (3) | + (4) |
| WSPEED | - | ns | ns (4) | ns | - (3) |
| WDIRSIN | ns | ns | ns | ns | ns |
| WDIRCOS | ns | ns | ns | ns | ns |
| SST | - | ns | ns | ns | ns |
| SSTC | ns | | | | |
| BT | - | ns | ns | ns | ns |
| BTC | ns | | | | |
| TGRAD | ns | | | | |
| TURBIDITY | ns | ns | - (3) | | |
| | $R^2$ | 0.23 | 0.36 | 0.06 | 0.06 |
| | n | 84 | 83 | 1481 | 1471 |
| Residual distribution | | normal | normal | non-normal | non-normal |

## 4.3.2 Weekly analysis

### 4.3.2.1 Weekly data series: Multiple correlation analysis

Thirteen environmental variables were considered. Five were found to be significantly correlated with abundance (Appendix F7), namely the linear variable (nWOY), the annual cycle (spring-autumn component), SST, SST anomaly and BT anomaly.

The linear variable (nWOY), similar to the daily data series analysis, showed a strong, positive relationship to catch rate. The negative relationship with sine of the week of year, suggested higher catch rates during spring. Catch rates were related to temperature, and has the strongest relationship with the variables representing temperature anomalies; all relationships were negative.

### 4.3.2.2 Weekly data series: Cross-correlation analysis

Cross-correlation between wind direction and the temperature was not considered on a weekly time-scale, since this relationship is expected to be affected by a daily scale. The mean of weekly SST anomalies were significantly correlated with catch rate up to a seven-week lag (Fig. 4.5a). At a two-week lag, the highest cross-correlation coefficient was double that of the direct correlation coefficient (no lags). Similarly there were significant correlations between mean BT anomalies and abundance (Fig. 4.5b). The strongest relationship was found at a three-week lag period. The negative correlations for both variables implied that catch rates increase two to three weeks after a cold-water period. The relationship between catch rates and wind direction showed no significant cross-correlations (Appendix G2).

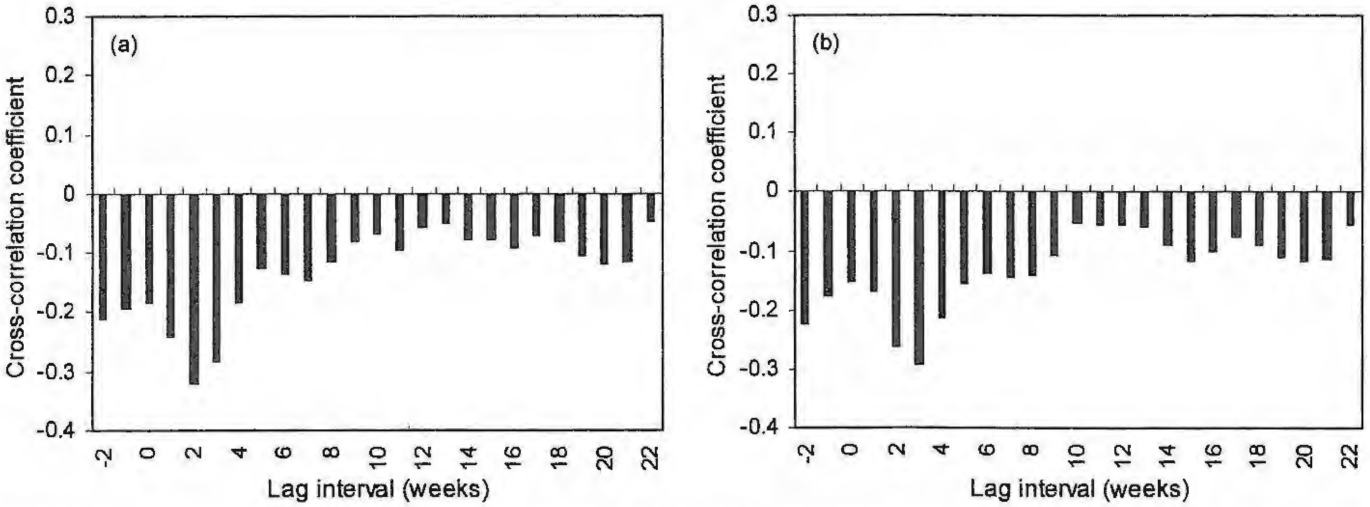

Fig. 4.5: Cross-correlation coefficients between CPUE and (a) weekly mean SST anomalies and (b) weekly mean BT anomalies in Kromme Bay. CPUE was transformed by the function $\ell n(\mathrm{CPUE} + 1)$. Significant correlations ($p<0.01$) are highlighted in blue.

By reapplying multiple correlation analysis to the lagged variables, namely SST, SST anomaly (both adjusted two weeks forward), BT and BT anomaly (both adjusted three weeks forward), the correlation coefficients increased two- to three-fold and were all statistically significant.

### 4.3.2.3 Weekly data series: Multiple regression analysis

All variables, except temperature gradient, were regressed against abundance. Results of the standard multiple and forward stepwise regressions were highly significant ($p<0.0002$, $n=212$) (Appendix F8) and the residual distribution was acceptably normal (Appendix F9). The multiple regression coefficient, however, was only 0.17. The linear variable (nWOY) and the sine of the week of year (WOYSIN) were the important predictor variables. Four explanatory variables were significant in the stepwise regression, namely WOYSIN, nWOY, SST anomaly and SST.

SST and BT were excluded and the optimum lagged relationship between catch and temperature, i.e., to the extent of two weeks for SST anomaly and three weeks for the BT anomaly, was incorporated into the model:

$$\ell n(\text{CPUE} + 1) = 2.83 + 0.0019\,(\text{NWOY}) - 0.42\,(\text{WOYSIN}) + 0.23\,(\text{WOYCOS}) + 0.23\,(\text{LUNARSIN}) + 0.01\,(\text{LUNARCOS}) + 0.051\,(\text{WSPEED}) - 0.25\,(\text{WDIRSIN}) - 0.05\,(\text{WDIRCOS}) - 0.209\,(\text{SSTA}) - 0.129\,(\text{BTA}) + \varepsilon$$

The model accounted for 20% of the variability in abundance (Table 4.3) and was highly significant ($p<0.000002$). The probability plot of the residuals also showed an acceptable normal distribution (Appendix F9). Inclusion of the lag period in the temperature anomaly variables substantially increased their importance in the regression model. Both the temperature anomaly variables were negatively correlated with catch rate. The SST anomaly was the most important variable ($p<0.000003$), and accounted for 10% of the variability in catch. The importance of the linear variable (nWOY) decreased relative to the previous regression models.

Table 4.3: Results of the standard and stepwise multiple regression analysis using the weekly data series. CPUE ($kg \cdot boat^{-1} \cdot day^{-1}$) is the dependent variable and NWOY (number of weeks), WOYSIN (autumn-spring component of a year), WOYCOS (summer-winter component), LUNARSIN, LUNARCOS, WSPEED, WDIRSIN, WDIRCOS, SSTA (sea surface temperature anomaly) and BTA (bottom temperature anomaly) as independent variables. SSTA was lagged 2 weeks forward, and BTA 3 weeks forward. CPUE was transformed by the function CPUE = ℓn(CPUE + 1); significance ($p<0.05$) is marked in bold type.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 5.0031 | Intercept | 2.8326 | 0.6245 | 4.536 | **9.9E-06** |
| p-value | **p<0.000002** | SSTA | -0.2094 | 0.0824 | -2.542 | **0.0118** |
| Multiple R | 0.449 | WOYSIN | -0.4235 | 0.1575 | -2.688 | **0.0078** |
| $R^2$ | 0.202 | BTA | -0.1289 | 0.0632 | -2.041 | **0.0426** |
| n | 209 | WSPEED | 0.0514 | 0.0252 | 2.039 | **0.0427** |
| df | 198 | LUNARSIN | 0.2253 | 0.1434 | 1.570 | 0.1179 |
| | | NWOY | 0.0019 | 0.0015 | 1.249 | 0.2131 |
| | | WDIRSIN | -0.2550 | 0.1520 | -1.678 | 0.0950 |
| | | WOYCOS | 0.2253 | 0.1602 | 1.406 | 0.1613 |
| | | WDIRCOS | -0.0493 | 0.2939 | -0.168 | 0.8668 |
| | | LUNARCOS | 0.0092 | 0.1454 | 0.063 | 0.9494 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| SSTA | 0.3172 | 0.1006 | 0.1006 | 23.1644 | **2.9E-06** |
| WOYSIN | 0.3860 | 0.1490 | 0.0483 | 11.6955 | **0.0008** |
| BTA | 0.4009 | 0.1607 | 0.0117 | 2.8675 | 0.0920 |
| WSPEED | 0.4161 | 0.1732 | 0.0125 | 3.0759 | 0.0810 |
| LUNARSIN | 0.4267 | 0.1821 | 0.0089 | 2.2084 | 0.1388 |
| NWOY | 0.4340 | 0.1883 | 0.0063 | 1.5611 | 0.2130 |
| WDIRSIN | 0.4402 | 0.1937 | 0.0054 | 1.3462 | 0.2473 |
| WOYCOS | 0.4490 | 0.2016 | 0.0079 | 1.9682 | 0.1622 |
| WDIRCOS | 0.4491 | 0.2017 | 0.0001 | 0.0255 | 0.8733 |
| LUNARCOS | 0.4491 | 0.2017 | 1.63E-05 | 0.0040 | 0.9494 |

The peak locations of the periodic variables showed similar results for both models. The peak locations for the week of year were the third and fourth weeks of October. The peak locations of the lunar cycle (3.6 and 7.2 days) were associated with a new moon to the first quarter phase. Both these results support those found for the daily time-series. The importance of the lunar cycle as an explanatory variable did, however, decrease with the time-scale shift from daily to weekly. The highest CPUE was predicted to occur during westerly winds (272 and 259°), which is slightly different from the wind directions found for the daily time-series.

Results and importance of the different environmental variables for the weekly data series analysis are summarised in Table 4.4.

Table 4.4: Summary table of the significance of the environmental variables in relation to chokka squid catch rates for the different statistical tests, using the weekly data series in Kromme Bay. Significance ($p<0.05$) and direction of Spearman's correlations and partial regression coefficients, and variables importance in the stepwise regressions are listed. Also listed are the significant multiple regression coefficients, the number of data points entered into the respective models, and the normality of the residual distribution. No listings imply that the variable was not considered for the specific analysis. Refer to Appendix F7 for a variable abbreviation key.

| Variable | $r_s$ | $\beta$ | $\beta$ (include lagged relationships: SSTA 2 weeks and BTA 3 weeks forward ) |
|---|---|---|---|
| NWOY | + | + (2) | ns |
| WOYSIN | - | ns (1) | - (2) |
| WOYCOS | ns | ns | ns |
| LUNARSIN | ns | ns | ns |
| LUNARCOS | ns | ns | ns |
| WSPEED | ns | ns | + |
| WDIRSIN | ns | ns | ns |
| WDIRCOS | ns | ns | ns |
| SST | - | ns (4) | |
| SSTA | - | ns (3) | - (1) |
| BT | ns | ns | |
| BTA | - | ns | - |
| TGRAD | ns | | |
| $R^2$ | | 0.17 | 0.20 |
| n | | 212 | 209 |
| Residual distribution | | normal | normal |

### 4.3.3 Monthly analysis

The mean monthly catch rates and corresponding sea surface and bottom temperature anomalies recorded in Kromme Bay (November 1991 to March 1998) are shown in Figure 4.6. Monthly catch means 'smoothed out' the daily catch variations. The temperature anomalies demonstrate the variability in water temperature more clearly than the mean water temperature, since the latter parameters exhibit strong seasonal and annual cycles. Variations in catch rates were erratic, but for most years, biannual, seasonal peaks occur. There was no obvious relationship between catch and temperature anomaly, although, extensive periods of poor catches seem to correspond to warm-water anomalies (e.g., November 1991 to March 1993 and again in the first half of 1997).

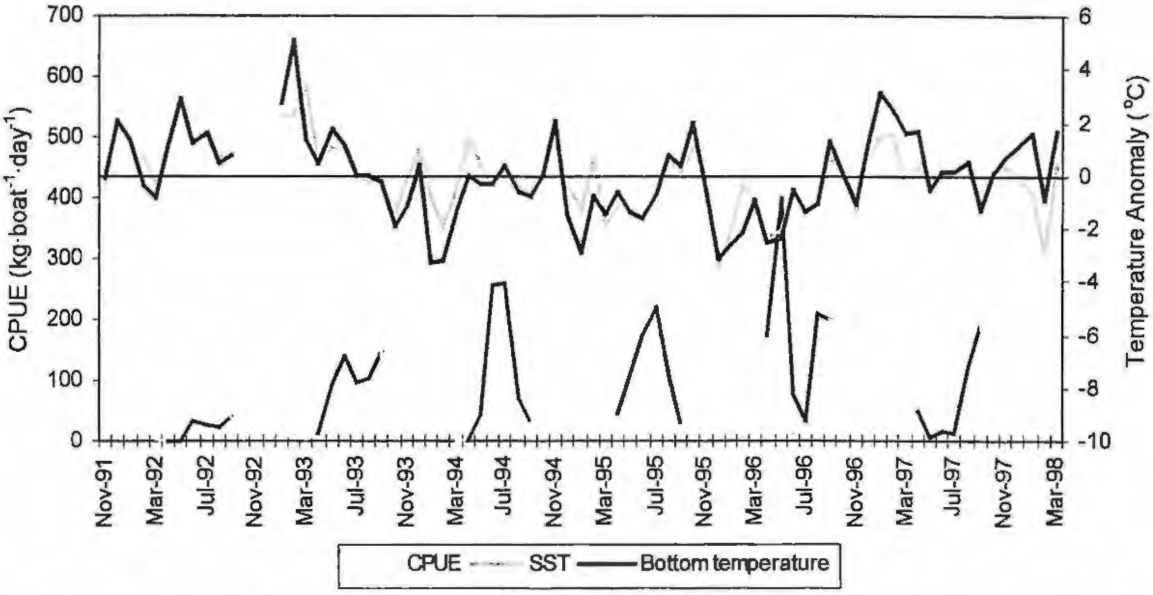

Fig. 4.6: Monthly catch per unit effort of *Loligo vulgaris reynaudii* in Kromme Bay compared to the monthly mean sea surface temperature and bottom temperature anomalies. Summer catch rates are illustrated in yellow and winter catch rates in blue.

### 4.3.3.1 Monthly data series: Multiple correlation analysis

Four of the 11 environmental variables were significantly ($p<0.05$) correlated to abundance, namely the linear variable (nMOY), SST, SST anomaly and BT anomaly (Appendix F10). The significant, positive correlation between nMOY and catch rate was confirmed. No seasonality in catches was found. The highest correlation coefficients for the relationship between water temperature and catch were found on the monthly time-scale. The temperature anomaly variables gave the strongest relationship,

### 4.3.3.2 Monthly data series: Cross-correlation analysis

Cross-correlating abundance and temperature anomalies revealed patterns similar to that found for the weekly analysis. As expected, the two-week lag period found for the SST anomaly in the weekly analysis was not present on a monthly time-scale (Fig. 4.7a). However, the three-week lag period for BT anomalies was supported, with an optimum relationship found at a one-month lag (Fig. 4.7b). These apparent lag periods were confirmed for mean monthly SST, but the relationship with BT was less obvious (Appendix G3). Nonetheless, re-subjecting these lagged variables to multiple correlation analysis resulted in a slight increase in the correlation coefficients. The difference in the apparent time lag periods between cold-water events and an increase in catch rate for the respective temperature anomaly variables highlights the complexity of the oceanographic regime within Kromme Bay.

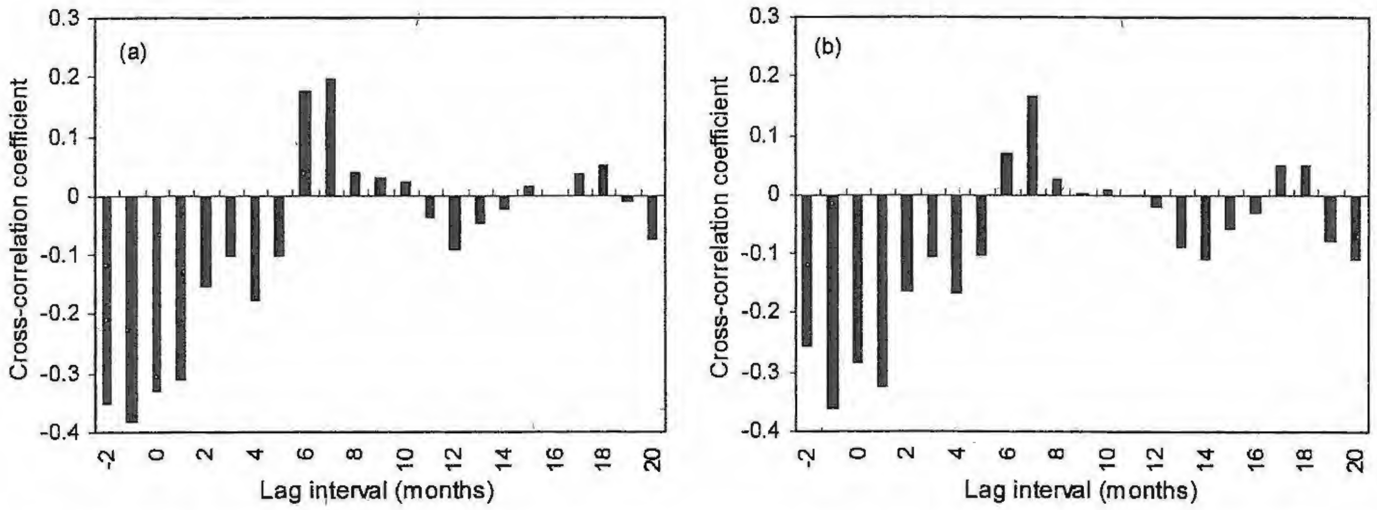

Fig. 4.7: Cross-correlation coefficients between CPUE and (a) monthly mean SST anomalies and (b) monthly mean BT anomalies in Kromme Bay. CPUE was transformed by the function $\ell n(\text{CPUE} + 1)$. Significant correlations ($p<0.01$) are highlighted in blue.

### 4.3.3.3 Monthly data series: Multiple regression analysis

Considering all the environmental variables, the model accounted for 36% of the variability in catch (Appendix F11); the relationship was significant ($p<0.05$) and an acceptable normal distribution was found for the probability plot of the residuals (Appendix F12). None of the variables had significant partial correlation coefficients. SST anomaly and the cosine of wind direction showed some importance in the stepwise regression analysis (Appendix F11).

The weaker explanatory variables, SST and BT, were removed. The lagged relationship between abundance and the monthly mean BT anomalies was also incorporated in the model:

$$\ell n(\text{CPUE} + 1) = 2.48 + 0.020\ (\text{NMOY}) + 0.06\ (\text{MOYSIN}) - 0.67\ (\text{MOYCOS}) + 0.058\ (\text{WSPEED}) + 0.96\ (\text{WDIRSIN}) - 1.33\ (\text{WDIRCOS}) - 0.20\ (\text{SSTA}) - 0.24\ (\text{BTA}) + \varepsilon$$

This model was highly significant ($p<0.005$) and accounted for 40% of variability in abundance (Table 4.5). The distribution of the probability plot of the residuals showed acceptable normality (Appendix F12). The BT anomaly variable (BTA), lagged one month forward, appeared the main determinant of catch.

Table 4.5: Results of the standard and stepwise multiple regression analysis using the monthly data series. CPUE ($kg \cdot boat^{-1} \cdot day^{-1}$) is the dependent variable and NMOY (number of months), MOYSIN (autumn-spring component of a year), MOYCOS (summer-winter component), WSPEED, WDIRSIN, WDIRCOS, SSTA (sea surface temperature anomaly) and BTA (bottom temperature anomaly) as independent variables. BTA was lagged 1 month forward. CPUE was transformed by the function CPUE = ℓn(CPUE + 1); significance ($p<0.05$) is marked in bold type.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 3.3423 | Intercept | 2.4794 | 1.7031 | 1.456 | 0.1533 |
| p-value | **p<0.005** | BTA | -0.2422 | 0.1048 | -2.312 | **0.0260** |
| Multiple R | 0.633 | MOYSIN | 0.0628 | 0.2861 | 0.220 | 0.8273 |
| $R^2$ | 0.401 | SSTA | -0.1998 | 0.1621 | -1.232 | 0.2250 |
| n | 49 | WDIRCOS | -1.3310 | 0.4810 | -2.767 | **0.0085** |
| df | 40 | NMOY | 0.0199 | 0.0117 | 1.697 | 0.0975 |
| | | WDIRSIN | 0.9648 | 0.4241 | 2.275 | **0.0283** |
| | | MOYCOS | -0.6697 | 0.3387 | -1.977 | 0.0549 |
| | | WSPEED | 0.0576 | 0.0780 | 0.739 | 0.4644 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| BTA | 0.3301 | 0.1090 | 0.1090 | 5.7492 | **0.0213** |
| MOYSIN | 0.4223 | 0.1783 | 0.0693 | 3.8820 | 0.0558 |
| SSTA | 0.4639 | 0.2152 | 0.0369 | 2.1165 | 0.1535 |
| WDIRCOS | 0.5271 | 0.2778 | 0.0625 | 3.8106 | 0.0580 |
| NMOY | 0.5507 | 0.3033 | 0.0255 | 1.5717 | 0.2172 |
| WDIRSIN | 0.5687 | 0.3234 | 0.0202 | 1.2532 | 0.2696 |
| MOYCOS | 0.6265 | 0.3925 | 0.0690 | 4.6585 | **0.0370** |
| WSPEED | 0.6330 | 0.4006 | 0.0082 | 0.5456 | 0.4644 |

The models, using monthly data, are the first in which wind direction has shown some importance. The highest catch rates were predicted to occur during wind directions of 143° and 139°, supporting the importance of easterly winds in the environment-catch relationship for chokka squid. However, the link between easterly winds, upwelling and catches is not clear from the Kromme Bay data series. The annual variables representing seasonality showed no significance in the model. The peak location was predicted at 5.75 months (towards the end of May). This is in contrast to all the other analyses carried out on the same data series.

The results and importance of the different environmental variables for monthly data series analysis are summarised in Table 4.6.

Table 4.6: Summary table of the significance of the environmental variables in relation to chokka squid catch rates for the different statistical tests, using the monthly data series in Kromme Bay. Significance ($p<0.05$) and direction of Spearman's correlations and partial regression coefficients, and variables importance in the stepwise regressions are listed. Also listed are the significant multiple regression coefficients, the number of data points entered into the respective models, and the normality of the residual distribution. No listings imply that the variable was not considered for the specific analysis. Refer to Appendix F10 for a variable abbreviation key.

| Variable | $r_s$ | $\beta$ | $\beta$ (include lagged relationships: BTA 1 month forward ) |
|---|---|---|---|
| NMOY | + | ns | ns |
| MOYSIN | ns | ns | ns |
| MOYCOS | ns | ns | ns |
| WSPEED | ns | ns | ns |
| WDIRSIN | ns | ns | - |
| WDIRCOS | ns | ns (2) | - |
| SST | - | ns | |
| SSTA | - | ns (1) | ns |
| BT | ns | ns | |
| BTA | - | ns | - (1) |
| TGRAD | ns | | |
| | $R^2$ | 0.36 | 0.40 |
| | n | 49 | 49 |
| | Residual distribution | normal | normal |

## 4.4 DISCUSSION

The use of particular spawning sites by chokka squid is sporadic and erratic; the oceanography of Kromme Bay is complex. Oceanographic processes, such as upwelling, involve lag periods that ultimately complicate the relationship of the environment to catch rate.

The 'cold water-good catch' hypothesis proved to be strongly related to upwelling. However, easterly winds do not cause immediate upwelling in Kromme Bay; thus the data analysis resulted in a poor association between squid catch and wind direction. There is approximately a two-day lag period between the onset of an easterly wind and cold water flooding the bay. Although the lag period was well incorporated into the daily environment-catch model, it was not represented in models based on the larger time-scale data. Roberts and Sauer (1994) found a strong relationship between good catch rates and months with a high frequency of easterly winds. The influence of the lag period associated with upwelling could thus be overcome by using a predictor variable indicating easterly wind frequency. The association between westerly winds and catch probably the reflects the use of Kromme Bay as a shelter during strong westerly winds, or indirectly, the association between westerly and cold-water penetrating the bays along the south coast (Goschen and Schumann 1988). In studies where the long-term effect of environmental factors on squid catch have been investigated (e.g. McInnis and Broenkow 1978, Dow 1979, Pierce 1995, Dawe *et al.* 1998), the influential role of water temperature was also emphasised.

A time lag between catch and temperature anomalies has been found for both squid (McInnis and Broenkow 1978) and fish (Kim *et al.* 1997). For example, McInnis and Broenkow (1978) found *Loligo opalescens* present in great numbers on the inshore spawning grounds during periods when water temperature warmed, following the cessation of upwelling. Peak squid catch was preceded, approximately two months on the long-term average, by the minimum water temperature. Similar to McInnis and Broenkow (1978), the lagged relationship between catch and water temperature found in this study may indicate an association between increased squid catch rate and the warming that follows the cessation of upwelling. Augustyn (1990) attempted to relate chokka squid catches in Algoa Bay to SST fluctuations and found that catches were best before the maximum temperature was recorded, and, furthermore, peaked during periods of relatively stable temperatures. The author did not state the exact lag period, but the results are nevertheless in contrast to this study. In the present study, SST was found to be a poorer predictor than BT, and a largely inconsistent or redundant variable in the majority of the prediction models.

McInnis and Broenkow (1978) also found a strong relationship between episodes of high temperature and the catch rates of *L. opalescens* at a lag of 18 months, suggesting that the mechanism which links temperature and stock abundance acts upon juvenile squid. Similar extended lag events have not been found for chokka squid catches. The lack of such a lagged relationship concerning this species is supported by the absence of a relationship between the size of the spawning biomass and subsequent recruitment (Roel 1998). The effect of temperature on chokka squid abundance (such as adult spawning squid) appears to be direct; anomalous temperature periods may not necessarily affect the strength of the next year-class.

The strong negative relationship between catch and turbidity, presented in the previous chapter, was less clear on a daily time-scale. Poor catch rates appear to precede turbidity events by two days. The mechanism behind this lag is unknown and speculative, since the lagged relationship may be a proxy to other variables.

The association between high catch rates and the period around the new moon agrees with the results found for some other squid species (see Ichikawa and Sato 1976, Long and Rathjen 1980, Mercer and Bucy 1983). The strong predictability of the lunar cycle found in the analyses of Chapter 3 was not reconfirmed here; however, the effect of the lunar cycle on catch rates may be masked if an annual cycle is considered.

The predictive value of the model based on the daily data series was low compared to the model presented in Section 3.3.2.2, wherein the residual distribution was considered non-normally distributed. Caution should be exercised in interpreting these results against the hourly data set given in Chapter 3. The difference in the predictive value of the models may be caused by the difference in spatial variation between the two data sets or differences in temporal variation (i.e. a continuous time-series versus a discrete data series). Spatial variation may cause stronger correlations between environmental parameters and squid catches, which might then correlate indirectly with other variables. The presence of inaccurate data (as explained in Chapter 2) is of primary concern, but is often unavoidable in fisheries data; yet the shift to larger time-scales (i.e., averaging of parameter estimates) may to some extent reduce the error in such a data series. The general increase in the efficiency of the fishing fleet, due to development of fishing technology and harvesting strategies (Chapter 2), was reflected in the positive relationship found between catch rate and the linear variable (nDOY, nWOY and nMOY). The linear variable accounted for a significant proportion of CPUE variability in the majority of the models and suggests a general increase in catch rates over the time period considered. An increase in vessel efficiency may have a masking effect on catch rates as an indicator of abundance on a larger time-scale.

The progressing temporal shift from daily to monthly time-scales resulted in a considerable increase in the predictive value of the regression models. $R^2$ often increased with the shift from a short to a larger time-scale (or with the averaging of data over intervals of independent variables), when the number of data points decrease (i.e. N changes). However, in many cases error will have negated the opposing effects. An $R^2$ value indicates what percentage of variation in individual catch rates for a specific time-scale can be accounted for (i.e., 0.06 for daily catch variation and 0.4 for monthly, which is not necessarily applicable to the overall environment-catch relationship). The choice and suitability of any model will, therefore, depend on its application. Since environmental influences and biological parameters (populations dynamics) vary simultaneously on several time-scales, the choice of environmental and oceanographic parameters and the time-scale at which their comparison to biological parameters is performed becomes crucial, and requires careful consideration. In this work, the masking of short-term detail by using mean values inevitably resulted in the varying importance of particular predictor variables on different time-scales.

The variability in explanatory value of individual environmental variables in the Kromme Bay data series can largely be explained by the degree of time-scale shift. Of particular interest is the relationship between the environmental variables, temperature and turbidity, and chokka squid catch rate. The effects of upwelling and turbidity on catch appear to be most pronounced in relation to the spawning process on a hourly time-scale (Chapter 3). On larger time-scales, which involve the use of mean values, error will increase and these variables will show a decreased importance as explanatory variables in terms of catch rate. Factors directly controlling squid catch (i.e. spawning intensity) can be delineated on an hourly time-scale (i.e. environmental triggers) and so serve to test causal relationship between environmental factors and catches. This information may then be used in models which utilise a larger time-scale. A monthly scale appears to optimal when considering the environmental-catch relationship in a prediction model.

Although the catch trends in Kromme Bay mimic that of the fishery, the lack of spatial variation became evident as the data series for the environment-catch prediction models was drawn from one specific area. A similar study, using data collected from an exposed coastline may provide results showing clearer relationships, since the lag relationships found in this study due to the effect of the bay will be greatly reduced.

## 4.5 CHAPTER SUMMARY

In this study the relationship between environmental conditions and chokka squid catch rates were investigated on daily, weekly and monthly time-scales in Kromme Bay, using multiple correlation and regression analysis, and cross-correlation analysis. The main results and conclusions include:

- The complex oceanographic condition in Kromme Bay resulted in lagged relationships, especially concerning the relationship between catch rates, easterly winds and upwelling (decrease in temperature).
- The importance of wind direction, temperature and, to a lesser extent, turbidity as influencing factors on chokka squid catch, found in Chapter 3, were confirmed.

- The progressing temporal shift from daily to monthly time-scales resulted in a considerable increase in the predictive value of the regression models. The variability in explanatory value of individual environmental variables can also be largely explained by the degree of time-scale shift.
- The best prediction model was on a monthly scale, accounting for 40% of the variability in catch. The principal determinant of catch, bottom temperature anomaly (11%), was found to lag one month forward.

# CHAPTER 5

# CONCLUSION AND MANAGEMENT IMPLICATIONS

The investigation of the environment-catch relationship for *Loligo vulgaris reynaudii* was approached systematically by examining increasingly larger temporal scales, smaller spatial scales and greater problem complexity. Direct relationships between chokka squid catch rates and environmental variables were found, but some environmental variables acted as proxy variables for oceanographic processes, e.g., the interrelation between water temperature, wind direction and upwelling. In contrast, the influential importance of wind direction, turbidity and temperature was confirmed. It appears that it is the dynamics of these variables that are important and not necessarily their static values at any point in time (Legendre and Demers 1984, Mendelssohn and Cury 1987). The interaction of these factors complicated the extraction of direct causal relationships among the biotic and abiotic factors examined. However, investigating the relationship on a short, hourly time-scale proved to be relatively useful for the definition of causal relationships. The real problem is, however, to be able to include these relationships into predictive models on larger time-scales.

The statistically simple, direct, 'black box' approach proved relatively successful. Such an approach is usually chosen before more complex methods, but it does not always provide a complete answer in terms of predictability. Most prediction models in this study were based on a set of environmental variables that included variables appearing to have little influence on catch rate variability. However, scientists often idealise these equations by eliminating certain parameters or making assumptions in order to keep the models simple and easy to interpret. Unfortunately this can be to the detriment of a representative or more realistic model. Robustness is a desirable feature of any model and unnecessary parameters will increase complexity, but the pursuit of these should not be at the expense of a more realistic perspective.

The principal difficulties in developing an environment-catch prediction model for chokka squid were two fold. Firstly, high variability was found for both biological parameters (i.e., catch rates) and physical parameters (see Chapter 2). Secondly, since the catch rates were largely linked to spawning activity, the complexities associated with the spawning process were appended to the relationship. The influence of the environment was thus not only directly related to catches or fishing success, but also to the timing and degree of spawning aggregation formation. An important factor which was excluded, is the possibility of real changes in the population size and its causal mechanisms.

Large irregularities were found in the abundance variable, which were mainly attributed to the absence of variables indicating fishing pressure and fishing efficiency. Separating the effects of man from those of the environment, and identifying mechanisms causing change is, however, difficult and has hampered long-term forecasting of population abundance world-wide (Crawford *et al.* 1990). Although fishing intensity is difficult to quantify, intense fishing activity on spawning aggregations adversely affect the spawning process, thereby not only compromising future recruitment (Sauer 1995a) but also influencing the environment-catch relationship. This effect was most noticeable in the hourly time-scale analysis (Chapter 3), but is also likely to have an effect on larger time-scales.

Short-term predictability remains essential (i.e., hourly time-scale) but long-term prediction models (e.g., monthly time-scales) are more important from a managerial perspective. Future research should concentrate on long-term analysis, similar to the analysis presented in Chapter 4 regarding catches in Kromme Bay. These analyses should include a greater spatial scale. The current changes within the fishery, especially the increased exploitation of the deeper spawning grounds, reduces the importance of predicting the abundance of squid on the inshore spawning grounds. Such changes are a further incentive for a shift in research focus towards larger temporal and spatial scales. The investigation of the environment-catch relationship on a larger time-scale would make research on potential environmentally induced distributional variations possible, which could be of primary importance to management. Environmental conditions may not only affect abundance (in terms of spawning intensity) on all spatial and temporal scales, but also alter the alongshore distribution of squid. For example, large scale climatic changes may increase squid abundance at the distribution limits of the inshore spawning grounds, in areas such as Cape Agulhas or East London. The possible effect of the environment on the inshore-offshore migration of chokka squid (Augustyn *et al.* 1992) also becomes more important in light of the increasing exploitation of squid over the deeper spawning grounds at night. Fleet distribution (Healey *et al.* 1990), using vessel monitoring systems, and remote sensing are potentially powerful tools for inferring the dominant factors that control distribution variations.

### *Management implications*

Squid fisheries are notoriously difficult to manage (Augustyn *et al.* 1994). Since the disruption of spawning activity may have disastrous consequences for the *L. v. reynaudii* stock (Sauer 1995a), the absence of a management strategy for the chokka fishery is highly risky (Augustyn *et al.* 1992). An intimate understanding of the spawning behaviour and movement of squid in these inshore areas is therefore essential. Defining the factors that control recruitment in exploited organisms that are short-lived is perhaps the most important task in squid fisheries management (Pauly 1985, Pinhorn and Halliday 1985). Recruitment is highly dependent on complex interactions, including environmental factors (Grant *et al.* 1981, Augustyn *et al.* 1992, 1994) and fishing pressure (Sauer 1995a). Finding reliable stock-recruitment relationships have so far been unsuccessful; Augustyn *et al.* (1992) pointed out that rational, but not necessarily optimal, management decisions can be made in the absence of such fisheries models by employing 'common-sense' measures which generally include some form of effort control. To date, management of the chokka squid resource has been conservative (Augustyn *et al.* 1992) but lately rather ineffective. This can be justified in the case of short-lived, semelparous species, because disruption of recruitment or a stock collapse in any single year could virtually annihilate stocks (Augustyn *et al.* 1992, O'Dor 1992).

At present, the chokka squid fishery is managed by means of effort control (Chapter 2). The basic premise is to ensure that the exploitation rate should not exceed some upper limit above which the future recruitment would be affected (Augustyn *et al.* 1992). The catchability coefficient (q), a measure of vessel efficiency ($F=qE$ where E is fishing effort and F is fishing mortality), is important for an effort controlled fishery (Pinhorn and Halliday 1985). Despite effort regulations and a conservative management strategy for the chokka squid fishery, effort and CPUE have increased (Chapters 2 and 4) primarily as a result of more effective fishing strategies and new technology. Relative departures from a constant catchability coefficient are crucial for an effort controlled fishery and are important in deciding management strategies (Pinhorn and Halliday 1985). However, the information is difficult to assess with inaccurate CPUE and effort data (Chapter 2). Contrary to the *Illex argentinus* fishery in Falkland Islands waters (Beddington *et al.* 1990), mitigating factors which can contribute to high quality catch data, such as license agreements and the absence of set catch quotas on individual or total landings, proved to be inadequate for the chokka squid fishery and need to be addressed. This highlights the need to re-evaluate effort and CPUE levels, particularly as these are presently incorporated in stock assessment models for *L. v. reynaudii* (Roel 1998, Roel *et al.*1998). Regular biomass surveys must be continued so that a time-series of biomass estimates is available to ensure the collection of fishery independent data.

An investigation into the environment-catch relationship for chokka squid, had predictability as its goal. This has important considerations as the jig fishery is based on spawning chokka squid where their location, timing and degree of aggregation or spawning activity relates to their catchability. Variation in abundance has a major impact on fishing success and hence on the profitability of the fishery over short time-scales, as well as on the practice of fishery management and interpretation of results. Improved understanding of the relationship between catch rates, abundance or spawning intensity, and variability within the physical environment is of substantial importance in terms of predictability. Short-term forecasting of squid catch is therefore of practical importance for fisheries management planning. For the chokka squid fishery the optimal number of licenses or the length of the closed season, for example, could be determined based on the expectations of fishing success.

Finding such a reliable environment-catch relationship has so far been elusive for squid (Roberts *et al.* 1998). Data presented in this study regarding the relationships between environmental factors and chokka squid, and the mechanisms which might govern these relationships, provide a basis for future research with the ultimate aim of producing a reliable predictive model. From a practical, stock assessment viewpoint, the variation in commercial catch rates induced by environmental influences can be sufficiently large to mask the relationship between catch rate and stock size, resulting in substantial variance around such relationships (Pinhorn and Halliday 1985). This often leads to many stock assessment and managerial difficulties. Future research should concentrate on assessing the stock status as an entity and not just concentrate on the inshore spawning grounds. The accurate collection of commercial catch and effort data, both on the inshore and offshore fishing grounds, should be priority, with the gathering of oceanographic data as auxiliary information. Ultimately, a number of observers on commercial fishing vessels are necessary to achieve this goal. Such information may then be used to improve the utility of fishery catch data to assess spawning population abundance, that can in turn be ultimately used to indicate stock status.

When managing marine resources the aim is to manage in the face of uncertainty. This entails taking management actions that are both robust to uncertainties, i.e., level of recruitment or resource abundance, and to assumptions made regarding parameters such as catchability, which could be highly influenced by the environment. Undoubtedly, gaining a better understanding of environmental influences on chokka squid catches, abundance or spawning behaviour is valuable, and using such information in forecasting catches have potential benefits for both the industry and fishery managers. However, the potential application to chokka fishery management in the near future, is still highly improbable.

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# **APPENDIX A1**: DATA DISTRIBUTION – HISTOGRAMS (see Chapter 3)

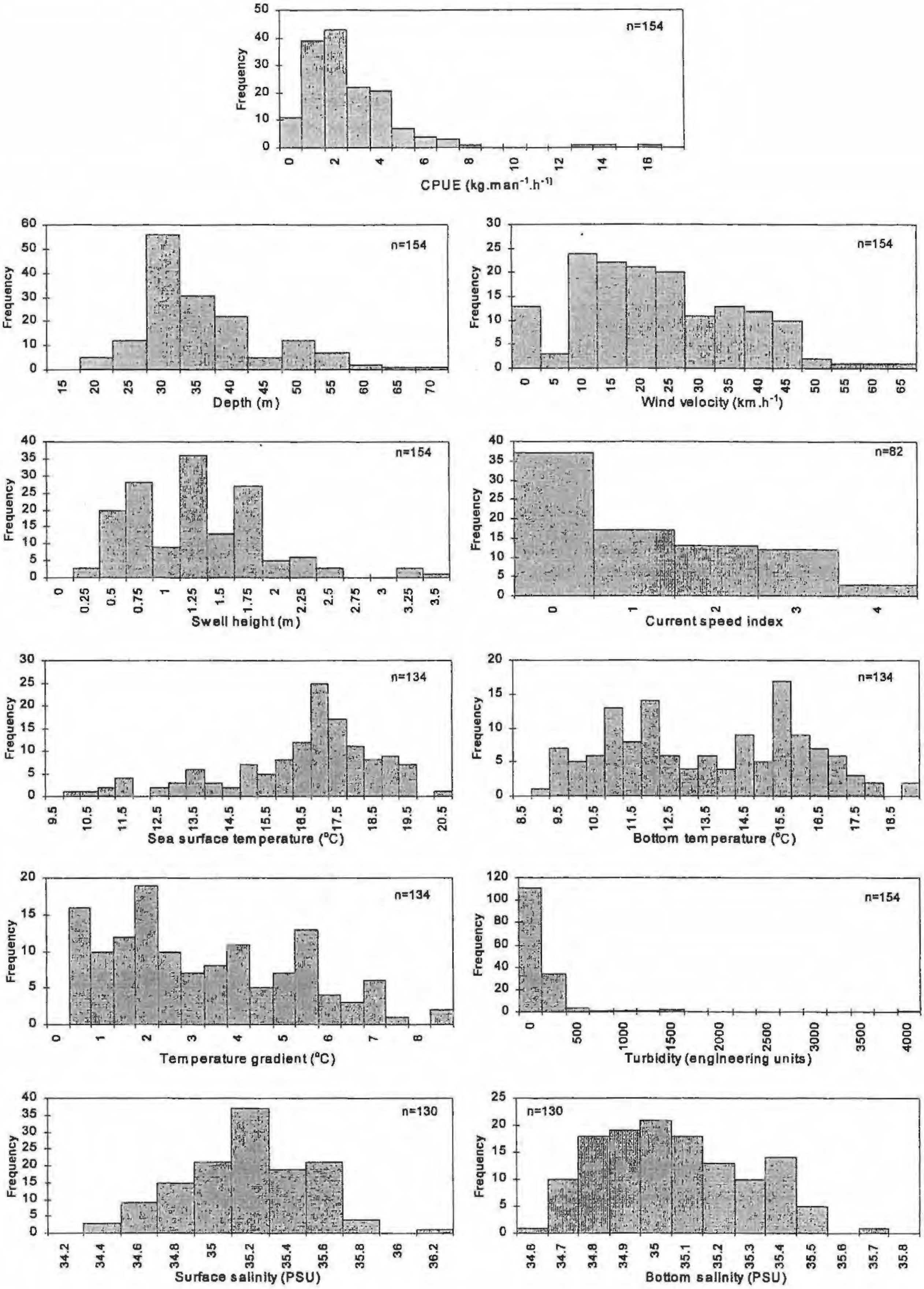

Figure A.1: Frequency distribution graphs of CPUE and independent variables, excluding circular variables.

# APPENDIX A2: DATA DISTRIBUTION – NORMALITY TESTING

(see Chapter 3)

Table A2: Assessment of normality using the Shapiro-Wilk W test ($p<0.05$ marked in red) for dependent and independent variables, excluding categorical variables, viz. season, diel, bottom structure.

| | Shapiro-Wilk W Test | | |
|---|---|---|---|
| Variable | N | W | P |
| CPUE | 154 | 0.7376 | 5.45E-61 |
| Depth | 154 | 0.9001 | 1.23E-15 |
| Lunar sine | 154 | 0.8646 | 1.27E-24 |
| Lunar cosine | 154 | 0.8245 | 1.47E-35 |
| Wind direction sine | 141 | 0.7472 | 1.91E-49 |
| Wind direction cosine | 141 | 0.8446 | 5.12E-26 |
| Wind velocity | 154 | 0.9488 | 3.4E-05 |
| Swell height | 154 | 0.9154 | 4.85E-12 |
| Current direction sine | 45 | 0.6234 | 2.49E-13 |
| Current direction cosine | 45 | 0.6943 | 3.08E-11 |
| Current speed | 82 | 0.7955 | 2.61E-16 |
| SST | 134 | 0.9094 | 3.92E-11 |
| Bottom temperature | 134 | 0.9389 | 5E-06 |
| Temperature gradient | 134 | 0.9299 | 1.68E-07 |
| Turbidity | 154 | 0.2592 | 0 |
| Surface salinity | 130 | 0.9797 | 0.435628 |
| Bottom salinity | 130 | 0.9560 | 0.002116 |

# APPENDIX B1: MULTIPLE CORRELATION ANALYSIS – CORRELATION MATRIX (COMPLETE DATA SET)

(see Chapter 3)

Table B1: Correlation matrix for the complete data set. Significant Spearman's correlation coefficients are marked in red (p<0.05) and bold red (p<0.005).

| | CPUE | SEASON | DIEL | DEPTH | LUNAR SIN | LUNAR COS | WDIR SIN | WDIR COS | WSPEED | SWELL | BSTRUC | CDIR SIN | CDIR COS | CSPEED | SST | BT | TGRAD | TURB | SSAL | BSAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPUE | 1 | 0.177 | 0.151 | **-0.232** | **-0.264** | 0.191 | **0.266** | -0.131 | -0.166 | -0.079 | -0.019 | -0.032 | 0.124 | -0.141 | -0.184 | -0.148 | 0.073 | **-0.280** | -0.068 | -0.096 |
| SEASON | 0.177 | 1 | 0.063 | **-0.510** | **-0.278** | **0.239** | -0.085 | -0.130 | 0.093 | 0.004 | **0.410** | 0.165 | 0.082 | 0.131 | **0.287** | -0.033 | 0.154 | -0.194 | **-0.483** | **-0.344** |
| DIEL | 0.151 | 0.063 | 1 | -0.105 | 0.073 | 0.162 | 0.222 | -0.072 | -0.160 | -0.117 | -0.022 | 0.263 | 0.143 | 0.052 | -0.162 | -0.019 | -0.012 | **-0.229** | 0.063 | 0.139 |
| DEPTH | **-0.232** | **-0.510** | -0.105 | 1 | 0.129 | -0.105 | -0.104 | 0.023 | 0.001 | 0.039 | -0.149 | -0.091 | 0.080 | 0.134 | 0.004 | -0.106 | 0.176 | 0.191 | **0.270** | 0.104 |
| LUNARSIN | **-0.264** | **-0.278** | 0.073 | 0.129 | 1 | 0.021 | 0.129 | 0.200 | -0.059 | 0.015 | -0.033 | -0.007 | -0.081 | **0.326** | 0.235 | 0.168 | 0.112 | 0.097 | **0.388** | **0.336** |
| LUNARCOS | 0.191 | **0.239** | 0.162 | -0.105 | 0.021 | 1 | 0.200 | -0.002 | **-0.242** | -0.067 | 0.000 | 0.136 | -0.113 | 0.195 | **0.393** | 0.196 | **0.248** | -0.064 | 0.178 | 0.226 |
| WDIRSIN | **0.266** | -0.085 | 0.222 | -0.104 | 0.129 | 0.200 | 1 | 0.110 | -0.001 | 0.046 | 0.119 | -0.147 | -0.076 | -0.034 | -0.187 | -0.126 | 0.015 | -0.073 | 0.099 | 0.019 |
| WDIRCOS | -0.131 | -0.130 | -0.072 | 0.023 | 0.200 | -0.002 | 0.110 | 1 | 0.014 | 0.040 | 0.152 | -0.131 | -0.105 | 0.051 | -0.077 | -0.110 | 0.039 | -0.098 | 0.051 | -0.073 |
| WSPEED | -0.166 | 0.093 | -0.160 | 0.001 | -0.059 | **-0.242** | -0.001 | 0.014 | 1 | **0.327** | 0.198 | -0.187 | 0.213 | 0.251 | -0.024 | -0.008 | -0.136 | 0.058 | -0.205 | -0.114 |
| SWELL | -0.079 | 0.004 | -0.117 | 0.039 | 0.015 | -0.067 | 0.046 | 0.040 | **0.327** | 1 | 0.247 | -0.038 | 0.156 | 0.068 | 0.149 | 0.109 | 0.002 | 0.053 | -0.170 | -0.085 |
| BSTRUC | -0.019 | **0.410** | -0.022 | -0.149 | -0.033 | 0.000 | 0.119 | 0.152 | 0.198 | 0.247 | 1 | -0.055 | 0.094 | 0.069 | -0.074 | -0.257 | 0.121 | -0.074 | **-0.417** | **-0.373** |
| CDIRSIN | -0.032 | 0.165 | 0.263 | -0.091 | -0.007 | 0.136 | -0.147 | -0.131 | -0.187 | -0.038 | -0.055 | 1 | **0.426** | 0.042 | 0.121 | 0.083 | 0.045 | -0.213 | -0.356 | -0.119 |
| CDIRCOS | 0.124 | 0.082 | 0.143 | 0.080 | -0.081 | -0.113 | -0.076 | -0.105 | 0.213 | 0.156 | 0.094 | **0.426** | 1 | 0.134 | 0.012 | -0.112 | 0.107 | -0.146 | -0.237 | -0.235 |
| CSPEED | -0.141 | 0.131 | 0.052 | 0.134 | **0.326** | 0.195 | -0.034 | 0.051 | 0.251 | 0.068 | 0.069 | 0.042 | 0.134 | 1 | 0.233 | 0.132 | 0.002 | -0.096 | 0.055 | 0.155 |
| SST | -0.184 | **0.287** | -0.162 | 0.004 | 0.235 | **0.393** | -0.187 | -0.077 | -0.024 | 0.149 | -0.074 | 0.121 | 0.012 | 0.233 | 1 | **0.576** | **0.244** | 0.168 | 0.155 | **0.294** |
| BT | -0.148 | -0.033 | -0.019 | -0.106 | 0.168 | 0.196 | -0.126 | -0.110 | -0.008 | 0.109 | -0.257 | 0.083 | -0.112 | 0.132 | **0.576** | 1 | **-0.559** | 0.203 | **0.412** | **0.744** |
| TGRAD | 0.073 | 0.154 | -0.012 | 0.176 | 0.112 | **0.248** | 0.015 | 0.039 | -0.136 | 0.002 | 0.121 | 0.045 | 0.107 | 0.002 | **0.244** | **-0.559** | 1 | -0.073 | -0.183 | **-0.464** |
| TURB | **-0.280** | -0.194 | **-0.229** | 0.191 | 0.097 | -0.064 | -0.073 | -0.098 | 0.058 | 0.053 | -0.074 | -0.213 | -0.146 | -0.096 | 0.168 | 0.203 | -0.073 | 1 | **0.251** | **0.276** |
| SSAL | -0.068 | **-0.483** | 0.063 | **0.270** | **0.388** | 0.178 | 0.099 | 0.051 | -0.205 | -0.170 | **-0.417** | -0.356 | -0.237 | 0.055 | 0.155 | **0.412** | -0.183 | **0.251** | 1 | **0.773** |
| BSAL | -0.096 | **-0.344** | 0.139 | 0.104 | **0.336** | 0.226 | 0.019 | -0.073 | -0.114 | -0.085 | **-0.373** | -0.119 | -0.235 | 0.155 | **0.294** | **0.744** | **-0.464** | **0.276** | **0.773** | 1 |

| **Key:** | | | |
|---|---|---|---|
| CPUE | Catch per unit Effort (kg·man$^{-1}$·h$^{-1}$) | BSTRUC | Bottom structure (sand/reef-sand/reef) |
| SEASON | Winter (1) / Summer (2) | CDIRSIN | Sine of radian of current direction |
| DIEL | Night (1) / Day (2) | CDIRCOS | Cosine of radian of current direction |
| DEPTH | Bottom depth (m) | CSPEED | Current speed (1-4 index) |
| LUNARSIN | Sine of radian of day since new moon | SST | Sea surface temperature |
| LUNARCOS | Cosine of radian of day since new moon | BT | Bottom temperature |
| WDIRSIN | Sine of radian of wind direction | TGRAD | Temperature gradient (difference between SST and BT) |
| WDIRCOS | Cosine of radian of wind direction | TURB | Turbidity |
| WSPEED | Wind speed (km·h$^{-1}$) | SSAL | Surface salinity |
| SWELL | Swell height (m) | BSAL | Bottom salinity |

# APPENDIX B2: MULTIPLE REGRESSION ANALYSIS – PROBABILITY PLOT OF RESIDUALS

(see Chapter 3)

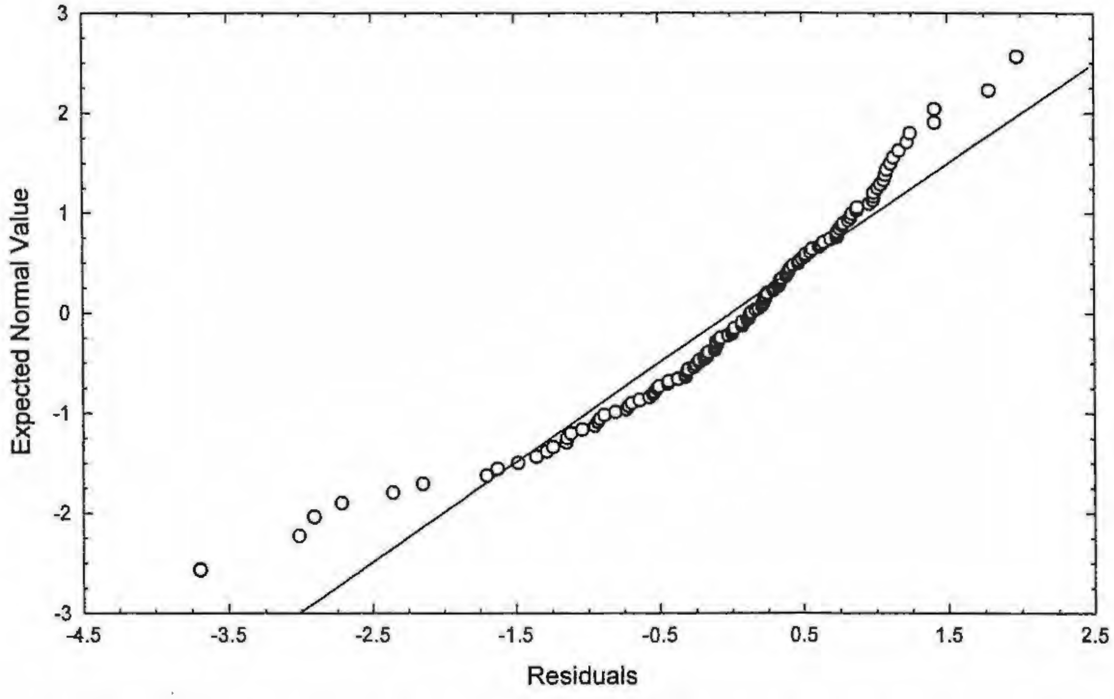

Figure B.2: Normal probability plot of residuals for the multiple regression analysis with CPUE as the dependent variable and SEASON, DEPTH, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SST and TURBIDITY as regressors.

## **APPENDIX B3**: MULTIPLE REGRESSION ANALYSIS – STEPWISE REGRESSION

(see Chapter 3)

Table B3: Summary of stepwise regression with CPUE ($kg \cdot man^{-1} \cdot h^{-1}$) as the dependent variable and SEASON (winter/summer), DEPTH (maximum depth), LUNARSIN (first-last-quarter component of the lunar cycle), LUNARCOS (new-full moon component), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), WSPEED (wind speed), SST and TURBIDITY as independent variables. CPUE was transformed by the function CPUE = $\ell n$(CPUE + 0.05); significance ($p<0.05$) is marked in red.

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F - to enter/remove | p-level |
|---|---|---|---|---|---|
| TURBIDITY | 0.3630 | 0.1317 | 0.1317 | 19.118 | 2.7E-05 |
| LUNARSIN | 0.4500 | 0.2025 | 0.0708 | 11.095 | 0.0012 |
| WDIRSIN | 0.5086 | 0.2587 | 0.0562 | 9.393 | 0.0027 |
| LUNARCOS | 0.5482 | 0.3006 | 0.0419 | 7.360 | 0.0077 |
| SEASON | 0.5540 | 0.3069 | 0.0063 | 1.116 | 0.2929 |
| SST | 0.5573 | 0.3106 | 0.0037 | 0.644 | 0.4238 |
| WDIRCOS | 0.5609 | 0.3146 | 0.0041 | 0.715 | 0.3995 |
| WSPEED | 0.5631 | 0.3171 | 0.0025 | 0.434 | 0.5115 |
| DEPTH | 0.5633 | 0.3173 | 0.0002 | 0.039 | 0.8442 |

## **APPENDIX B4**: MULTIPLE CORRELATION ANALYSIS – CORRELATION MATRIX (SUMMER DATA SET)

(see Chapter 3)

Table B4: Correlation matrix for the summer data set (Oct-Apr). Significant Spearman's correlation coefficients are marked in red (p<0.05) and bold red (p<0.005).

| | CPUE | DIEL | DEPTH | LUNAR SIN | LUNAR COS | WDIR SIN | WDIR COS | WSPEED | SWELL | BSTRUC | CDIR SIN | CDIR COS | CSPEED | SST | BT | TGRAD | TURB | SSAL | BSAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPUE | 1 | 0.181 | **-0.389** | -0.117 | -0.002 | **0.391** | -0.051 | -0.267 | -0.135 | 0.061 | -0.139 | -0.147 | -0.152 | **-0.364** | -0.149 | -0.116 | -0.162 | -0.090 | 0.020 |
| DIEL | 0.181 | 1 | -0.065 | 0.101 | 0.153 | 0.138 | -0.010 | -0.160 | -0.053 | 0.047 | 0.223 | 0.140 | 0.031 | -0.165 | -0.008 | 0.020 | -0.269 | -0.193 | 0.033 |
| DEPTH | **-0.389** | -0.065 | 1 | 0.055 | -0.046 | -0.289 | -0.002 | 0.268 | 0.054 | 0.037 | 0.092 | 0.103 | 0.256 | 0.219 | -0.069 | 0.278 | 0.124 | 0.079 | -0.036 |
| LUNARSIN | -0.117 | 0.101 | 0.055 | 1 | 0.239 | 0.103 | 0.099 | -0.089 | 0.050 | -0.045 | -0.070 | 0.129 | **0.425** | **0.547** | 0.211 | **0.354** | -0.027 | 0.215 | 0.163 |
| LUNARCOS | -0.002 | 0.153 | -0.046 | 0.239 | 1 | 0.302 | 0.149 | -0.062 | -0.035 | 0.119 | 0.246 | -0.087 | 0.200 | 0.331 | 0.326 | 0.032 | -0.007 | 0.186 | **0.355** |
| WDIRSIN | **0.391** | 0.138 | -0.289 | 0.103 | 0.302 | 1 | 0.114 | 0.017 | 0.040 | 0.095 | -0.314 | -0.013 | 0.069 | -0.160 | 0.007 | -0.181 | 0.007 | 0.139 | 0.125 |
| WDIRCOS | -0.051 | -0.010 | -0.002 | 0.099 | 0.149 | 0.114 | 1 | 0.127 | -0.018 | 0.347 | -0.101 | 0.053 | 0.098 | -0.101 | -0.235 | 0.041 | -0.206 | -0.055 | -0.289 |
| WSPEED | -0.267 | -0.160 | 0.268 | -0.089 | -0.062 | 0.017 | 0.127 | 1 | **0.298** | 0.039 | -0.310 | 0.162 | **0.365** | 0.023 | -0.062 | -0.042 | 0.119 | 0.042 | -0.024 |
| SWELL | -0.135 | -0.053 | 0.054 | 0.050 | -0.035 | 0.040 | -0.018 | **0.298** | 1 | 0.072 | -0.054 | 0.168 | 0.107 | 0.134 | 0.224 | -0.068 | 0.202 | 0.055 | 0.160 |
| BSTRUC | 0.061 | 0.047 | 0.037 | -0.045 | 0.119 | 0.095 | 0.347 | 0.039 | 0.072 | 1 | -0.001 | 0.321 | -0.037 | -0.172 | -0.271 | 0.054 | 0.190 | -0.276 | -0.322 |
| CDIRSIN | -0.139 | 0.223 | 0.092 | -0.070 | 0.246 | -0.314 | -0.101 | -0.310 | -0.054 | -0.001 | 1 | 0.386 | -0.073 | 0.145 | 0.180 | 0.078 | -0.074 | -0.270 | 0.018 |
| CDIRCOS | -0.147 | 0.140 | 0.103 | 0.129 | -0.087 | -0.013 | 0.053 | 0.162 | 0.168 | 0.321 | 0.386 | 1 | 0.010 | 0.067 | -0.036 | 0.229 | 0.209 | -0.016 | -0.131 |
| CSPEED | -0.152 | 0.031 | 0.256 | **0.425** | 0.200 | 0.069 | 0.098 | **0.365** | 0.107 | -0.037 | -0.073 | 0.010 | 1 | 0.284 | 0.220 | 0.052 | 0.005 | 0.237 | 0.287 |
| SST | **-0.364** | -0.165 | 0.219 | **0.547** | 0.331 | -0.160 | -0.101 | 0.023 | 0.134 | -0.172 | 0.145 | 0.067 | 0.284 | 1 | **0.623** | 0.235 | 0.211 | **0.377** | **0.458** |
| BT | -0.149 | -0.008 | -0.069 | 0.211 | 0.326 | 0.007 | -0.235 | -0.062 | 0.224 | -0.271 | 0.180 | -0.036 | 0.220 | **0.623** | 1 | **-0.508** | 0.179 | **0.473** | **0.809** |
| TGRAD | -0.116 | 0.020 | 0.278 | **0.354** | 0.032 | -0.181 | 0.041 | -0.042 | -0.068 | 0.054 | 0.078 | 0.229 | 0.052 | 0.235 | **-0.508** | 1 | 0.037 | -0.126 | **-0.415** |
| TURB | -0.162 | -0.269 | 0.124 | -0.027 | -0.007 | 0.007 | -0.206 | 0.119 | 0.202 | 0.190 | -0.074 | 0.209 | 0.005 | 0.211 | 0.179 | 0.037 | 1 | 0.187 | 0.231 |
| SSAL | -0.090 | -0.193 | 0.079 | 0.215 | 0.186 | 0.139 | -0.055 | 0.042 | 0.055 | -0.276 | -0.270 | -0.016 | 0.237 | **0.377** | **0.473** | -0.126 | 0.187 | 1 | **0.605** |
| BSAL | 0.020 | 0.033 | -0.036 | 0.163 | **0.355** | 0.125 | -0.289 | -0.024 | 0.160 | -0.322 | 0.018 | -0.131 | 0.287 | **0.458** | **0.809** | **-0.415** | 0.231 | **0.605** | 1 |

| **Key:** | | | |
|---|---|---|---|
| CPUE | Catch per unit Effort (kg·man$^{-1}$·h$^{-1}$) | CDIRSIN | Sine of radian of current direction |
| DIEL | Night (1) / Day (2) | CDIRCOS | Cosine of radian of current direction |
| DEPTH | Bottom depth (m) | CSPEED | Current speed (1-4 index) |
| LUNARSIN | Sine of radian of day since new moon | SST | Sea surface temperature |
| LUNARCOS | Cosine of radian of day since new moon | BT | Bottom temperature |
| WDIRSIN | Sine of radian of wind direction | TGRAD | Temperature gradient (difference between SST and BT) |
| WDIRCOS | Cosine of radian of wind direction | TURB | Turbidity |
| WSPEED | Wind speed (km·h$^{-1}$) | SSAL | Surface salinity |
| SWELL | Swell height (m) | BSAL | Bottom salinity |
| BSTRUC | Bottom structure (sand/reef-sand/reef) | | |

# APPENDIX B5: MULTIPLE REGRESSION ANALYSIS – STANDARD AND STEPWISE REGRESSION (SUMMER DATA SET)

(see Chapter 3)

Table B5: Results of the standard and stepwise multiple regression analysis considering only the summer data. CPUE (kg·man$^{-1}$·h$^{-1}$) is the dependent variable and DEPTH (maximum depth in meters), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), WSPEED (wind speed in km·h$^{-1}$) and SST (sea surface temperature in °C) as independent variables. CPUE was transformed by the function CPUE = ℓn(CPUE + 0.05); significance ($p<0.05$) is marked in red.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 1.504 | Intercept | 1.77416 | 1.034 | 1.716 | 0.0912 |
| p-value | p<0.20 | DEPTH | -0.01266 | 0.0239 | -0.530 | 0.5978 |
| Multiple R | 0.329 | WDIRSIN | 0.293537 | 0.1607 | 1.826 | 0.0726 |
| $R^2$ | 0.108 | WDIRCOS | -0.21265 | 0.2653 | -0.802 | 0.4258 |
| n | 68 | WSPEED | -0.00321 | 0.0112 | -0.286 | 0.7755 |
| df | 62 | SST | -0.05675 | 0.0501 | -1.132 | 0.262 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F - to enter/remove | p-level |
|---|---|---|---|---|---|
| WDIRSIN | 0.2748 | 0.0755 | 0.0755 | 5.3907 | 0.0235 |
| SST | 0.3049 | 0.0930 | 0.0175 | 1.2525 | 0.2674 |
| WDIRCOS | 0.3194 | 0.102 | 0.0090 | 0.6421 | 0.426 |
| DEPTH | 0.3271 | 0.1070 | 0.0050 | 0.3538 | 0.5541 |
| WSPEED | 0.3289 | 0.1081 | 0.0011 | 0.0820 | 0.7755 |

# **APPENDIX C1**: ANALYSIS OF VARIANCE (COMPLETE DATA SET)

(see Chapter 3)

Table C1: Results of the Kruskal-Wallis analyses of variance of the CPUE (kg·man$^{-1}$·h$^{-1}$) data. The environmental variables examined were: depth, wind speed, sea surface temperature (SST), bottom temperature, temperature gradient (difference between SST and bottom temperature) and turbidity. Significance ($p<0.05$) is marked in red. ($H_c$ - Kruskal-Wallis test statistic corrected for tied ranks)

| Variable (unit) | Categories | $H_c$ | p-value |
|---|---|---|---|
| Depth (m) | <30 | 13.946 | 0.0030 |
| | 30-39 | | |
| | 40-49 | | |
| | ≥50 | | |
| Wind speed (km·h$^{-1}$) | <10 | 4.517 | 0.341 |
| | 10-19 | | |
| | 20-29 | | |
| | 30-39 | | |
| | ≥40 | | |
| SST (°C) | <13 | 5.615 | 0.585 |
| | 13.0-13.9 | | |
| | 14.0-14.9 | | |
| | 15.0-15.9 | | |
| | 16.0-16.9 | | |
| | 17.0-17.9 | | |
| | 18.0-18.9 | | |
| | ≥19 | | |
| Bottom temperature (°C) | <10 | 14.663 | 0.066 |
| | 10.0-10.9 | | |
| | 11.0-11.9 | | |
| | 12.0-12.9 | | |
| | 13.0-13.9 | | |
| | 14.0-14.9 | | |
| | 15.0-15.9 | | |
| | 16.0-16.9 | | |
| | ≥17 | | |
| Temperature gradient (°C) | 0-0.9 | 4.783 | 0.572 |
| | 1.0-1.9 | | |
| | 2.0-2.9 | | |
| | 3.0-3.9 | | |
| | 4.0-4.9 | | |
| | 5.0-5.9 | | |
| | ≥6 | | |
| Turbidity (engineering units) | 0 | 17.069 | 0.0007 |
| | 1-100 | | |
| | 101-200 | | |
| | >200 | | |

# **APPENDIX C2**: ANALYSIS OF VARIANCE (SUMMER DATA SET)

(see Chapter 3)

Table C2: Results of the two one-way analyses of variance of the CPUE ($\mathrm{kg \cdot man^{-1} \cdot h^{-1}}$) summer data in bottom temperature and sea surface temperature (SST) categories. Significance ($p<0.05$) is marked in red.

| Variable (unit) | Categories | Mean CPUE | F | p-value |
|---|---|---|---|---|
| Bottom temperature | <13 | 2.211 | 3.282 | 0.0263 |
| (°C) | 13.0-14.9 | 1.006 | | |
| | 15.0-16.9 | 2.439 | | |
| | ≥17 | 1.252 | | |
| SST (°C) | <13 | 2.011 | 3.742 | 0.0085 |
| | 13.0-14.9 | 2.273 | | |
| | 15.0-16.9 | 3.230 | | |
| | 17.0-18.9 | 1.629 | | |
| | ≥19 | 1.394 | | |

# **APPENDIX D1**: CONTINGENCY TABLES – OBSERVED FREQUENCIES

(see Chapter 3)

Table D1: The 2 x 2 summary tables for the observed frequencies in each category. CPUE ($kg \cdot man^{-1} \cdot h^{-1}$) was considered against wind direction, turbidity and SST. Summer data was also considered separately from the full data set (all data).

| All data: | | | | Summer data: | | | |
|---|---|---|---|---|---|---|---|
| Variable code | Observed frequency | | Row total | Variable code | Observed frequency | | Row total |
| | CPUE L | CPUE H | | | CPUE L | CPUE H | |
| Wind direction 0 | 56 | 36 | 92 | Wind direction 0 | 36 | 19 | 55 |
| Wind direction E | 17 | 32 | 49 | Wind direction E | 7 | 19 | 26 |
| Total: | 73 | 68 | 141 | Total: | 43 | 38 | 81 |
| SST 0 | 46 | 37 | 83 | SST 0 | 34 | 22 | 56 |
| SST 15 | 26 | 25 | 51 | SST 15 | 3 | 10 | 13 |
| Total: | 72 | 62 | 134 | Total: | 37 | 32 | 69 |
| Turbidity 0 | 49 | 62 | 111 | Turbidity 0 | 35 | 36 | 71 |
| Turbidity H | 28 | 15 | 43 | Turbidity H | 10 | 8 | 18 |
| Total: | 77 | 77 | 154 | Total: | 45 | 44 | 89 |

# APPENDIX E1: DATA DISTRIBUTION – NORMALITY TESTING (KROMME BAY, DAILY DATA SERIES)

(see Chapter 4)

Table E1: Assessing normality by calculating Shapiro-Wilk W statistic ($p<0.05$ marked in red) for dependent and independent variables from daily data of the Kromme Bay time series, excluding the linear variable NDOY (number of days). Number of data points is restricted to 2000 for this test, actual N=2374.

| | Shapiro-Wilk W Test | | |
|---|---|---|---|
| Variable | N | W | P |
| CPUE | 2000 | 0.785747 | 0 |
| Day of year sine | 2000 | 0.879948 | 0 |
| Day of year cosine | 2000 | 0.876657 | 0 |
| Lunar sine | 2000 | 0.879546 | 0 |
| Lunar cosine | 2000 | 0.87844 | 0 |
| Wind velocity | 1620 | 0.959546 | 0 |
| Wind direction sine | 1799 | 0.761975 | 0 |
| Wind direction cosine | 1799 | 0.909343 | 0 |
| SST | 1864 | 0.969755 | 2.50E-62 |
| Bottom temperature | 1864 | 0.97267 | 1.57E-41 |
| Temperature gradient | 1864 | 0.82714 | 0 |
| Turbidity | 84 | 0.833928 | 2.31E-13 |

## **APPENDIX F1**: MULTIPLE CORRELATION ANALYSIS – CORRELATION MATRIX (KROMME BAY, DAILY DATA SERIES)

(see Chapter 4)

Table F1: Correlation matrix for the daily Kromme Bay data set. Significant Spearman's correlation coefficients are marked in red ($p<0.05$) and bold red ($p<0.005$).

| | CPUE | NDOY | DOYSIN | DOYCOS | LUNARSIN | LUNARCOS | WSPEED | WDIRSIN | WDIRCOS | SST | SSTC | BT | BTC | TGRAD | TURB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPUE | 1 | **0.157** | **-0.135** | 0.052 | 0.038 | 0.021 | -0.054 | 0.029 | -0.006 | **-0.092** | -0.028 | **-0.066** | 0.011 | 0.005 | -0.072 |
| NDOY | **0.157** | 1 | 0.005 | 0.000 | -0.004 | -0.002 | **0.105** | 0.034 | -0.001 | **-0.231** | -0.024 | **-0.085** | -0.005 | **-0.150** | **0.427** |
| DOYSIN | **-0.135** | 0.005 | 1 | 0.000 | -0.004 | 0.001 | **-0.132** | -0.001 | **0.074** | **0.282** | -0.017 | **-0.112** | -0.017 | **0.349** | **-0.427** |
| DOYCOS | 0.052 | 0.000 | 0.000 | 1 | 0.000 | 0.001 | 0.008 | **0.343** | **-0.235** | **0.411** | **-0.132** | **-0.122** | -0.044 | **0.524** | **-0.427** |
| LUNARSIN | 0.038 | -0.004 | -0.004 | 0.000 | 1 | -0.001 | -0.027 | 0.003 | 0.031 | 0.000 | -0.001 | -0.032 | 0.002 | 0.041 | -0.017 |
| LUNARCOS | 0.021 | -0.002 | 0.001 | 0.001 | -0.001 | 1 | 0.033 | 0.005 | 0.016 | -0.010 | 0.012 | -0.007 | 0.024 | 0.002 | **0.355** |
| WSPEED | -0.054 | **0.105** | **-0.132** | 0.008 | -0.027 | 0.033 | 1 | 0.026 | **-0.103** | 0.034 | **0.135** | **0.158** | 0.038 | **-0.174** | -0.032 |
| WDIRSIN | 0.029 | 0.034 | -0.001 | **0.343** | 0.003 | 0.005 | 0.026 | 1 | **0.328** | **0.220** | **-0.121** | -0.014 | 0.033 | **0.189** | 0.103 |
| WDIRCOS | -0.006 | -0.001 | **0.074** | **-0.235** | 0.031 | 0.016 | **-0.103** | **0.328** | 1 | **-0.103** | -0.013 | **-0.084** | **0.180** | -0.008 | 0.074 |
| SST | **-0.092** | **-0.231** | **0.282** | **0.411** | 0.000 | -0.010 | 0.034 | **0.220** | **-0.103** | 1 | **-0.143** | **0.499** | 0.011 | **0.313** | **-0.334** |
| SSTC | -0.028 | -0.024 | -0.017 | **-0.132** | -0.001 | 0.012 | **0.135** | **-0.121** | -0.013 | **-0.143** | 1 | **-0.082** | **0.267** | **-0.087** | -0.094 |
| BT | **-0.066** | **-0.085** | **-0.112** | **-0.122** | -0.032 | -0.007 | **0.158** | -0.014 | **-0.084** | **0.499** | **-0.082** | 1 | **-0.191** | **-0.580** | 0.094 |
| BTC | 0.011 | -0.005 | -0.017 | -0.044 | 0.002 | 0.024 | 0.038 | 0.033 | **0.180** | 0.011 | **0.267** | **-0.191** | 1 | **0.180** | 0.025 |
| TGRAD | 0.005 | **-0.150** | **0.349** | **0.524** | 0.041 | 0.002 | **-0.174** | **0.189** | -0.008 | **0.313** | **-0.087** | **-0.580** | **0.180** | 1 | -0.291 |
| TURB | -0.072 | **0.427** | **-0.427** | **-0.427** | -0.017 | **0.355** | -0.032 | 0.103 | 0.074 | **-0.334** | -0.094 | 0.094 | 0.025 | -0.291 | 1 |

**Key:**

| | | | |
|---|---|---|---|
| CPUE | Catch per unit Effort (kg·boat$^{-1}$·day$^{-1}$) | WDIRCOS | Cosine of radian of wind direction |
| NDOY | Number of days (linear function) | SST | Sea surface temperature |
| DOYSIN | Sine of radian of day of year | SSTC | Daily sea surface temperature change |
| DOYCOS | Cosine of radian of day of year | BT | Bottom temperature |
| LUNARSIN | Sine of radian of day since new moon | BTC | Daily bottom temperature change |
| LUNARCOS | Cosine of radian of day since new moon | TGRAD | Temperature gradient (difference between SST and BT) |
| WSPEED | Wind speed (km·h$^{-1}$) | TURB | Turbidity |
| WDIRSIN | Sine of radian of wind direction | | |

# **APPENDIX F2**: MULTIPLE REGRESSION ANALYSIS – STANDARD AND STEPWISE REGRESSION (KROMME BAY, DAILY TURBIDITY DATA SERIES)

(see Chapter 4)

Table F2: Results of the standard and stepwise multiple regression analysis considering the daily Kromme Bay turbidity data series. CPUE ($kg \cdot man^{-1} \cdot h^{-1}$) is the dependent variable and DOYSIN (autumn-spring component of a year), DOYCOS (summer-winter component), LUNARSIN (first-last-quarter component of the lunar cycle), LUNARCOS (new-full moon component), WSPEED (wind speed in $km \cdot h^{-1}$), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), SST (sea surface temperature in °C), BT (bottom temperature in °C) and TURBIDITY (engineering units) as independent variables. CPUE was transformed by the function CPUE = ℓn(CPUE + 1); significance ($p<0.05$) is marked in red.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 2.1665 | Intercept | 1.5411 | 6.4835 | 0.238 | 0.8128 |
| p-value | p<0.030 | LUNARSIN | 0.9887 | 0.3656 | 2.704 | 0.0085 |
| Multiple R | 0.478 | DOYSIN | -4.6824 | 2.5869 | -1.810 | 0.0744 |
| $R^2$ | 0.229 | SST | 0.5033 | 0.4096 | 1.229 | 0.2231 |
| n | 84 | LUNARCOS | 0.4190 | 0.3848 | 1.089 | 0.2798 |
| df | 73 | TURBIDITY | -0.0043 | 0.0051 | -0.848 | 0.3993 |
| | | WDIRSIN | -0.0660 | 0.6921 | -0.095 | 0.9243 |
| | | WSPEED | 0.0234 | 0.0357 | 0.655 | 0.5148 |
| | | WDIRCOS | 0.3659 | 0.8094 | 0.452 | 0.6526 |
| | | DOYCOS | 1.0571 | 2.3796 | 0.444 | 0.6582 |
| | | BT | 0.0204 | 0.2201 | 0.093 | 0.9264 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| LUNARSIN | 0.2564 | 0.0657 | 0.0657 | 5.7686 | 0.0189 |
| DOYSIN | 0.4126 | 0.1703 | 0.1045 | 10.2050 | 0.0021 |
| SST | 0.4483 | 0.2010 | 0.0307 | 3.0782 | 0.0835 |
| LUNARCOS | 0.4551 | 0.2071 | 0.0061 | 0.6100 | 0.4373 |
| TURBIDITY | 0.4685 | 0.2195 | 0.0123 | 1.2340 | 0.2703 |
| WDIRSIN | 0.4723 | 0.2231 | 0.0036 | 0.3563 | 0.5524 |
| WSPEED | 0.4749 | 0.2255 | 0.0025 | 0.2427 | 0.6238 |
| WDIRCOS | 0.4761 | 0.2267 | 0.0012 | 0.1119 | 0.7390 |
| DOYCOS | 0.4783 | 0.2288 | 0.0021 | 0.1991 | 0.6568 |
| BT | 0.4784 | 0.2289 | 0.0001 | 0.0086 | 0.9264 |

## APPENDIX F3: MULTIPLE REGRESSION ANALYSIS – PROBABILITY PLOT OF RESIDUALS (KROMME BAY, DAILY TURBIDITY DATA SERIES)

(see Chapter 4)

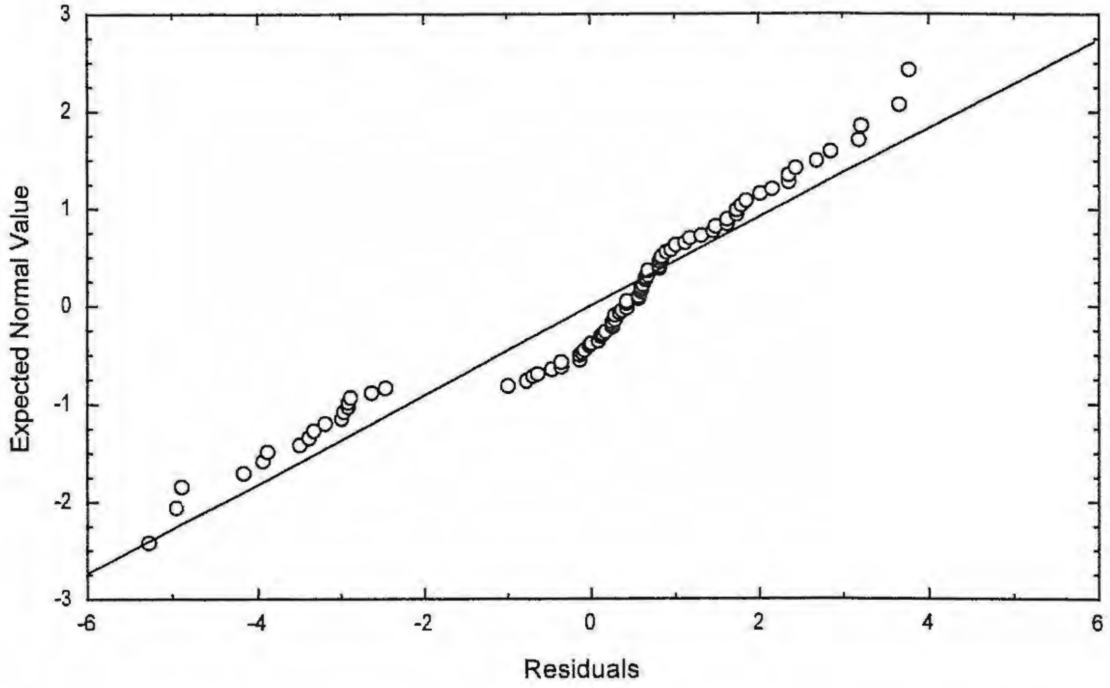

Figure F.3a: Normal probability plot of residuals for the multiple regression analysis of the daily turbidity data series in Kromme Bay with CPUE as the dependent variable and DOYSIN, DOYCOS, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SST, BT and TURBIDITY as regressors.

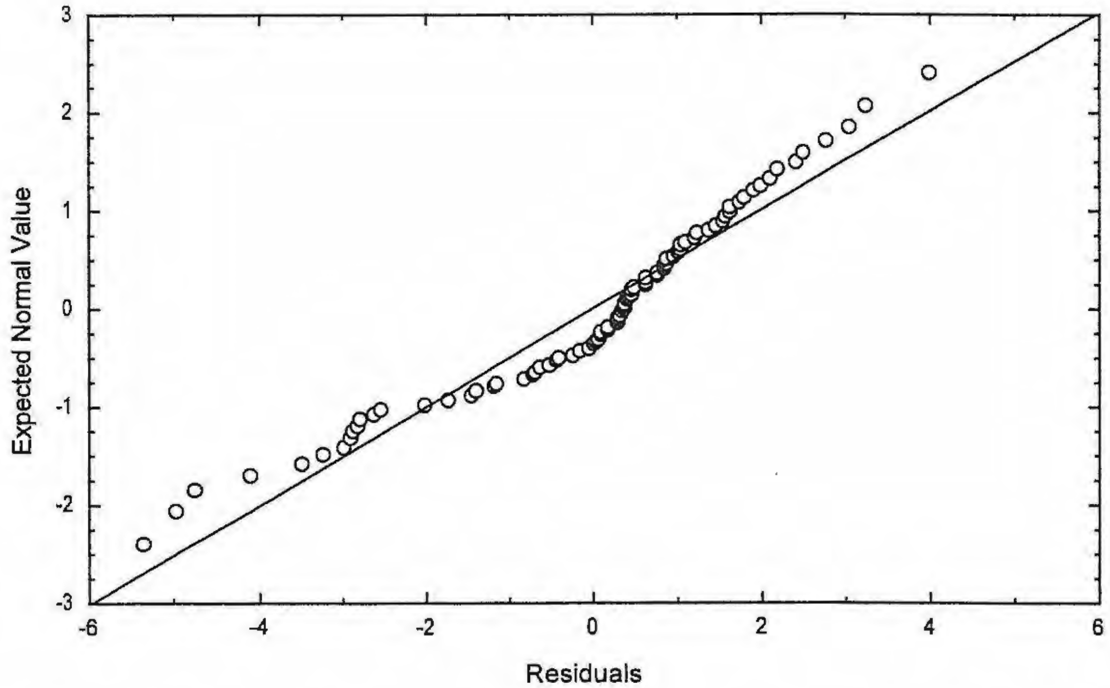

Figure F.3b: Normal probability plot of residuals for the multiple regression analysis of the daily turbidity data series in Kromme Bay with CPUE as the dependent variable and DOYSIN, DOYCOS, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SST, BT and TURBIDITY as regressors. Wind components (WDIRSIN, WDIRCOS and WSPEED) lagged 1 day forward and TURBIDITY lagged 2 days backward.

# **APPENDIX F4**: MULTIPLE REGRESSION ANALYSIS – STANDARD AND STEPWISE REGRESSION (KROMME BAY, COMPLETE DAILY DATA SERIES)

(see Chapter 4)

Table F4: Results of the standard and stepwise multiple regression analysis considering the full daily Kromme Bay data series. CPUE ($kg \cdot man^{-1} \cdot h^{-1}$) is the dependent variable and NDOY (number of days), DOYSIN (autumn-spring component of a year), DOYCOS (summer-winter component), LUNARSIN (first-last-quarter component of the lunar cycle), LUNARCOS (new-full moon component), WSPEED (wind speed in $km \cdot h^{-1}$), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), SST (sea surface temperature in °C) and BT (bottom temperature in °C) as independent variables. CPUE was transformed by the function CPUE = $\ell n$(CPUE + 1); significance ($p<0.05$) is marked in red.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 9.0198 | Intercept | 3.7199 | 0.6323 | 5.883 | 5.0E-09 |
| p-value | $p<0.00001$ | NDOY | 0.0006 | 0.0001 | 5.401 | 7.7E-08 |
| Multiple R | 0.240 | DOYSIN | -0.4582 | 0.0918 | -4.992 | 6.7E-07 |
| $R^2$ | 0.058 | LUNARCOS | 0.2101 | 0.0806 | 2.607 | 0.0092 |
| n | 1481 | DOYCOS | 0.1712 | 0.1096 | 1.562 | 0.1185 |
| df | 1470 | LUNARSIN | 0.1311 | 0.0808 | 1.621 | 0.1052 |
| | | WSPEED | -0.0065 | 0.0065 | -0.999 | 0.3181 |
| | | BT | -0.0305 | 0.0322 | -0.948 | 0.3433 |
| | | WDIRCOS | 0.0842 | 0.1323 | 0.637 | 0.5244 |
| | | WDIRSIN | -0.0391 | 0.1045 | -0.374 | 0.7086 |
| | | SST | 0.0116 | 0.0423 | 0.275 | 0.7835 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| NDOY | 0.1761 | 0.0310 | 0.0310 | 47.3282 | 8.9E-12 |
| DOYSIN | 0.2155 | 0.0464 | 0.0154 | 23.9262 | 1.1E-06 |
| LUNARCOS | 0.2254 | 0.0508 | 0.0044 | 6.7732 | 0.0093 |
| DOYCOS | 0.2318 | 0.0537 | 0.0029 | 4.5568 | 0.0330 |
| LUNARSIN | 0.2360 | 0.0557 | 0.0020 | 3.0825 | 0.0793 |
| WSPEED | 0.2382 | 0.0567 | 0.0010 | 1.6183 | 0.2035 |
| BT | 0.2398 | 0.0575 | 0.0008 | 1.2061 | 0.2723 |
| WDIRCOS | 0.2402 | 0.0577 | 0.0002 | 0.2878 | 0.5917 |
| WDIRSIN | 0.2403 | 0.0578 | 8E-05 | 0.1249 | 0.7238 |
| SST | 0.2404 | 0.0578 | 4.84E-05 | 0.0755 | 0.7835 |

# **APPENDIX F5**: MULTIPLE REGRESSION ANALYSIS – STANDARD AND STEPWISE REGRESSION (KROMME BAY, COMPLETE DAILY DATA SERIES – INCLUDING LAG RELATIONSHIPS)

(see Chapter 4)

Table F5: Results of the standard and stepwise multiple regression analysis using the full daily Kromme Bay data series. CPUE ($kg \cdot boat^{-1} \cdot day^{-1}$) is the dependent variable and NDOY (number of days), DOYSIN, DOYCOS, LUNARSIN, LUNARCOS, WSPEED, WDIRSIN, WDIRCOS, SST and BT as independent variables. The wind component variables (WDIRSIN, WDIRCOS and WSPEED) were lagged 1 day forward. CPUE was transformed by the function CPUE = $\ell n$(CPUE + 1); significance ($p<0.05$) is marked in red.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 9.9850 | Intercept | 3.9496 | 0.6344 | 6.226 | 6.2E-10 |
| p-value | p<0.00001 | NDOY | 0.0006 | 0.0001 | 5.392 | 8.1E-08 |
| Multiple R | 0.252 | DOYSIN | -0.4659 | 0.0916 | -5.088 | 4.1E-07 |
| $R^2$ | 0.064 | WSPEED | -0.0193 | 0.0065 | -2.969 | 0.0030 |
| n | 1482 | LUNARCOS | 0.2274 | 0.0802 | 2.834 | 0.0047 |
| df | 1471 | DOYCOS | 0.2032 | 0.1077 | 1.887 | 0.0594 |
| | | LUNARSIN | 0.1194 | 0.0805 | 1.484 | 0.1381 |
| | | WDIRCOS | 0.1453 | 0.1315 | 1.104 | 0.2696 |
| | | BT | -0.0078 | 0.0335 | -0.232 | 0.8165 |
| | | WDIRSIN | -0.0241 | 0.1051 | -0.230 | 0.8183 |
| | | SST | -0.0031 | 0.0425 | -0.073 | 0.9421 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| NDOY | 0.1736 | 0.0301 | 0.0301 | 45.9639 | 1.7E-11 |
| DOYSIN | 0.2142 | 0.0459 | 0.0158 | 24.4324 | 8.6E-07 |
| WSPEED | 0.2297 | 0.0528 | 0.0069 | 10.7496 | 0.0011 |
| LUNARCOS | 0.2406 | 0.0579 | 0.0051 | 8.0105 | 0.0047 |
| DOYCOS | 0.2465 | 0.0608 | 0.0029 | 4.5387 | 0.0333 |
| LUNARSIN | 0.2496 | 0.0623 | 0.0015 | 2.3837 | 0.1228 |
| WDIRCOS | 0.2519 | 0.0634 | 0.0012 | 1.8240 | 0.1770 |
| BT | 0.2520 | 0.0635 | 0.0001 | 0.1253 | 0.7234 |
| WDIRSIN | 0.2521 | 0.0636 | 3.7E-05 | 0.0586 | 0.8088 |
| SST | 0.2521 | 0.0636 | 3.4E-06 | 0.0053 | 0.9421 |

## **APPENDIX F6:** MULTIPLE REGRESSION ANALYSIS – PROBABILITY PLOT OF RESIDUALS (KROMME BAY, COMPLETE DAILY DATA SERIES)

(see Chapter 4)

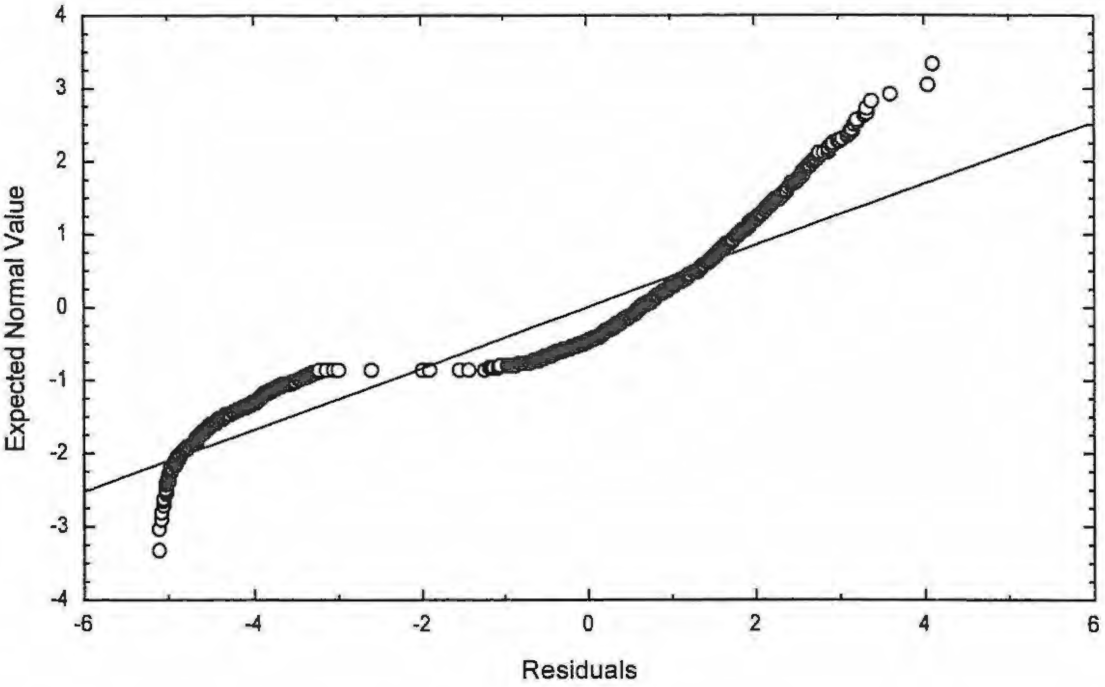

Figure F.6a: Normal probability plot of residuals for the multiple regression analysis of the full daily data series in Kromme Bay with CPUE as the dependent variable and NDOY, DOYSIN, DOYCOS, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SST and BT as regressors.

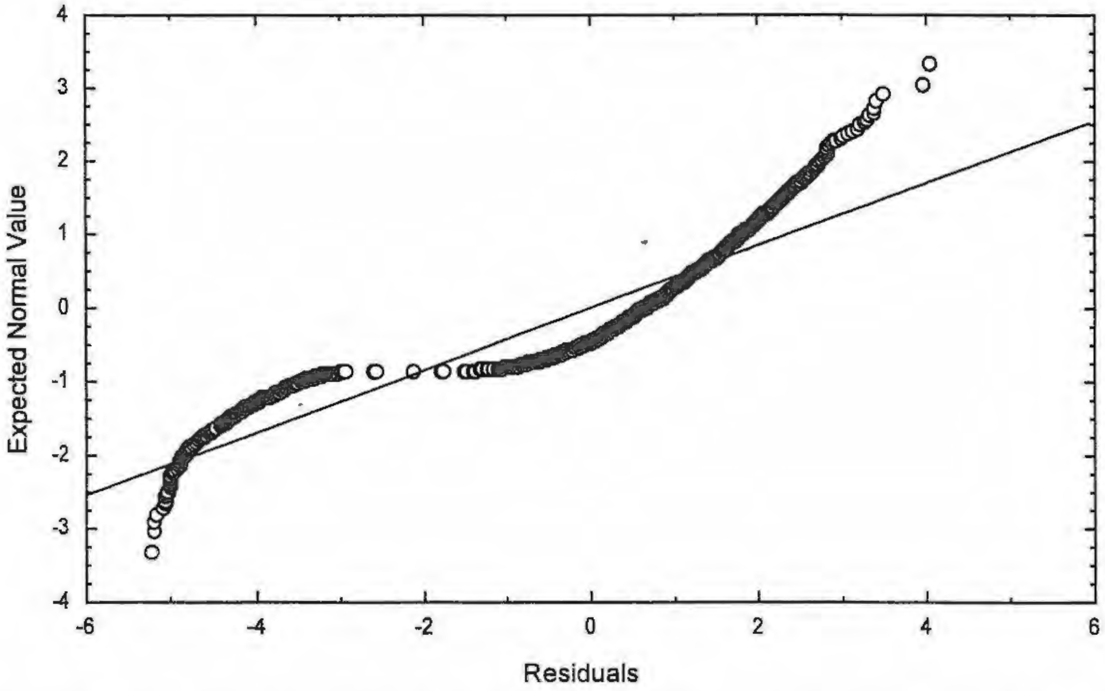

Figure F.6b: Normal probability plot of residuals for the multiple regression analysis of the full daily data series in Kromme Bay with CPUE as the dependent variable and NDOY, DOYSIN, DOYCOS, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SST and BT as regressors. Wind components (WDIRSIN, WDIRCOS and WSPEED) lagged 1 day forward.

## **APPENDIX F7**: MULTIPLE CORRELATION ANALYSIS – CORRELATION MATRIX (KROMME BAY, WEEKLY DATA SERIES)

(see Chapter 4)

Table F7: Correlation matrix for the weekly Kromme Bay data set. Significant Spearman's correlation coefficients are marked in red ($p<0.05$) and bold red ($p<0.005$).

| | CPUE | NWOY | WOYSIN | WOYCOS | LUNARSIN | LUNARCOS | WSPEED | WDIRSIN | WDIRCOS | SST | SSTA | BT | BTA | TGRAD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPUE | 1 | **0.256** | **-0.198** | 0.015 | 0.077 | 0.010 | 0.002 | -0.050 | 0.039 | -0.138 | **-0.241** | -0.083 | **-0.192** | -0.068 |
| NWOY | **0.256** | 1 | -0.002 | 0.006 | -0.010 | 0.020 | **0.210** | 0.068 | 0.145 | **-0.265** | **-0.316** | -0.100 | -0.125 | -0.154 |
| WOYSIN | **-0.198** | -0.002 | 1 | 0.000 | -0.008 | -0.010 | **-0.261** | -0.031 | -0.048 | **0.249** | 0.017 | -0.116 | -0.024 | **0.343** |
| WOYCOS | 0.015 | 0.006 | 0.000 | 1 | -0.001 | 0.000 | -0.059 | **0.191** | **0.222** | **0.454** | 0.064 | -0.133 | 0.006 | **0.649** |
| LUNARSIN | 0.077 | -0.010 | -0.008 | -0.001 | 1 | 0.026 | -0.073 | -0.029 | 0.113 | -0.001 | -0.011 | -0.022 | -0.030 | 0.053 |
| LUNARCOS | 0.010 | 0.020 | -0.010 | 0.000 | 0.026 | 1 | 0.037 | -0.028 | 0.153 | 0.034 | 0.064 | 0.054 | 0.053 | -0.030 |
| WSPEED | 0.002 | **0.210** | **-0.261** | -0.059 | -0.073 | 0.037 | 1 | **0.217** | -0.032 | -0.026 | 0.154 | **0.302** | **0.302** | **-0.342** |
| WDIRSIN | -0.050 | 0.068 | -0.031 | **0.191** | -0.029 | -0.028 | **0.217** | 1 | **-0.315** | 0.025 | -0.060 | -0.088 | -0.034 | 0.057 |
| WDIRCOS | 0.039 | 0.145 | -0.048 | **0.222** | 0.113 | 0.153 | -0.032 | **-0.315** | 1 | 0.045 | -0.045 | -0.081 | -0.044 | 0.151 |
| SST | -0.138 | **-0.265** | **0.249** | **0.454** | -0.001 | 0.034 | -0.026 | 0.025 | 0.045 | 1 | **0.779** | **0.537** | **0.584** | **0.342** |
| SSTA | **-0.241** | **-0.316** | 0.017 | 0.064 | -0.011 | 0.064 | 0.154 | -0.060 | -0.045 | **0.779** | 1 | **0.688** | **0.794** | -0.005 |
| BT | -0.083 | -0.100 | -0.116 | -0.133 | -0.022 | 0.054 | **0.302** | -0.088 | -0.081 | **0.537** | **0.688** | 1 | **0.887** | **-0.535** |
| BTA | **-0.192** | -0.125 | -0.024 | 0.006 | -0.030 | 0.053 | **0.302** | -0.034 | -0.044 | **0.584** | **0.794** | **0.887** | 1 | **-0.370** |
| TGRAD | -0.068 | -0.154 | **0.343** | **0.649** | 0.053 | -0.030 | **-0.342** | 0.057 | 0.151 | **0.342** | -0.005 | **-0.535** | **-0.370** | 1 |

| **Key:** | | | |
|---|---|---|---|
| CPUE | Catch per unit Effort (kg·boat$^{-1}$·day$^{-1}$) | WDIRSIN | Sine of radian of wind direction |
| NWOY | Number of weeks (linear function) | WDIRCOS | Cosine of radian of wind direction |
| WOYSIN | Sine of radian of week of year | SST | Sea surface temperature |
| WOYCOS | Cosine of radian of week of year | SSTA | Sea surface temperature anomaly |
| LUNARSIN | Weekly average of sine of radian of day since new moon | BT | Bottom temperature |
| LUNARCOS | Weekly average of cosine of radian of day since new moon | BTA | Bottom temperature anomaly |
| WSPEED | Wind speed (km·h$^{-1}$) | TGRAD | Temperature gradient (difference between SST and BT) |

# APPENDIX F8: MULTIPLE REGRESSION ANALYSIS – STANDARD AND STEPWISE REGRESSION (KROMME BAY, WEEKLY DATA SERIES)

(see Chapter 4)

Table F8: Results of the standard and stepwise multiple regression analysis considering the weekly Kromme Bay data series. CPUE ($kg \cdot man^{-1} \cdot h^{-1}$) is the dependent variable and NWOY (number of weeks), WOYSIN (autumn-spring component of a year), WOYCOS (summer-winter component), LUNARSIN (first-last-quarter component of the lunar cycle), LUNARCOS (new-full moon component), WSPEED (wind speed in $km \cdot h^{-1}$), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), SST (sea surface temperature in °C), SSTA (sea surface temperature anomaly), BT (bottom temperature in °C) and BTA (bottom temperature anomaly) as independent variables. CPUE was transformed by the function CPUE = $\ell n$(CPUE + 1); significance ($p<0.05$) is marked in red.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 3.3940 | Intercept | -3.3752 | 2.7904 | -1.210 | 0.2279 |
| p-value | p<0.0002 | WOYSIN | -0.4459 | 0.2734 | -1.631 | 0.1045 |
| Multiple R | 0.412 | NWOY | 0.0033 | 0.0016 | 2.105 | 0.0365 |
| $R^2$ | 0.170 | SSTA | -0.1895 | 0.2752 | -0.689 | 0.4919 |
| n | 212 | SST | 0.1405 | 0.2554 | 0.550 | 0.5827 |
| df | 199 | WDIRSIN | -0.2600 | 0.1550 | -1.678 | 0.0950 |
| | | WSPEED | 0.0426 | 0.0267 | 1.595 | 0.1124 |
| | | WOYCOS | 0.1601 | 0.4107 | 0.390 | 0.6971 |
| | | LUNARSIN | 0.1337 | 0.1466 | 0.912 | 0.3628 |
| | | LUNARCOS | 0.1375 | 0.1486 | 0.925 | 0.3559 |
| | | BTA | -0.3012 | 0.2093 | -1.439 | 0.1516 |
| | | BT | 0.2422 | 0.1939 | 1.249 | 0.2131 |
| | | WDIRCOS | 0.0070 | 0.3021 | 0.023 | 0.9816 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| WOYSIN | 0.2347 | 0.0551 | 0.0551 | 12.2414 | 0.0006 |
| NWOY | 0.2943 | 0.0866 | 0.0315 | 7.2188 | 0.0078 |
| SSTA | 0.3225 | 0.1040 | 0.0174 | 4.0383 | 0.0458 |
| SST | 0.3525 | 0.1243 | 0.0203 | 4.7905 | 0.0298 |
| WDIRSIN | 0.3708 | 0.1375 | 0.0132 | 3.1531 | 0.0773 |
| WSPEED | 0.3844 | 0.1477 | 0.0103 | 2.4668 | 0.1179 |
| WOYCOS | 0.3908 | 0.1527 | 0.0050 | 1.1984 | 0.2750 |
| LUNARSIN | 0.3962 | 0.1570 | 0.0043 | 1.0268 | 0.3121 |
| LUNARCOS | 0.4013 | 0.1611 | 0.0041 | 0.9821 | 0.3229 |
| BTA | 0.4042 | 0.1634 | 0.0023 | 0.5557 | 0.4569 |
| BT | 0.4122 | 0.1699 | 0.0065 | 1.5682 | 0.2119 |
| WDIRCOS | 0.4122 | 0.1699 | 2.2E-06 | 0.0005 | 0.9816 |

## APPENDIX F9: MULTIPLE REGRESSION ANALYSIS – PROBABILITY PLOT OF RESIDUALS (KROMME BAY, WEEKLY DATA SERIES)

(see Chapter 4)

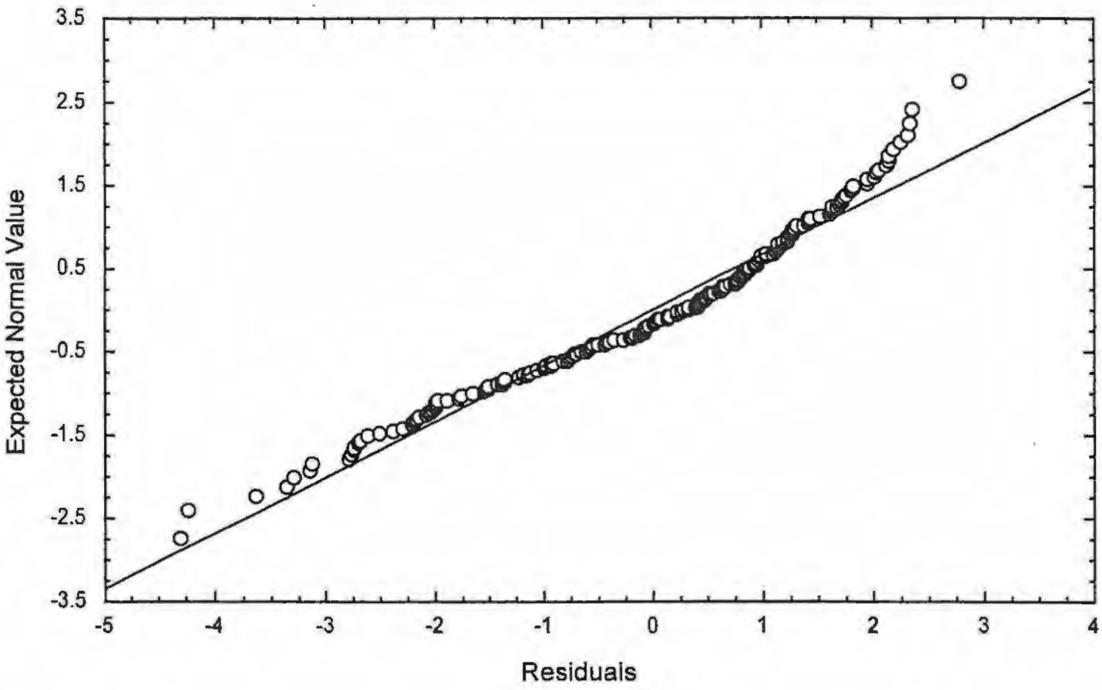

Figure F.9a: Normal probability plot of residuals for the multiple regression analysis of the weekly data series in Kromme Bay with CPUE as the dependent variable and NWOY, WOYSIN, WOYCOS, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SST, SSTA, BT and BTA as regressors.

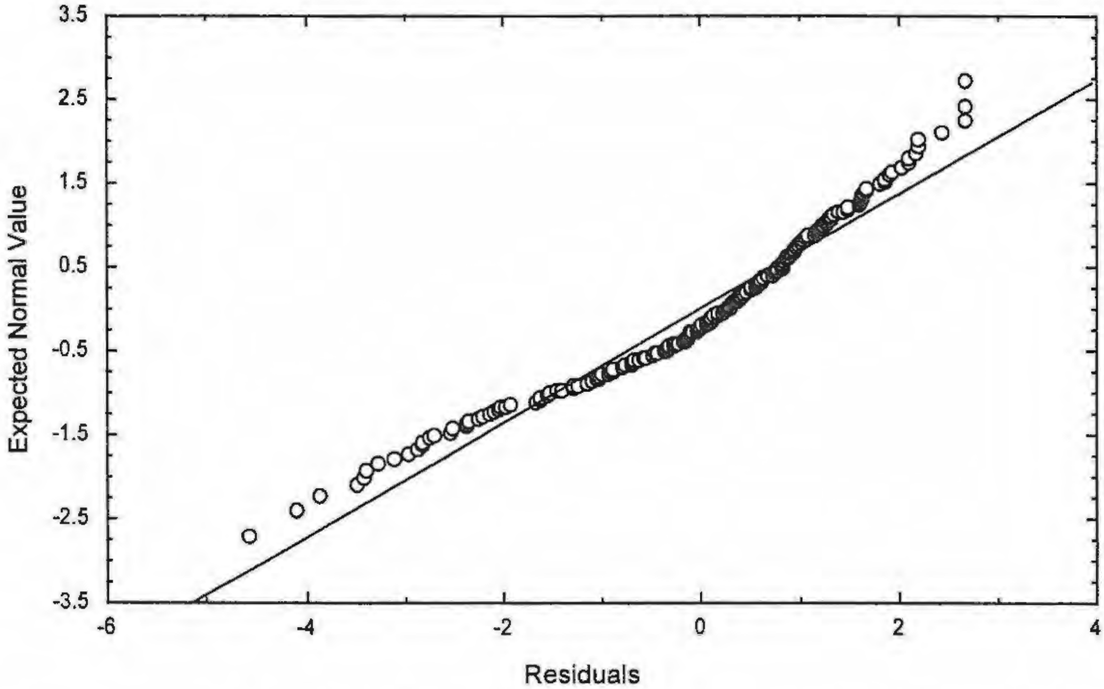

Figure F.9b: Normal probability plot of residuals for the multiple regression analysis of the weekly data series in Kromme Bay with CPUE as the dependent variable and NWOY, WOYSIN, WOYCOS, LUNARSIN, LUNARCOS, WDIRSIN, WDIRCOS, WSPEED, SSTA and BTA as regressors. SSTA lagged 2 weeks forward and BTA lagged 3 weeks forward.

# **APPENDIX F10**: MULTIPLE CORRELATION ANALYSIS – CORRELATION MATRIX (KROMME BAY, MONTHLY DATA SERIES)

(see Chapter 4)

Table F10: Correlation matrix for the monthly Kromme Bay data set. Significant Spearman's correlation coefficients are marked in red ($p<0.05$) and bold red ($p<0.005$).

| | CPUE | NMOY | MOYSIN | MOYCOS | WSPEED | WDIR SIN | WDIR COS | SST | SSTA | BT | BTA | TGRAD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPUE | 1 | **0.389** | -0.151 | -0.065 | 0.076 | 0.150 | -0.158 | -0.245 | **-0.391** | -0.203 | **-0.356** | -0.093 |
| NMOY | **0.389** | 1 | -0.031 | -0.003 | **0.413** | 0.093 | 0.017 | -0.299 | **-0.369** | -0.112 | -0.104 | -0.132 |
| MOYSIN | -0.151 | -0.031 | 1 | -0.005 | **-0.448** | -0.152 | 0.339 | 0.176 | -0.019 | -0.121 | -0.025 | 0.273 |
| MOYCOS | -0.065 | -0.003 | -0.005 | 1 | -0.231 | **0.707** | **-0.474** | **0.562** | 0.024 | -0.189 | -0.008 | **0.827** |
| WSPEED | 0.076 | **0.413** | **-0.448** | -0.231 | 1 | -0.204 | -0.240 | -0.130 | 0.220 | **0.487** | **0.447** | **-0.573** |
| WDIRSIN | 0.150 | 0.093 | -0.152 | **0.707** | -0.204 | 1 | -0.253 | **0.393** | -0.005 | -0.174 | -0.099 | **0.562** |
| WDIRCOS | -0.158 | 0.017 | 0.339 | **-0.474** | -0.240 | -0.253 | 1 | **-0.513** | -0.312 | -0.295 | -0.290 | -0.165 |
| SST | -0.245 | -0.299 | 0.176 | **0.562** | -0.130 | **0.393** | **-0.513** | 1 | **0.701** | **0.490** | **0.560** | **0.434** |
| SSTA | **-0.391** | **-0.369** | -0.019 | 0.024 | 0.220 | -0.005 | -0.312 | **0.701** | 1 | **0.747** | **0.858** | -0.089 |
| BT | -0.203 | -0.112 | -0.121 | -0.189 | **0.487** | -0.174 | -0.295 | **0.490** | **0.747** | 1 | **0.876** | **-0.507** |
| BTA | **-0.356** | -0.104 | -0.025 | -0.008 | **0.447** | -0.099 | -0.290 | **0.560** | **0.858** | **0.876** | 1 | -0.288 |
| TGRAD | -0.093 | -0.132 | 0.273 | **0.827** | **-0.573** | **0.562** | -0.165 | **0.434** | -0.089 | **-0.507** | -0.288 | 1 |

| **Key:** | | | |
|---|---|---|---|
| CPUE | Catch per unit Effort ($kg \cdot man^{-1} \cdot h^{-1}$) | WDIRCOS | Cosine of radian of wind direction |
| NMOY | Number of months (linear function) | SST | Sea surface temperature |
| MOYSIN | Sine of radian of month of year | SSTA | Sea surface temperature anomaly |
| MOYCOS | Cosine of radian of month of year | BT | Bottom temperature |
| WSPEED | Wind speed ($km \cdot h^{-1}$) | BTA | Bottom temperature anomaly |
| WDIRSIN | Sine of radian of wind direction | TGRAD | Temperature gradient (difference between SST and BT) |

## **APPENDIX F11**: MULTIPLE REGRESSION ANALYSIS – STANDARD AND STEPWISE REGRESSION (KROMME BAY, MONTHLY DATA SERIES)

(see Chapter 4)

Table F11: Results of the standard and stepwise multiple regression analysis considering the monthly Kromme Bay data. CPUE ($kg\cdot man^{-1}\cdot h^{-1}$) is the dependent variable and NMOY (number of months), MOYSIN (autumn-spring component of a year), MOYCOS (summer-winter component), WSPEED (wind speed in $km\cdot h^{-1}$), WDIRSIN (E-W component of wind direction), WDIRCOS (N-S component), SST (sea surface temperature in °C), SSTA (sea surface temperature anomaly in °C), BT (bottom temperature in °C) and BTA (bottom temperature anomaly) as independent variables. CPUE was transformed by the function CPUE = ℓn(CPUE + 1); significance ($p<0.05$) is marked in red.

| Model: | | Variable | B coefficient | Std. Error of B | t-value | p-level |
|---|---|---|---|---|---|---|
| F-value | 2.1086 | Intercept | -4.8391 | 6.2035 | -0.780 | 0.4402 |
| p-value | p<0.048 | SSTA | -0.0942 | 0.6145 | -0.153 | 0.8790 |
| Multiple R | 0.597 | WDIRCOS | -0.7643 | 0.6100 | -1.253 | 0.2179 |
| $R^2$ | 0.357 | WSPEED | 0.1142 | 0.0947 | 1.205 | 0.2355 |
| n | 49 | BTA | -0.5531 | 0.5996 | -0.922 | 0.3622 |
| df | 38 | BT | 0.3627 | 0.5470 | 0.663 | 0.5113 |
| | | NMOY | 0.0170 | 0.0126 | 1.348 | 0.1855 |
| | | WDIRSIN | 0.5792 | 0.5223 | 1.109 | 0.2744 |
| | | MOYCOS | -0.1958 | 1.0710 | -0.183 | 0.8559 |
| | | MOYSIN | 0.0686 | 0.4566 | 0.150 | 0.8813 |
| | | SST | 0.0244 | 0.5436 | 0.045 | 0.9644 |

Stepwise regression:

| Variables | Multiple R | Multiple $R^2$ | $R^2$ change | F – to enter/remove | p-level |
|---|---|---|---|---|---|
| SSTA | 0.2963 | 0.0878 | 0.0878 | 4.5248 | 0.0400 |
| WDIRCOS | 0.4105 | 0.1685 | 0.0807 | 4.4664 | 0.0412 |
| WSPEED | 0.4667 | 0.2178 | 0.0492 | 2.8318 | 0.1006 |
| BTA | 0.4994 | 0.2494 | 0.0317 | 1.8557 | 0.1811 |
| BT | 0.5541 | 0.3070 | 0.0576 | 3.5742 | 0.0663 |
| NMOY | 0.5730 | 0.3283 | 0.0213 | 1.3306 | 0.2559 |
| WDIRSIN | 0.5954 | 0.3545 | 0.0262 | 1.6649 | 0.2047 |
| MOYCOS | 0.5963 | 0.3556 | 0.0011 | 0.0680 | 0.7957 |
| MOYSIN | 0.5974 | 0.3568 | 0.0012 | 0.0740 | 0.7871 |
| SST | 0.5974 | 0.3569 | 0.0000 | 0.0020 | 0.9644 |

# **APPENDIX F12**: MULTIPLE REGRESSION ANALYSIS – PROBABILITY PLOT OF RESIDUALS (KROMME BAY, MONTHLY DATA SERIES)

(see Chapter 4)

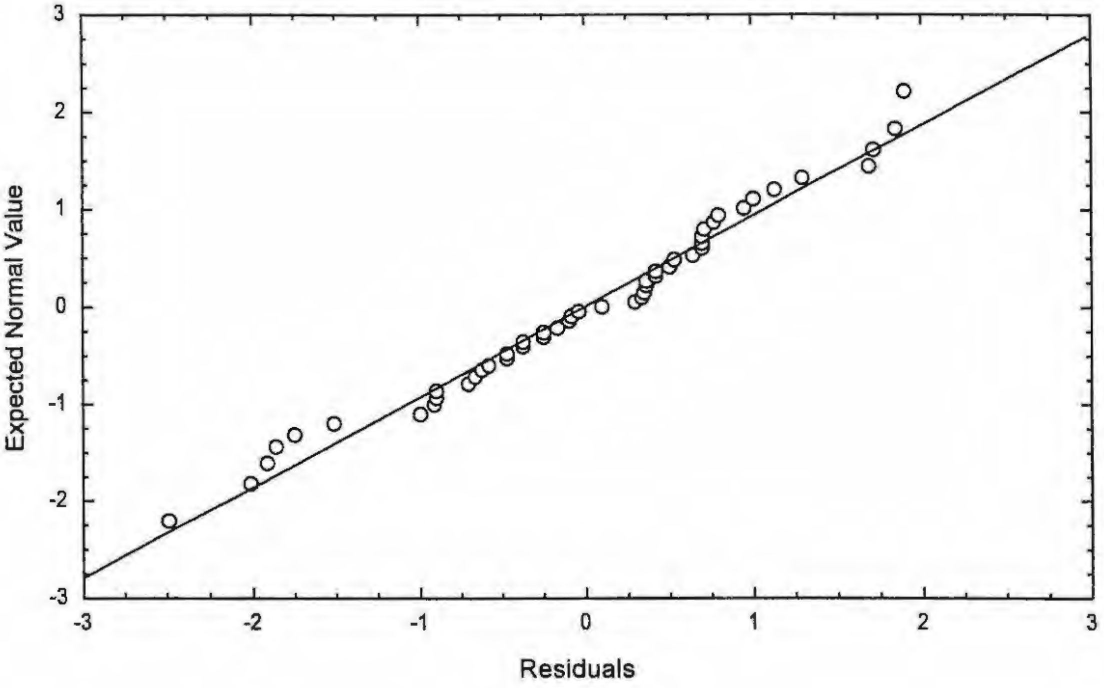

Figure F.12a: Normal probability plot of residuals for the multiple regression analysis of the monthly data series in Kromme Bay with CPUE as the dependent variable and NMOY, MOYSIN, MOYCOS, WDIRSIN, WDIRCOS, WSPEED, SST, SSTA, BT and BTA as regressors.

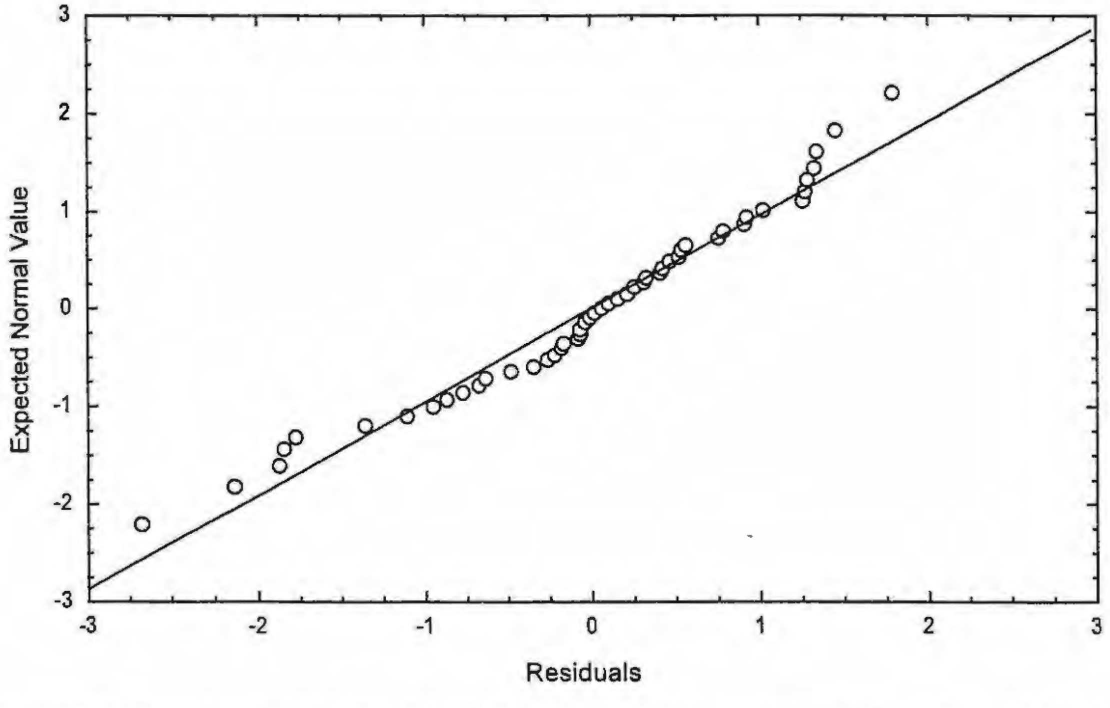

Figure F.12b: Normal probability plot of residuals for the multiple regression analysis of the monthly data series in Kromme Bay with CPUE as the dependent variable and NMOY, MOYSIN, MOYCOS, WDIRSIN, WDIRCOS, WSPEED, SSTA and BTA as regressors. BTA lagged 1 month forward.

## APPENDIX G1: CROSS-CORRELATION ANALYSIS (KROMME BAY, DAILY DATA SERIES)

(see Chapter 4)

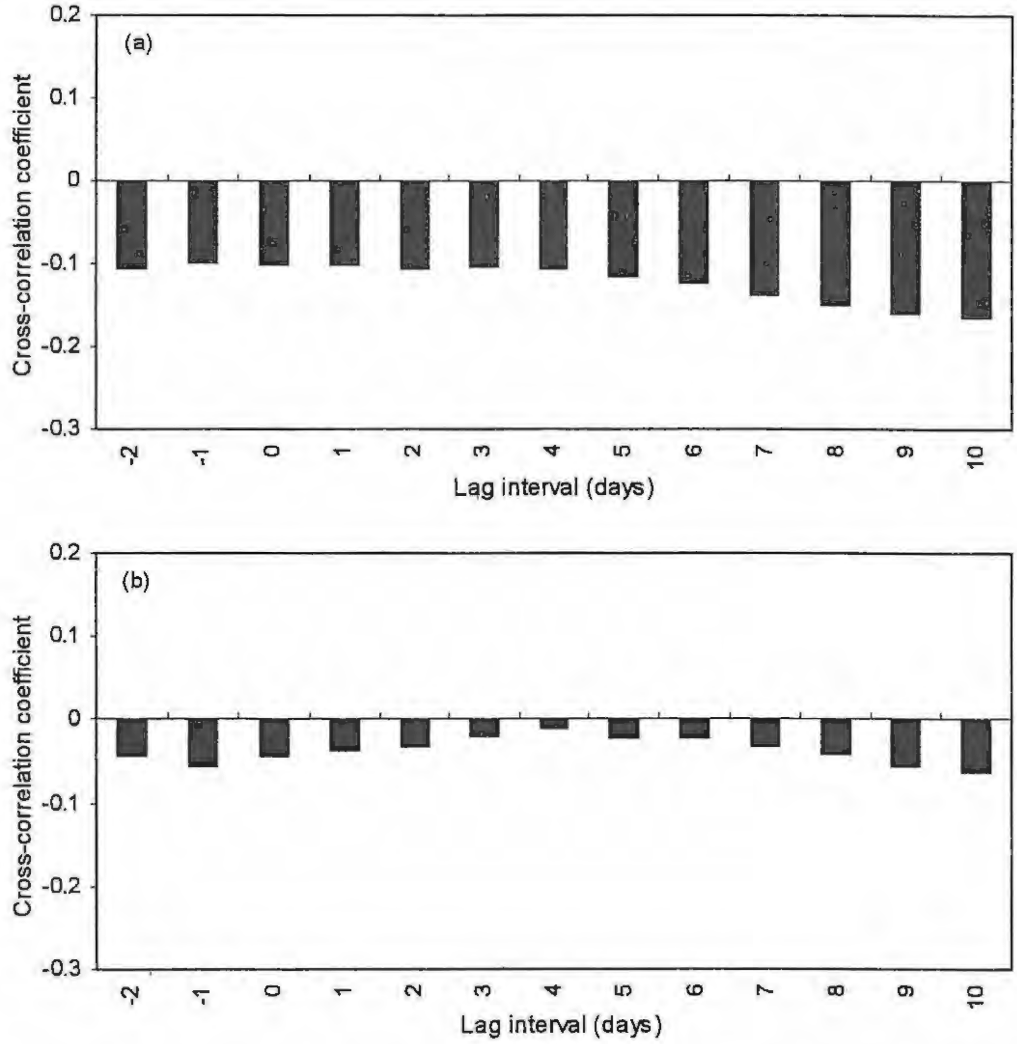

Figure G.1: Cross-correlation coefficients between daily CPUE and (a) sea surface temperature; and (b) bottom temperature. CPUE was transformed by the function ℓn(CPUE + 1). Significant correlations ($p<0.01$) are highlighted in blue.

## APPENDIX G2: CROSS-CORRELATION ANALYSIS (KROMME BAY, WEEKLY DATA SERIES)

(see Chapter 4)

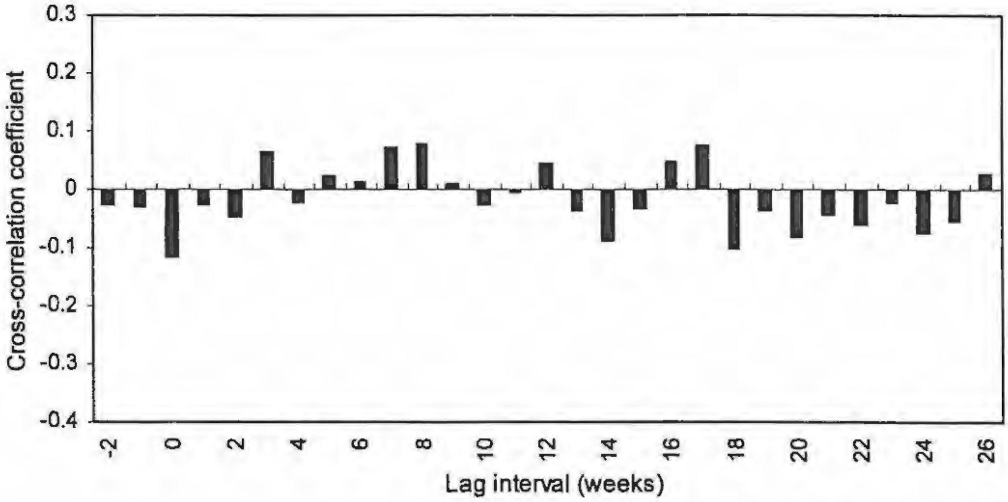

Figure G.2: Cross-correlation coefficients between mean weekly CPUE and WDIRSIN (east-west component of wind direction). CPUE was transformed by the function $\ell n(\text{CPUE} + 1)$. Significant correlations ($p<0.01$) are highlighted in blue.

## **APPENDIX G3**: CROSS-CORRELATION ANALYSIS (KROMME BAY, MONTHLY DATA SERIES)

(see Chapter 4)

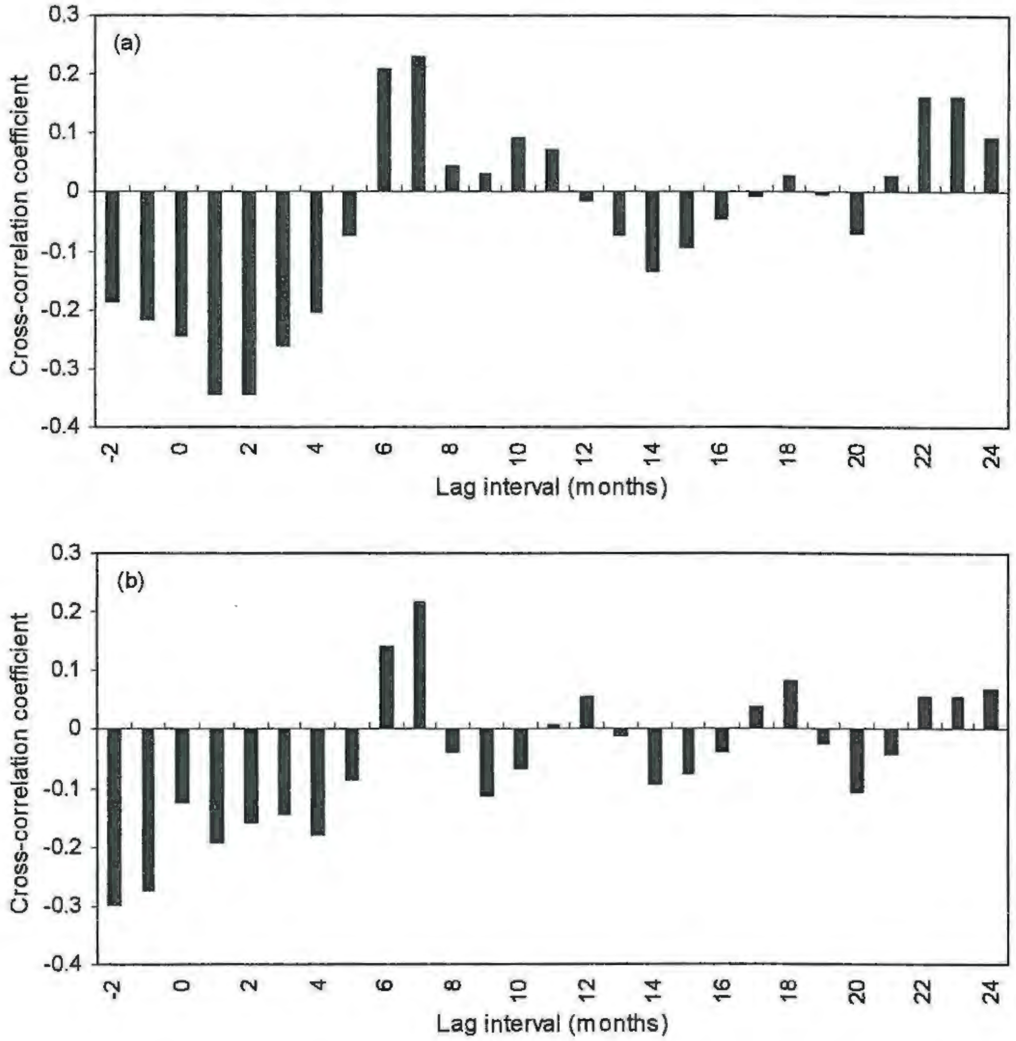

Figure G.3: Cross-correlation coefficients between monthly CPUE and (a) mean monthly sea surface temperature; and (b) mean monthly bottom temperature. CPUE was transformed by the function $\ell n(\text{CPUE} + 1)$. Significant correlations ($p<0.01$) are highlighted in blue.