PRELIMINARY ASSESSMENT OF THE DISTRIBUTION AND POTENTIAL IMPACT OF THE INTRODUCED STARFISH ASTERIAS AMURENSIS IN TASMANIAN WATERS

Status report to Fisheries Research and Development Corporation

Stephanie Davenport and Richard McLoughlin

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Gerry Hawkes and Dr Rob Day of the Department of Zoology at the University of Melbourne carried out the literature review of *A. amurensis* and related species (Chapter 4 of this report).

From CSIRO's Division of Fisheries, Dr Vince Lyne modelled the dispersal of A. *amurensis* eggs and larvae (Chapter 5), Thor Carter photographed specimens of A. *amurensis* collected by Bruce Barker and one of the authors and Denis Abbott, Librarian at the CSIRO Marine Laboratories, ran a literature search for information on the biology of A. *amurensis*.

Robert Rowell of Landfile Consultancy mapped the current distribution of *A. amurensis* based on sightings compiled by the Tasmanian Museum.

1 EXECUTIVE SUMMARY

- Asterias anurensis is a five armed starfish, normally found around Japan through the Bering Sea and as far as Alaska, A. anurensis was probably introduced into Tasmanian waters sometime in the early 1980's. In about a decade, it has become well established in large numbers in the Derwent Estuary and D'Entrecasteaux Channel and is also present in the vicinity of Triabunna on the east coast of Tasmania.
- A. amurensis is reported to be a voracious feeder, and as such, poses a significant threat to some existing wild fisheries and aquaculture enterprises. Shellfish, such as mussels, scallops and clams are the preferred diet. The starfish are opportunistic feeders and have also been observed feeding on crabs, other starfish, dead fish and are at times cannibalistic.
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- The prognosis for its potential distribution is not good. Although in its first decade of introduction, *A. amurensis* has remained largely confined to the Derwent Estuary, there is a high probability of much more rapid dispersal once the spawn are carried out of Storm Bay. The population now established on the east coast of Tasmania could provide a source of rapid dispersal into Bass Strait and beyond. The species has a *potential* distribution of much of the east coast of Australia, possibly as far as Sydney (this is based solely on a temperature tolerance of approximately 22°C). Its western distribution is not known an invasion to the west would be against prevailing winds and currents.
- The pattern of dispersal of A. amurensis in Tasmania, over its first decade of residence (largely confined to the Derwent Estuary), is consistent with the model of an initial contamination in the Derwent River. The model predicts that once the spawn are carried out of Storm Bay, the rate of dispersal will increase dramatically.
- So far, physical removal appears to have been the only successful means of reducing the numbers of this pest, and therefore limited control of numbers is the best that can be hoped for. Research on the potential for more effective solutions, such as a biological control, should begin immediately.
- An obvious means to reduce the pest problem is to turn the pest into a desirable commodity. There is room for further exploration of the chemistry of Asterias amurensis with a view to commercial exploitation.
- Much of the information required to model the potential dispersion and effects of *Asterius amurensis* is sketchy or unavailable. There is a need to fill in the information gaps with directed research in an Australian context.
- Asterias anurensis, like most other introduced animals, is here to stay. There is no record of either commercial harvesting or pest control having caused the complete removal of any animal introduced into Australia.

2 INTRODUCTION AND SUMMARY REPORT

CSIRO Division of Fisheries was commissioned by the Fisheries Research and Development Corporation in early May 1993 to undertake a desk study to assess the distribution and potential impact of the introduced Pacific starfish *Asterias amurensis* in Tasmanian waters. This report is the result of this short (4 weeks) study.

1 OBJECTIVES OF THIS REPORT

- 1 The objectives of this study were to answer the following broad questions:
- 2 What is the current distribution of Asterias amurensis in Tasmanian waters? What is known about this species in terms of its biology, ecology and scope for impact on Australian ecosystems?
- 3 What is the potential distribution of A. amurensis in southern Australian waters ?

2 PRINCIPAL FINDINGS

Why is the presence of Asterias amurensis in Tasmanian waters considered to be a problem?

A. amurensis is a five armed starfish, normally found around Japan through the Bering Sea and as far as Alaska. From the pattern of distribution of A. amurensis in Tasmania, it is thought that it was introduced through the ballast water from foreign-going ships. The starfish has been recorded from the Derwent River to grow as large as 40 cm in diameter (E. Turner, Tasmanian Museum).



A. amurensis is reported to be a voracious feeder. Shellfish, such as mussels, scallops and clams are the preferred diet. The starfish are opportunistic feeders and have also been observed feeding on crabs, other starfish, dead fish and are at times cannibalistic, presumably when other food is short.

In Japan, while these starfish are constantly present, outbreaks of *A. amurensis* occur in large numbers about every 10 years. Each outbreak lasts 2 to 3 years. These starfish are of particular concern to aquafarmers because of the damage they cause to fished and cultured shellfish beds.

When did Asterias amurensis appear in Tasmania?

The starfish Asterias amurensis was present in the waters around Hobart in 1986. The first record of its presence in the Derwent River comes from a starfish that was collected from Rosny Point and lodged with the Tasmanian Museum in October 1986. At the time the specimen was incorrectly identified. In 1992 its identity was confirmed to be Asterias amurensis.

In 1992 the potential problem of *Asterias amurensis* and its successful colonisation of Derwent River waters was first properly understood. Elizabeth Turner of the Tasmanian Museum became aware of large numbers of these starfish around Hobart and initiated moves to draw attention to the seriousness of the invasion.

Current distribution of Asterias amurensis in Tasmania

The known distribution in Tasmania of *A. amurensis* is shown on Map 1. This map is based on confirmed and unconfirmed sightings of the starfish by members of the public, scientists and aquafarmers. In the Derwent River, it is found some kilometres north and south of Hobart, into the D'Entrecasteaux Channel and south to the mouth of the Huon River. Its distribution in the Channel may not be continuous but concentrated in areas around aquafarms where food is plentiful.

Its presence has been confirmed in scallop bags off Triabunna and there have been unconfirmed reports of the starfish from the northern reaches of Great Oyster Bay on the east coast of Tasmania.

Spawning and larvae of Asterias amurensis

Spawning is thought to occur just after the minimum winter temperatures occur. There is no information available on the triggers for spawning or the duration of spawning. Fecundity of *A. amurensis* is not well known. The sexes of the starfish are separate. One female was measured to contain 19 million eggs. Fecundity increases with size. The depth of spawning is not known although the species is known to occur in water to at least 60 m depth (Nojima *et al.* 1986).

The eggs of A. *amurensis* are about 100 μ m in size and are planktotrophic. They are thought to be buoyant and to metamorphose after 3 or 4 days into the first larval stage. The larvae possess cilia and appear to be capable of limited motility. The time between spawning and settlement of the young starfish is thought from laboratory observations to be about 40 days (at 14–15°C) and is temperature dependent.

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What is the potential distribution and rate of spread of *Asterias amurensis* in Tasmanian waters and beyond?

The ability of *A. amurensis* to disperse in Tasmanian waters was predicted using a model to forecast the likely movements of buoyant eggs and larvae that are distributed in the top half of the water column (a 'worst case' scenario). In the model, the eggs are largely wind driven and the larvae are moved by a composite of surface drift components and tidal currents.

Three simulations were run using detailed wind data from 1988. The simulations were terminated after 50 days – the assumed time between spawning and settlement for A. *amurensis*.

In the first simulation, five 'seeds', or spawning events, (Fig. 3) were released, one in the Derwent River near Hobart, two in the D'Entrecasteaux Channnel, one near the eastern shore of Storm Bay and inshore of Maria Island. The simulation shows restricted dispersal for the Derwent River and D'Entrecasteaux seeds, and broad dispersal for the Storm Bay and Maria Island seeds.

In the second simulation, seeds were broadcast from more open areas in the northern portion of the Tasmanian east coast (Fig. 4). One seed was released from Great Oyster Bay, another from St Marys and another from the south eastern corner of Bass Strait. This simulation shows complete entrapment of the spawn released in Great Oyster Bay with extensive contamination of the eastern shore and some contamination of the western shore. The seed released from St Marys showed some coastal contamination within about 20 km of the release site while most of the spawn has moved well offshore. The seed released in Bass Strait shows a similar easterly and northward drift with contamination of Clarke and Cape Barren Islands.

The third simulation (Fig. 5) examines the effects of mean drift currents, imposing a mean northward drift for the spawn on the continental shelf from the second simulation. This simulation resulted in a dramatic drift effect for the seed off St Marys. During the 50 day simulation the drift extended beyond the model's northern domain (40.2°S) in Bass Strait.

These simulations examined the 1988 wind drift conditions, a warm *La Nina* year. Experimental simulations where the wind record was rotated suggest the possibility of seed from the Derwent River moving well out into Storm Bay, and the seed from Storm Bay drifting past Cape Pillar.

These simulations are for one season's spawn and for a main spawning period of 50 days only. Simulations of successive spawning events over a period of years and the possibility of resuspension and drift of 'settled' larvae in the bottom boundary layer would undoubtedly indicate an even more worrying picture.

Damage and control

The detrimental effects of large starfish populations on shellfish industries have been

documented in Japan (Nojima *et al.* 1986) and along the west coast of the United States (Galtsoff and Loosanoff 1939).

Mechanical and chemical methods of control have been tried with varying degrees of success. Galtsoff and Loosanoff (1939) recorded some success in the control of starfish in Narragansett Bay by mechanical collection using starfish mops and dredges.

Methods of chemical control have had negative or inconclusive results and have attached dangers of poisoning other animals and plants.

There can be no doubt that the presence of the starfish *Asterias amurensis* in south eastern Tasmania is irreversible. Physical collection and removal of the starfish seems to be the best way of reducing its numbers and controlling infestations in shellfish farms.

The possibility of composting starfish has been addressed by some writers. Any attempt to utilise these starfish as feedstuffs or fertilisers should be tempered by the knowledge that these starfish contain toxic saponins (Yasumoto *et al.* 1964). The isolated saponin from *Asterias amurensis* has been shown to be toxic to fish, earthworms and some vertebrates. Saponin is also claimed to cause retardation in the growth of plants.

3 CONCLUSIONS

- 1 Asterias amurensis, like most other introduced animals, is here to stay. There is no record of either commercial harvesting or pest control having caused the complete removal of any animal introduced into Australia (Anon. 1993).
- 2 Asterias amurensis was probably introduced into Tasmanian waters sometime in the early 1980's. In about a decade, it has become well established in large numbers in the Derwent Estuary and D'Entrecasteaux Channel and is also present in the vicinity of Triabunna on the east coast of Tasmania.
- 3 The prognosis for its potential distribution is not good. Although in its first decade of introduction, *A. amurensis* has remained largely confined to the Derwent Estuary, there is a high probability of much more rapid dispersal once the spawn are carried out of Storm Bay. The population now established on the east coast of Tasmania could provide a source of rapid dispersal into Bass Strait and beyond.
- 4 Ocean dispersion is not the only vector for the dispersal of *A. amurensis*. Each time a vessel takes on seawater from an environment contaminated with starfish eggs and larvae, it has the potential to disperse the starfish to wherever that seawater is unloaded.
- 5 It would be prudent to consider the risk of infestation anywhere that habitat tolerances would allow *Asterias amurensis* to survive and reproduce. We need also to consider the

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habitat tolerances of *Asterias anurensis versicolor*, which lives in warmer conditions than *A. anurensis*. It is not clear whether *A. anurensis versicolor* is a genetically different organism or just an example of very successful adaptation of *A. anurensis* to different conditions.

- 6 Perhaps this starfish should be likened to the 'rabbit' it is highly fecund; it eats voraciously; its preferred diet is valuable to humans, and it has the capacity to inhabit large areas causing damage to endemic and commercially valuable species.
- 7 Asterius amurensis is a considerable threat to the success of shellfish farms and fisheries. It also is a threat to endemic bottom dwelling species, through direct predation and competition for food.

4 RECOMMENDATIONS

- 1 So far, physical removal appears to have been the only successful means of reducing the numbers of this pest, and therefore limited control of numbers is the best that can be hoped for. Research on the potential for more effective solutions, such as a biological control, should begin immediately.
- 2 Much of the information required to model the potential dispersion of *Asterias anurensis* is sketchy or unavailable. There is an obvious need to fill in the gaps with reliable data on the reproductive and larval biology and ecology of the starfish time of spawning, duration of spawning, fecundity, larval duration, where eggs and larvae are dispersed in the water column, habitat requirements of larvae and adults especially temperature, salinity and substrate tolerances.
- 3 An obvious means to reduce the pest problem is to turn the pest into a desirable commodity. There is room for further exploration of the chemistry of *Asterias anurensis* with a view to commercial exploitation.

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3 CURRENT DISTRIBUTION OF ASTERIAS AMURENSIS IN TASMANIA

1 KNOWN DISTRIBUTION IN 1993

The known distribution in Tasmania of *A. amurensis* is shown on Map 1. This map is based on confirmed and unconfirmed sightings of the starfish by members of the public, scientists and aquafarmers. In the Derwent River, it is found some kilometres north and south of Hobart, into the D'Entrecasteaux Channel and south to the mouth of the Huon River. Its distribution in the Channel may not be continuous but concentrated in areas around aquafarms where food is plentiful.

Its presence has been confirmed in scallop bags off Triabunna and there have been unconfirmed reports of the starfish from the northern reaches of Great Oyster Bay on the east coast of Tasmania.

Young A. amurensis are generally found near shore and larger adults occur in deeper water. In May 1993, CSIRO diver surveys found A. amurensis in average densities of 19 per metre² in shallow water (0–1.5 m) off the Domain in Hobart (water temps. $11.8^{\circ}-14.3^{\circ}$ C). At the same time, off the eastern shore of the CSIRO Marine Laboratories in Hobart (water temps. $14.0-14.4^{\circ}$ C), there were on average, 2 A. amurensis per metre² in a similar depth range.

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Distribution of <u>Asterias</u> <u>amurensis</u> in Tasmania: sightings reported to the Tasmanian Museum to 26 May 1993



4 REVIEW OF THE BIOLOGY AND ECOLOGY OF ASTERIAS AMURENSIS

Gerry Hawkes and Rob Day, Zoology Department, The University of Melbourne

1 INTRODUCTION

Objectives

Established populations of the northern Pacific starfish Asterias amurensis have been discovered in the cool temperate waters of southern Tasmania, Australia (Turner 1992). To predict its population dynamics, its dispersal, its effect on the natural marine ecosystem, and possible damage to lucrative fisheries within southern waters, it is essential to know the biology of the animal, for example its life history strategies and rate of reproduction, the optimun temperature regimes for adult and larval growth, and its feeding ecology.

The objectives of this review are therefore to assess the relevant biology and life history strategies of populations of *A. amurensis* that have been studied elsewhere, and attempt to pinpoint the critical factors that may help biologists and modellers predict the possible outcome of the introduction of this exotic species.

Background

The first reported sighting was in 1986, near Rosny Point, on the eastern shore of the Derwent River (Anon. 1993). Since the initial sighting of *Asterias amurensis*, populations of the starfish have been reported off the east coast of Tasmania at Triabunna, and south to the D'Entrecasteaux Channel. Large aggregations of the starfish have been found. Within the Derwent Estuary the starfish has been sighted several kilometres upstream and downstream of the Port of Hobart (Anon. 1993). Within these areas of $42.5-43.5^{\circ}$ S, open water temperatures vary from $10-21^{\circ}$ C on the east coast, and $9-18^{\circ}$ C on the southeast coast (R. McLoughlin, pers. comm.). In the Derwent River, *A. amurensis* is known to spawn between between July and October when water temperatures are $8-10^{\circ}$ C. Juveniles have been reported to appear one to two months after spawning and reach four cm in arm length in one year. While depth distributions are not stated, sightings have been reported in shallow water by dockside observers, scuba divers, aquaculturalists, and fishers on small trawlers (Turner 1992; Anon. 1993).

Introductions are thought to have occurred through the transport of larvae in the ballast water of ocean going vessels, similar to the importation of a toxic dinoflagellate alga and the Japanese seaweed Undaria pinnatifida. Increasingly frequent visits by international cargo and fishing fleets to Tasmanian waters have enhanced the chances of exotic species such as *A. amurensis* becoming established. A survey of Japanese ships arriving in various ports of Australia regularly found live plankton at the bottom of ballast tanks (Parr 1985). This issue is not considered any further in this report, but should be addressed internationally as a matter of urgency.

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The natural range of Asterias amurensis is between 33° and 49°N. Populations have been recorded around the east and west coasts of Japan, the south-east coast of Russia, and within the Bering Sea, Alaska. Table 1 lists known populations of A. amurensis. Although we did not find reports of A. amurensis living along the east coast of Korea, the starfish probably occurs there also.

Sources of information

For this report, information on *Asterias amurensis* was sought mainly from Japanese and Russian journals available in Australia. Time restrictions and language barriers prevented an exhaustive literature review of Japanese and Russian articles not available in Australia. Further information on *A. amurensis* may be found in Korean articles, but these are largely unavailable in Australia.

To supplement the scarce information on the species itself, and cover gaps in the available information, we have examined work published on related species to indicate what to expect from Asterias amurensis. It should be noted that although there is a considerable body of literature and modelling on movements and infestations of the Crown-of-Thorns starfish, Acanthaster planci, this was not considered because temperature regimes and biological strategies of Acanthaster planci and Asterias amurensis appear to differ markedly. Literature that deals exclusively with the biochemistry or cell or organ physiology of the animal has also been omitted from this review, as it appears irrelevant.

Table 1: KNOWN DISTRIBUTION OF ASTERIAS AMURENSIS IN THE NORTHERN HEMISPHERE

PLACE	Area	Source
USSR		
Sea of Japan	Vladivostok	Drozdov & Kasyanov 1985
Peter the Great Bay *	Vladivostok	Novikova 1978
Vostok Bay *	Vladivostok	Korenbaum & Vorob'ev 1988
Vostok Bay *	Vladivostok	Propp et al. 1983
Ussari Bay *	Vladivostok	Khotimchenko & Deridovich 1988
Vityaz Bay *	Vladivostok	Volkov et al. 1982
Sea of Japan	Vladivostok	Kasyanov et al. 1985
Sea of Japan	Vladivostok	Kasyanov 1988
Ussuri Bay *	Vladivostok	Khotimchenko & Deridovich 1988
Popov Island *	Vladivostok	Podol'skii 1975
HOKKAIDO		
(1) Akkesi Bay	Hokkaido	Nojima et al. 1986
(2) Mutsu Bay	north Aomori	Kim 1968
HONSHU		
(3) Hakodate	Hiyama	Kaneniwa et al. 1987
(4) Sagami Bay	east Kanagawa	Suzuki <i>et al.</i> 1982
(5) Sendai Bay	east Miyagi	Hatanaka & Kosaka 1959
(6) Yokohama	east Kanagawa	Thomson & Murray 1889
(7) Tokyo Bay	east Kanagawa	Ino et al. 1955
(8) Tokyo Bay	east Kanagawa	Sagara & Ino 1954
KYUSHU		
9) Ariake Sea **	Nagasaki	Nojima et al. 1986
ALASKA		
Bering Sea	Alaska	Fukuyama & Oliver 1985
Bering Sea	Alaska	Oliver et al. 1985

* = Sea of Japan

** = Sub species — Asterias amurensis versicolor

() = refers to Fig. 1

Figure 1. Known distributions of Asterias amurensis in Japan





- () refers to authors listed in Table 1
 ** = sub-species Asterias amurensis versicolor

2 ASTERIAS AMURENSIS

Description of the speciesPHYLUM:EchinodermataCLASS:AsteroideaORDER:ForcipulataFAMILY:AsteriidaeGENUS:AsteriasSPECIES:Asterias amurensis

Asterias amurensis belongs to the order Forcipulata, as described by D'Yakonov (1968). Order Forcipulata is the most highly advanced group within the class Asteriidae. Asterias amurensis typifies the genus Asterias. The species is extremely variable, expressing gradual variations between geographical populations (D'Yakanov 1968; Onguru and Okutani 1991). There appear to be six very similar sub-species, that represent distinct morphological variants of A. amurensis. One of these, the sub-species Asterias amurensis versicolor occurs in the warmer waters of south-western Japan. This sub-species is smaller than A. amurensis (70–80 mm ray length).

A. amurensis has a broad flattened body, mostly yellow to red in colour, with (usually) five long rays (arms) extending from a small central disk. A characteristic feature of this species is the very finely pointed tip on each ray (D'Yakanov 1968). The species is dioecious (separate males and females), although asexual reproduction can occur through regeneration from an arm with part of the disk attached following damage to the animal. In sexually mature animals the internal body mainly consists of two organs with branches down each ray, the pyloric caeca and the gonads. After the gonads mature (see 'Gametogenesis'), eggs and sperm are shed into the water. The externally fertilised progeny pass through a free swimming pelagic stage, first as bipinnaria larvae and then as brachiolaria larvae (see 'Larval stages'), before settling on the substrate and metamorphosing to become tiny juveniles.

Juveniles are initially very immobile, remaining in sheltered areas usually on the under-side of rocks. Although this is not mentioned in other papers, D'Yakonov (1968) states that young individuals differ considerably in appearance from adults. Their similarity to other juvenile starfish (in the Sea of Japan) makes it difficult to identify the species at this stage. Juveniles grow rapidly in the first year, and although growth slows thereafter, the starfish may reach a maximum ray length of 192 mm (see 'Population statistics').

Asterias amurensis is a boreal species, inhabiting cold to temperate, sublittoral and shallow waters of the north and north-eastern areas of the Pacific Ocean (Kim 1968; Onguro and Okutani 1991) (see 'Temperature requirements'). The starfish inhabits predominantly mud, sand, and pebble substrates. It either scavenges or preys on other small epifauna (Fukuyama and Oliver 1985; Oliver *et al.* 1985), and can dig shallow pits in search of prey (Cavey and Wood 1988) (see 'Feeding strategies').

Dense aggregations of Asterias amurensis can appear suddenly (Hatanaka and Kosaka 1959; Nojima *et al.* 1986). This apparently cyclic phenomenon has caused extensive damage to natural and cultured populations of scallops and mussels in Japan. Because of this, and the fact that it is apparently without value to humans, this starfish is regarded as a pest in Japan.

Spawning season

Although the timing of spawning of Asterias amurensis populations varies between localities in Japan (Fig. 1), the onset of spawning almost invariably occurs at low temperatures (about 10°C), as temperatures start to rise. In Tokyo Bay (35°N) and Sendai Bay (38°N), spawning peaks between late February and the beginning of March when the sea temperature is 6.2-13.6°C (Takashi et al. 1955). In Mutsu Bay (41°N) spawning occurs in March and April at 5-10°C (Kim 1968). In Hokkaido (43°N), the spawning season is in July at a temperature of 6-14°C. However, Asterias amurensis in Peter the Great Bay (off Vladivostok, 43°N) have a different reproductive strategy (Novikova 1978; Nojima et al. 1986; Korenbaum and Vorob'ev 1988). These starfish spawn twice, initially in June (autumn) when the sea surface is 17°C and then in September (spring) when the surface temperature is 23°C. There is some evidence to suggest that populations within Japanese waters also spawn a second time: Kim (1968) found unspent eggs in animals after the normal spawning season of March-May. It was considered that these eggs were either reabsorbed or released at a later stage. Hatanaka and Kosaka (1959) noted that ova were released only when they reach full size and that there were several spawning periods.

Several studies have shown that the sex ratio is 1:1 in Asterias amurensis and does not vary between populations (Hatanaka and Kosaka 1959; Nemoto and Ishida 1983)

Gametogenesis

The development of mature gonads in *Asterias amurensis* has been divided into several stages. Kim (1968) identified seven stages of gametogenesis in starfish from Mutsu Bay, including the initial production of gonads by young adults. Novikova (1977) divided gonad development of the starfish in Peter the Great Bay into five stages. Both studies recognised four periods of annual gonad development in *A. amurensis*: reorganization of gonads during post-spawning; growth of spermatocytes and spermatogonia; maturation or active spermatogenesis and oogenesis forming spermatozoa and ova respectively; the gonads attain maximal size and discharge gametes.

The reorganization of gonads in the starfish from Peter the Great Bay is bypassed in the period between from the first spawning in June and the second in September (Khotimchenko and Deridovich 1988). Gonads immediately start the second stage (growth) of gametogenesis and quickly develop mature gonads after the initial spawning. The reorganisation stage only occurs during January and February when sea temperatures are low.

Gonad indices vary seasonally and according to the size of A. amurensis (Takashi et al.

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1955; Hatanaka and Kosaka 1959). The seasonal variations in the size or weight of gonads depend on the stage of gametogenesis. The stages of gonad development in individuals can overlap, but a regular cycle of reorganization, growth, maturation and spawning persists (Kim 1968; Novikova 1978).

Gonad indices increase as the size or age of starfish increases (Takashi *et al.* 1955). Kim (1968) showed that gonad weights increase linearly at a rate dependent on ray length. The gonads of starfish of 40–50 mm ray length increase at a greater rate than do the gonads of starfish of ray length greater than 60 mm. Histological observations showed that starfish with rays shorter than 55 mm have predominantly immature gonads while mature gonads occur in larger individuals. This suggests that mature gonads develop only in *A. amurensis* with ray lengths greater than 55 mm. Similarly, in a study in Sendai Bay the minimum size of biologically mature female and male starfish is 55 mm and 56 mm respectively (Hatanaka and Kosaka 1959). Ino *et al.* (1955) found that in Tokyo Bay gonad indices were less than 40% in starfish smaller than 60 mm ray length and 100% in starfish with ray lengths of 110 mm.

The average egg diameter varied between populations of *A. amurensis*. Ovarian egg diameter was 150 μ m in Tokyo Bay (35°N) and 185 μ m in Sendai Bay (38°N) (Hatanaka and Kosaka 1959). In Mutsu Bay (41°N) eggs were 100–150 μ m (Kim 1968). Similarly, Drozdov and Kastanov (1985) found an egg diameter of 100 μ m in animals from the Sea of Japan. The smaller eggs in Mutsu Bay starfish do not fit Thorson's hypothesis that egg size in marine invertebrate populations increases with more northerly distribution (Hatanaka and Kosaka 1959).

In a review of starfish Kasyanov (1988) reported the fecundity of A. *amurensis* to be 19 million eggs, with an egg diameter of 110 μ m. However, animal size was not stated, and fecundity increases with the size of the starfish. Levels of fecundity increased from 2.1–10.7 million eggs in starfish with ray lengths from 9.1–14.0 mm respectively (Hatanaka and Kosaka 1959). These values may be underestimates, as the measurements were made well into the spawning season. A sample taken a month earlier gave an estimated fecundity of 15.5 million eggs for a starfish of ray length 118 mm.

In Peter the Great Bay (43°N) the reproductive effort of *A. amurensis* accounts for approximately 12–13% of the total energy budget (Kasyanov *et al.* 1985). Other studies have shown that reproductive effort is high compared to other echinoderms (Novikova 1978). Thus, in favourable conditions the biological potential of *A. amurensis* is immense. The gonad development expressed by *A. amurensis* is characteristic of planktotrophic strategists, which have small eggs with little nutrient storage, high fecundities, a sex ratio of 1:1, and large populations with very variable recruitment (Kasyanov 1988). The literature suggests that the potential for high recruitment and sudden outbreaks of populations of *A. amurensis* appears to be favoured during low summer temperatures. For example, a population explosion of *A. amurensis* in Tokyo Bay, from 1953–54 coincided with unusually low temperatures during the summer of 1953 (Sagara and Ino 1954).

Larval stages

Larval growth and development is a critical step in the life cycle of *A. amurensis*. Free swimming larvae can disperse a population widely. The amount of dispersal depends on duration of the larval period and water movement. However, ecological costs are incurred with increased larval duration. Mortality rates increase through predation by planktivores and unfavourable physico-chemical environments, such as temperature and salinity.

Larvae of A. amurensis initially form a short gastrula stage before entering a feeding pelagic period. The planktotrophic larvae develop 'indirectly': first into a bipinnaria stage, and then gradually taking the form of brachiolaria (Oguro *et al.* 1976; Oguro 1989). The length of the larval stage is uncertain. Nakajima (1987) detected a single precursor cell for the bipinnaria in the late (35 hours) gastrula stage of A. amurensis and cultured bipinnaria in petri-dishes at $17-20^{\circ}$ C for 20 days. Bipinnaria larvae that were cultured in temperatures of 0.6–31.3°C lived for 40 days in medium temperatures (5–10°C) (Sagara and Ino 1954). Nojima *et al.* (1986) suggested that the total larval stage of Asterias species lasts for 3–4 weeks. This appears to be an underestimate since Sagara and Ino (1954) cultured bipinnaria larvae over a 40 day period. The length of the brachiolaria stage is unknown; we found no literature on the development of the brachiolaria larvae of A. amurensis. The larval stage of A. rubens has been estimated (Barker and Nichols 1983) to last up to 3 months; the brachiolaria stage lived from approximately the 30th to the 81 st day (see 'Related species').

Sagara and Ino (1954) conducted temperature tolerance tests on bipinnaria larvae over a 22 day period. Their conclusion, that the optimum temperature of *A. amurensis* bipinnaria larvae is 5–20°C, needs clarifying and confirmation. Larvae died and others lost weight within eight days at temperatures of 22°C and at 0.6°C. Between 5.6° and 11.9°C larvae survived for 22 days, but after 20 days the larvae at 11.9°C shrank and became less mobile. Larvae cultured at temperatures of 14.3–19.5°C died after 20 days in aquaria. The authors reasoned however, that larvae in these medium range temperatures died from causes not related to temperature since another batch of larvae survived for 40 days at the same temperatures.

Population statistics

Age and year classes of populations of *A. amurensis* and sub-species have been estimated from samples collected by trawling the sea bed over a 12 month cycle. Hatanaka and Kosaka (1959) used 34 sampling periods to collect 5,147 starfish from the Sendai Bay population. Using ray length as a measure of age they found the population consisted of four cohorts, interpreted as year classes. A possible fifth cohort is indicated from the size frequency histogram, at the beginning of the spawning season. The rate of growth of cohorts decreased with age. Within one year the zero age class cohort reached a ray length of 78 mm and a weight of 45 g, and the second a length of 100 mm and a weight of 85 g. The third and fourth year-classes had average ray lengths of 118 and 131 mm and weights of 125 and 168g respectively, at the end of the year.

The length attained by *A. amurensis* in the first year of growth suggests that sexual maturity in these starfish is reached in 12 months. However the estimate of growth of the first age class was based on rays longer than 40 mm as no starfish smaller than this were sampled by trawling (Hatanaka and Kosaka 1959). Frequency histograms of ray lengths of starfish from Tokyo Bay show a small sized cohort with mean ray lengths of 2.5 mm in late March (Takashi *et al.* 1955). The spawning season is from January to April, with a peak in late February to early March. Later samples indicated that this cohort grew to a mean size of 25 mm by late May, at a growth rate of approximately 0.5 mm per day. A second cohort in the Tokyo samples had a mean ray length of 70 mm. This is consistent with the first cohort of Hatanaka and Kosaka (1959). A comparable rate of growth was observed in populations of *A. amurensis versicolor* in the Ariake Sea, Kyushu (33°N) (Nojima *et al.* 1986). The average size of this species is smaller and the currents along this coast are warmer, but temperature ranges for this enclosed shallow sea are not available.

Trawl samples in Sendai Bay suggested an exponential negative correlation of density to depth. A maximum density of 0.43 kg per 1000 m² was found when trawling 0.6 km² per sample at a depth of 20 m. This is approximately 44 starfish per 1000 m². Starfish were rare at 50 m with a density of 0.44 per 1000 m² (Hatanaka and Kosaka 1959). The maximum density of *A. amurensis* in the Bering Sea, measured by visual surveys, was 270 starfish per 1000 m² at approximately 20 m. They were less dense at shallower depths (Oliver *et al.* 1985). The two areas differ greatly in measured density. Density estimates from visual surveys should by more accurate than estimates from trawling. Hatanaka and Kosaka (1959) estimated the trawl efficiency at 0.5.

In the studies of Hatanaka and Kosaka (1959), Nojima *et al.* (1986) and Kaneniwa *et al.* (1987) starfish were found to a depth of 60 m. The largest *A. amurensis* recorded had a ray length of 192 mm and a central disk radius of 75 mm (Onguro and Okutani 1991). The sample came from a depth of 45 m but the locality is not recorded. In Sendai Bay, the largest starfish collected reached 186 mm (Hatanaka and Kosaka 1959).

Hatanaka and Kosaka (1959) estimated, by modelling the population statistics obtained from Sendai Bay, that a population of 45.7 million starfish consumed 8.245 tonnes of biomass annually. They estimated that cohorts decreased exponentially in number as they increased in size, at a rate of a = 0.85 between each cohort.

Temperature requirements

Mean monthly sea water temperatures at Japanese localities inhabited by *A. amurensis* are 5–21°C in Tokyo Bay (Takashi *et al.* 1955), 9.8–19.3°C in Sendai Bay (Hatanaka and Kosaka 1959), and 2–21°C in Mutsu Bay (Kim 1968). Seasonal temperatures near Vladivostok and in the Bering Sea are expected to be lower still.

Sagara and Ino (1954) considered that the optimum temperature range for juvenile starfish (ray length < 10 mm) is 5–26°C, but this is based on the juveniles surviving these temperatures for 30 days. The optimum temperature for starfish within Sendai

Bay, based on average seasonal growth rates, is 9-13°C (Hatanaka and Kosaka 1959), and 15-17°C for Tokyo Bay, calculated using 'digestive velocities' (Ino et al. 1955). However, determining optimum temperature regimes from either rates of digestion or changes in weight per mass of food incurs errors. The conversion of food to weight gained varied with temperature (over seasons) and with size. These factors were confounded in this experiment. For instance, the data show younger animals to have a higher efficiency in food conversion because they grow fast but eat less daily. The highest two percentage efficiencies of food conversion occured at temperatures of 6.2-11.4° and 11.2-14.8°C in April-May and October-November, but lower efficiencies occurred for temperatures between 11.8-15° and 7.6-12.5°C at other times and with other sizes of starfish. When the temperature remained above 19°C or below 5°C, the starfish lost weight. It seems likely that respiration overtakes digestion at high temperatures. Propp et al. (1983) showed that the monthly respiration rates of A. amurensis increased proportionally with seasonal changes in temperature, and similar trends occurred with ammonia and phosphate excretion. The increases in respiration coincided with increases in enzyme activity associated with changes in reproductive stages.

Absolute temperature limits have been determined from feeding experiments. Sagara and Ino (1954) found that juveniles died within two days at 29°C and four days at 1.1°C. Other studies found that adult starfish lose weight above 20° and below 4.0°C, and died at 25°C (Hatanaka and Kosaka 1959; Park and Kim 1985). High mortalities of both juvenile and adult starfish occurred during high summer temperatures in Tokyo Bay (Sagara and Ino 1954).

In summary, the optimum temperatures for A. amurensis are unclear, however, it is evident from the literature that this species can withstand temperatures of $5-20^{\circ}$ C, and survive for a limited time outside this range.

Effects of salinity

There was no information available on the salinity levels required for the survival of adult populations of *A. amurensis*. However, several studies in Russia have shown that adult starfish respond differently in 'freshened water' with and without potassium ions (Podol'skii 1975, 1978; Podol'skii and Tishchenko 1979). We were unable to obtain further details. Starfish are sensitive to changes in salinity, and will move to avoid decreased salinities as well as strong lights (Zafiriou 1972; Podol'skii and Tishchenko 1979).

Sagara and Ino (1954) found that the optimum specific gravity for culturing bipinnaria larvae is 1.011–1.026. This corresponds to 50–144% of the local sea water chloride concentration. Our interpretation is that these figures are equivalent to standard salinities of 15–43 parts per thousand. Larvae held in salinities outside this range died rapidly.

Feeding strategies

A. amurensis is an opportunistic predator showing some prey selectivity. It is known to

feed on a variety of epifauna including molluscs, tunicates, crustaceans, polychaetes, and echinoderms, including its own species (Fukuyama and Oliver 1985). It can search out buried prey by digging shallow pits to 10 cm deep in soft substrate (Oliver *et al.* 1985). Arima *et al.* (1972) observed that the depth of digging did not vary with ray length. Oliver *et al.* (1985) showed experimentally that *A. amurensis* touched and humped significantly more empty shells with Amphipoda sheltering beneath them than without, suggesting that they are able to detect such prey at a distance. *A. amurensis* have been observed to follow moving cultured Yeso scallops along the bottom in the Sea of Japan (Volkov *et al.* 1982).

Kim (1969 a, b) showed that A. *amurensis* selected certain prey depending on the habitat and the availability of other species. The preference for different bivalves was related to the difficulty of catching and opening these species. For example the electivity index for the scallop *Patinopecten yessoensis* was low in the presence of other bivalves, due to its violent escape reaction when attacked.

Park and Kim (1985) found that the feeding rate of *A. amurensis* on ark shell bivalves in aquaria increased with temperature, reaching a maximum at 20°C. Feeding rates rapidly decreased at higher temperatures. Below 20°C feeding rates decreased gradually. In another experiment on feeding behaviour on bivalves, maximum feeding rates were found between 10–20°C. Arima *et al.* (1972) showed that in aquaria the feeding rate was higher at high temperatures on gravel substrates, than on sand. At lower temperatures the feeding rate was higher on sand. It was suggested that variations in activity on each substrate with temperature are associated with seasonal movements between deep and shallow water. In Japan a gradient of mud, sand and gravel exists with increasing depth (Nojima *et al.* 1986). High summer temperatures kill starfish and migration to deeper waters is likely during these periods.

There is a linear relationship between ray length and the size of prey eaten. Park and Kim (1985) calculated that ark-shells longer than 1.5 times the ray length of starfish were not eaten. The restriction in prey size suggests that the feeding of *A. amurensis* shifts the size structure of the prey populations (Fukuyama and Oliver 1985), depending on the size distribution of the starfish population; especially if the size distribution, highly skewed towards smaller sizes as found by Hatanaka and Kosaka (1959), is typical. Nojima *et al.* claims that starfish predation generally produces a bimodal distribution of prey sizes.

Aggregations

Outbreaks of populations of A. amurensis and A. amurensis versicolor have occurred in waters around Japan. In 1954, a sudden increase in numbers of these starfish caused a loss of approximately 400 million yen worth of shellfish of marketable size within Tokyo Bay (Kim 1968). In Sendai Bay, when an abundant population of starfish was caught in commercial fishing nets (Hatanaka and Kosaka 1959), the average density was 4.2 starfish per m² and maximum density 93 per m² (Nojima *et al.* 1986). Large population increases of the smaller sub-species A. amurensis versicolor were recorded on a cyclic basis in Ariake Sea, west of Kyushu (Nojima *et al.* 1986). Population

densities peaked in 1964, 1974 and 1984. Densities of 6.07 and 3.4 animals per m^2 were recorded in 1964 and 1984 (no data from 1974). These outbreaks in the Ariake Sea consisted of only one cohort that persisted for approximately three years.

3 OTHER SPECIES

Reproductive strategies of related species

The sizes of mature eggs in other Asterias species vary. Egg diameters in Asterias vulgaris, A. forbesi, and A. rubens are 110, 110 and 175 μ m, respectively (Thompson and Murray 1889; Emlet *et al.* 1987).

Studies have shown that the reproduction of starfish is sensitive to environmental conditions such as temperature, salinity, and the availability of food. In starving *Asterias rubens*, gametogenesis regresses and priority is given to the maintenance of body tissue (Nichols and Barker 1984; Bouland and Jangoux 1988). The size of the gonads of *A. vulgaris* has been related to the density of mussels in the vicinity (Menge 1986). Pearse and Eernisse (1982) concluded that in the more distantly related *Pisaster ochraceus*, photoperiod substantially effects the initiation of gametogenesis and stages of growth.

Crump and Barker (1985) compared sexual strategies in four New Zealand populations of *Coscinasterias calamaria*. Extreme variations in sex ratios were found. Two populations consisted of a 1:1 ratio of males to females; in the third group most were males and in the fourth group, most were females. An inverse relationship of pyloric caeca levels and gonad indices was consistent in all populations. A similar relationship exists in other asteroids of the order Forcipulata. Interestingly, fission and the effort placed into sexual reproduction differed. Fission in starfish was pronounced in populations where food availability was low and its quality poor. Threlfall (1977) (also Johnson and Threlfall 1987), regularly observed fission in populations of *C. calamaria* near Rottnest Island, Western Australia. No seasonal variation or size distinction in the frequency of fission was evident in these populations. However, juveniles of *Coscinasterias calamaria* were found by Klemke (1985) in Victoria to undergo extensive asexual reproduction by fission such that the numbers of juveniles could build up rapidly in local habitats.

Larval growth in other species

Barker and Nichols (1983) have described the larval stage of Asterias rubens. The devlopment from fertilization to juvenile in this species is similar to that of A. *amurensis*, with the larvae passing through several stages. The gastrula phase in A. *rubens* lasts for 40–50 hours after fertilization. Within 3–4 days bipinnaria larvae have developed and by 22 days the larvae have grown to a length of 1.5-1.8 mm. Brachiolaria arms form after about 30 days and are long and sinuous by 70 days. Search and settlement of the cultured larvae proceeded after 81–87 days. Metamorphosis was completed by the end of the sixth day after settlement, and juveniles were feeding within another six days. These time estimates of development in A. *rubens*, using laboratory studies, correspond to results from plankton samples at

sea. Bipinnaria larvae were found in plankton samples one month after spawning and brachiolaria 2.5 months after spawning.

Although Emlet *et al.* (1987) in a review of larval ecology, argued that small egg size increases the development time of larvae, *A. rubens*, with an egg size of 175 μ m, has a much longer larval life than *A. forbesi*, with an egg size of 110 μ m, and a larval stage estimated as approximately 25 days. At metamorphosis juvenile *A. forbesi* are 1 mm in length. The egg sizes of *A. amurensis* are between those of *A. rubens* and *A. forbesi*, and the same may hold for the duration of the larval development.

The long duration of larvae of Asterias rubens may have contributed to its wide distribution in the northern hemisphere (Barker and Nichols 1983; Emlet *et al.* 1987). It has been estimated that oceanic drifts could displace larvae across the Atlantic within 300 days. Longer larval periods however, mean that larvae are susceptible to greater mortality. It was earlier thought that food availability was the principal cause of death in pelagic larvae (Paulay *et al.* 1985). Recent studies consider that high mortality in larvae is due to low levels of fertilization, variation in hydrographic conditions, the failure of larvae to settle on substrates, and predation (Fujisawa 1989; Olson and Olson 1989).

Growth and development of related species

The size of juveniles after metamorphosis in *Asterias rubens* is 0.75–0.85 mm and within 76 days they grow to 7.5 mm ray length (Barker and Nichols 1983). Growth is fastest in the first year of development, but this rate is considerably slower than that reported in *A. amurensis. Asterias rubens* inhabits cold waters and reaches a mean size of only 32 mm ray length. Growth slows in the second and third years with greater effort directed to gonad development. Sexual maturity in *A. rubens* does not occur until the second year (Nichols and Barker 1984).

Klemke (1985) found that growth of juveniles was effectively arrested in populations undergoing extensive fission. The environmental trigger for growth of juveniles was not found. It seems possible that *A. amurensis* may also be able to undergo fission as a juvenile, but this has not been recorded, perhaps because very few studies found juveniles in the field. Juvenile *Coscinasterias calamaria* occur in restricted habitats such as foliose algal beds and mussel beds (Day 1992), and this may also apply to *Asterias amurensis*.

Feeding behaviour and aggregations of other starfish

The size of the prey depends on the ray length of a starfish. O'Neill *et al.* (1983) studied the effects of size selection on cultured mussels. Adult *Asterias vulgaris* move to deeper water in search of large prey, so that small starfish have the greatest impact on cultured mussel populations in shallow water (Himmelman and Dutil 1991). Similarly, Klemke (1985) found that juveniles of *Coscinasterias calamaria* select different, smaller prey from the adults, and adults show distinct preferences for those prey species that are easily captured.

When feeding, Asterias forbesi randomly search for food and apparently show no directional movement (Campbell 1984). Other studies have shown that Asterias species can detect food from some distance. Asterias rubens responds to food from a distance of 2.5 m (Zafiriou 1972). Experiments have shown that the response to the introduction of food in the Australian starfish, Coscinasterias calamaria, is rapid (Day 1992; Klemke 1985; Shaw 1988). C. calamaria forms aggregations in mussel beds, as these prey are more easily handled than scallops and abalone. In aggregations however, they attack abalone very successfully (Day 1992). Fishermen have also reported aggregations on beds of scallops. These may occur when the starfish begin feeding on damaged scallops after dredging. While scallops can detect Coscinasterias from about 0.3 m distance, and escape by swimming (R. Day, personal observations), they would not escape predation in a dense aggregation of starfish. It is not known whether Australian scallops and abalone can detect, and have an effective escape response from, Asterias amurensis.

The triggering mechanism for aggregations appears to be the release of chemical stimuli from feeding starfish (Zafiriou 1972; Moore and Campbell 1985). Moore and Campbell showed that starfish were attracted to other feeding starfish in a 'Y' maze aquarium. Lack of intraspecific avoidance in *Asterias* species results in large aggregations of starfish at sources of food (Barker and Nichols 1983; O'Neill *et al.* 1983; Sloan 1984; Himmelman and Dutil 1991). The complete destruction of an Icelandic scallop bed by a carpet of foraging *Asterias rubens* was recorded in 1967 (Brun 1968). The starfish population spanned an area of 1000 m² with a 10 m moving front. Middle and outer densities of 97 and 48 animals per m² were found. The aggregation of starfish left behind only empty scallop shells. Himmelman and Dutil (1991) postulated that starfish aggregations may intensify during reproduction when they need more food. However, the aggregation of the Icelandic starfish persisted past the post-spawning stage (Brun 1968). Aggregated feeding can alter the size of prey selected. Aggregations of small *Asterias vulgaris* fed on larger mussels than when the starfish were not aggregated (O'Neill et al. 1983).

4 CONCLUSIONS

Intraspecific variations in the life history strategies of *Asterias amurensis* are evident from the literature. Differences in spawning season and cycle, and egg size illustrate its ecological plasticity and ability to adapt to altered environments. The evolution of a second spawning in warm summer temperatures in Peter the Great Bay is significant.

The species appears to be limited in its range in Japan by warm temperatures, and the fact that adults lose weight and larvae die at temperatures over 20°C may mean there is some barrier to its dispersal north from Hobart along the east coast of Tasmania. In relation to this, the sub-species *A. amurensis versicolor*, which occurs in Kyushu, Japan, should perhaps be a focus of further study, as it occurs in warmer waters. It is possible that this sub-species is not genetically distinct, and merely represents another aspect of the plasticity of this species, and that the Australian animals will adapt in a similar way to warmer conditions.

There is every reason to suspect that *A. amurensis* will pose a serious threat to stocks of shellfish, especially scallops, in the cool waters around Australia's southern coasts, as it appears to grow rapidly, is extremely fecund, forms aggregations in areas where prey are abundant, and is known to follow fleeing scallops. However, the native seastar *Coscinasterias calamaria* is also able to prey on these shellfish, and it is difficult to predict how much extra effect the new species would have. From the fact that many terrestrial ecological introductions, once established, have very severe effects, it is obvious that the prognosis is not good.

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MODELLING OF THE DISPERSAL OF ASTERIAS AMURENSIS EGGS AND LARVAE IN TASMANIAN WATERS

Vincent Lyne CSIRO Division of Fisheries

1 REPORT BRIEF

The work reported here is an analysis of the dispersal in Tasmanian waters of *Asterias amurensis* eggs and larvae. The principal aim is to provide preliminary information on the potential rate of spread of *Asterias* and the areas likely to be affected. The report does not analyse the recruitment success of *Asterias*; this would require additional investigations of water temperatures at the time of settlement, predators and natural mortality, food availability and suitability of substrates for settlement.

Much of the biological information for this study was obtained from Dr Robert Day of the University of Melbourne and from information being collated by Ms Stephanie Davenport of CSIRO.

2 BACKGROUND

The approach adopted was to develop a model for the dispersal of eggs and larvae taking into account relevant information currently available on the distribution of adults, their spawning behaviour, the movement characteristics of eggs/larvae and the nature of water currents during the spawning period.

Present information on the infestation is based on reported sightings from the public at large. As such, the information is scattered and biased (to beaches and locations most frequented and to locations of concern to aquaculture interests). Even from this limited information, it is clear that the infestation is widespread in the Derwent River and D'Entrecasteaux Channel in the south, and on the Tasmanian east coast to the west of Maria Island. There have also been sightings in Great Oyster Bay. What is not clear at this stage, and one of the questions posed for the model, is whether the infestations were derived from an initial contaminated site — the first reported sighting was from Rosny Point on the Derwent River — or whether several contaminations were involved.

Young Asterias are sighted most frequently near shore and the larger adults (10-15 cm arm length) occur in deeper water (depth of 4 m or greater).

Limited information relevant to this investigation is currently available on the spawning behaviour of the adults. Spawning is thought to occur just after the minimum temperature in winter although the duration of spawning is uncertain. No information is available on the cues for spawning (moon phase, tides, temperature).

Eggs of Asterias are thought to be buoyant and to exist for 3 to 4 days before undergoing transformation to the other larval stages. The buoyancy of the eggs is one of the critical elements in the dispersal of Asterias. The larvae possess cilia and appear to be capable of limited motility. The size of the eggs is about 100 μ m and the larval period before settlement is estimated from laboratory observations to last for 40 days (at 14–15°C) and is temperature dependent. This dependence is not incorporated in the model.

Only one measurement of fecundity of 19 million eggs is available for *Asterias*. No information is available on the depth of spawning although the species is known to occur in deep water (106 m).

3 MODEL STRUCTURE

Given the biological background on *Asterias*, it was decided to model the movement of the eggs and larvae by following the movement of 'clouds' or clusters of eggs/larvae represented by individual particles in the model. For the buoyant eggs, the relevant water current driving the dispersal is the surface drift current in the top tens of centimetres of the water column. Currents in this region are primarily strongly wind-driven and substantially exceed mean currents experienced in the bulk of the water column. As such, the movement of the eggs in the first 100 hours is modelled as surface wind-driven. For the subsequent larval phase, and to examine the 'worst case' scenario, it is assumed that the larvae are distributed in the top half of the water column (rather than throughout the water column). The larval drift at each time step (of one hour) is one half the surface drift plus a random component of one half the surface drift. Dispersion by tidal currents is incorporated as a random current velocity with a magnitude of 0.2 cm/s (about 20% of the tidal current in the Derwent River). This value would be much larger in the open ocean and for exposed stretches of water such as Storm Bay.

The nature of the dispersion of the eggs and larvae is likely to be critically affected by the interaction of the drifting eggs and larvae with the rugged coastline. The ruggedness of the coast, with distribution of dead waters and recirculation in the lee of bluffs and headlands causes entrapment of drifting eggs and larvae. This interaction can be simulated in an artificial way by specifying a 'stickiness factor' that will entrap eggs and larvae along an idealised smooth or straight coast (Lyne and Thresher 1993). However this 'stickiness factor' will depend on the ruggedness of the coast and there are no accepted rules for specifying such a factor. These uncertainties led us to develop a high-resolution model incorporating as much detail of the coast as possible. The entrapment in such a model is then a natural consequence of the interaction of the drift with the coast. However, our model does not model fine-scale entrapment features (occurring on scale of tens of meters) and in viewing the model results, any particle or cloud making contact with the coast should be assumed to have left some larvae behind to settle.

Winds used in the study were derived from detailed hourly records kept by the Tasmanian Hydro-Electric Commission for the Granville Harbour site on the west coast of Tasmania (Figs. 1&2). (Whilst such detailed records may exist for the Tasmanian east coast, given the time and budgetary constraints for the study, we proceeded to use the existing detailed records.)

4 MODEL IMPLEMENTATION

The model was implemented on an IBM-PC clone (Compaq Deskpro 386/16) running under the DOS operating environment. Due to the memory limitations of this computer architecture, the implementation of the model required innovative use of the video memory to achieve the high resolution coastal boundary. The number of particles that could be tracked was also limited to a few hundred. The video memory consisting of 640 (width) by 480 (height) cells, for a total of 307,200 cells, was used as the environmental mask for land and water. Each cloud was however modelled as a vector so that the movement was continuous rather than digital, this is necessary to prevent unwanted numerical dispersion that would arise from a cell-to-cell movement model.

Eggs and larvae were released from strategically placed rectangles in the model domain. Initial distributions in the rectangles (0.005 degrees in latitude and longitude) were randomised and the spawning was assumed to take place over a period of five days during which a continuous stream of clouds was released from the rectangles. After the spawning period, movement of the clouds was subject to wind and impeded by the coast. After every two days, the location of the clouds were marked on the video map so that the evolving distribution could be visualised.

The simulation was started with the wind record at 1 August 1988 and terminated after 50 days – the assumed period before settlement of *Asterias* larvae. The simulation time step was one hour. The rose plot of frequency of wind events as a function of direction shows that the predominant strong winds are from the west and there is a bias of winds blowing to the north. The period of reversals in the EW wind suggests a cycle of about a week or so.

Two simulations were run: the first run was populated with 5 'seeds', one in the Derwent river, two in the D'Entrecasteaux Channel, one just off the eastern shore of Storm Bay and one in the channel west of Maria Island. The second simulation concentrated on the open areas in the northern half of Tasmania with one seed in the wide Great Oyster Bay, one offshore of St Marys and another at the south-eastern end of Bass Strait. A third simulation was run to test the effect of mean drift currents operating on the continental shelf.

5 RESULTS

The southern Tasmanian simulation (Fig. 3) shows extensive dispersal for the Maria Island and Storm Bay seeds and restrictive dispersal in the Derwent River. The Maria Island dispersal stretches north and eastward with a maximum extent of about 60 km.



Figure 1. Plot of the frequency of wind events as a function of direction for the hourly wind record from Granville Harbour on the west Tasmanian coast. Note the direction is the direction to which the wind is blowing.



Figure 2. Plot of North—South (a) and East—West (b) wind for the hourly wind record from Granville Harbour on the west Tasmanian coast. Note that positive NS wind is blowing northward and positive EW wind is blowing eastward. The start time is 1 August 1988, 0000 hrs.



Time (hrs)

Coastal sites 20 km or so of the seed site appear contaminated as does the coast on the north eastern part of Maria Island. The Storm Bay seed shows a dramatic transit of some clouds right across the Bay to the western shore, contamination of extensive parts of the eastern shore and transit of clouds into Frederick Henry Bay. One cloud proceeded south eastward towards the entrance of the Bay. The Derwent River seed displays a restrictive spread by comparison with the contamination area extending from the northern edge of the entrance to Ralphs Bay up into the Derwent. The resolution of the model, in particular the accuracy of coastlines, at these small scales is most probably unduly restricting the spread of the two seed areas in the D'Entrecasteaux Channel. The spread in all areas is biased to the north in keeping with the driving by the wind.

The northern simulation (Fig. 4) shows complete entrapment of the clouds released in the Great Oyster Bay with extensive contamination of the eastern shore and some contamination at the southern end of the western shore. Coastal sites up to 20 km or so of the St Marys seed appear contaminated but the bulk of the cloud has proceeded to drift well offshore. In interpreting the results it must be kept in mind that the model does not include the mean drift current on the shelf, which according to data collected by CSIRO in 1988 was about 10 cm/s for a winter shelf mooring at 100 m water depth. The spread rate of clouds subject to entrapment at the coast may be much less than the drift of currents (Lyne and Thresher 1993) and as evident from the results of this study. None the less, the mean drift may be sufficient to advect clouds a substantial way towards Bass Strait. The seed in Bass Strait shows a similar eastward and northward drift impinging on the shores of Clarke and Cape Barren Islands. The long axis of the cloud spread is about 80 km or so.

To test the effect of mean drift currents, a mean northward drift was imposed for the clouds on the continental shelf. The assumed mean drift was set at a conservative value of 2 cm/s and the second simulation was re-run. The results (Fig. 5) demonstrates the substantial drift effect for the seed off St Marys. During the 50 day simulation, the drift extended up to and beyond the model's northern domain $(40.2^{\circ}S)$.

6 DISCUSSION

The model results paint a rather bleak picture of extensive spread of eggs and larvae of *Asterias*. We should not take comfort in the result that the spread in offshore waters was predominantly eastward to deeper waters. It should be kept in mind that 1988, the year from which the wind record was derived, was a warm *LaNina* year. Winds in othe years may well be quite different. We did experiment with rotating the wind record and found for example that with the right winds, the clouds in the Derwent River proceeded well into Storm Bay and the seed in Storm Bay drifted well past Cape Pillar.

We should also keep in mind that the simulations were for a main spawning period of 50 days. Further spread of *Asterias* is possible from the re-suspension and drift of 'settled' larvae in the bottom boundary layer and by the motility of adult *Asterias*.



Figure 3. Simulation of the drift of eggs and larvae of *Asterias* for a 50 day period from seed areas marked by (yellow) rectangles. The positions of the drifting clouds (magenta) are marked at the end of each two days. The final position of the clouds is marked by markers twice in size and red in colour. A total of 240 clouds were used in the simulation.

Over page:

Figure 4. As in Fig. 3, for northern Tasmania and south-eastern Bass Strait.

Figure 5. As in Fig. 4, for northern Tasmania and south-eastern Bass Strait but with a mean drift of 2 cm/s imposed on the continental shelf.



Fig. 4



The model results are of course no indication of recruitment but merely a necessary condition for recruitment. Extensions of the model simulations should consider the conditions of temperature, food, substrate and mortality which will affect survival and settlement. These conditions can be incorporated in the model but the model is only at best as good as the data it is fed. Much more quantitative information is required of the biological factors affecting drift and survival.