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Evaluating source-sink relationships of the western rock lobster fishery using oceanographic modelling

Final FRDC Report – Project 2008/087

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Non-Technical Summary

2008/087 Evaluating source-sink relationships of the western rock lobster fishery using oceanographic modelling

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Objectives

1. To determine the relative contribution of larval production from different areas to the abundance and spatial distribution of puerulus settlement over 15 years using a larval advection model.

Outcomes achieved to date

The project has provided a preliminary assessment of the source-sink relationship in the western rock lobster fishery, with the model indicating a general north-south trend in the likelihood of successful settlement from releases from the main part of the fishery i.e.from Abrolhos (28°S) to the Fremantle region (32°S). While the average trend in settlement success was from north to south, there was variability in this trend between years that will be examined further. The modelling results also suggest that settlement sucess is better from phyllosoma released from deeper water areas closer to the edge of the continental shelf. These results suggest that breeding stocks in all regions need to be maintained, but particularly those in the northern areas, including the deep-water Big Bank stocks.

The low puerulus settlement of the western rock lobster (WRL) in 2006/07, 2007/08 and 2008/09 generated a need to better understand how recruitment is affected by the location of spawning combined with the oceanic conditions during the entire 9-11 month larval and puerulus stages. Consequently, this FRDC tactical research funded project has generated an initial oceanographic model of the larval stage of the WRL to enable a preliminary assessment of the source-sink relationships for this stock. This project will also provide the basis for a three-year FRDC project that will examine the relative importance of environmental factors and breeding stock in the resultant low settlements (FRDC 2009/018 Identifying factors affecting the low western rock lobster puerulus settlement in recent years).

The approach adopted in this preliminary assessment of the source-sink relationship of the WRL was to (a) review the literature relevant to the larval behaviour of the WRL; (b) develop a preliminary larval tracking model that could be used to represent the larval behaviour of the WRL; (c) develop appropriate model parameters reflecting larval behaviour that could be input into the oceanographic model; (d) evaluate potential source-sink relationships.

A hydrodynamic model, BRAN (Bluelink ReANalysis), was used to provide the 3-dimensional wind and density driven horizontal velocity fields. A correction term was applied to the surface layer (0-20 m) velocity of the hydrodynamic model outputs, based on scatterometer satellite (QuikScat) derived wind fields. The Stokes drift was taken into account in the hydrodynamic model surface layer using the wave model (Wave Watch 3) outputs and added to the velocity profiles from BRAN at each grid cell.

The individual-based model simulated larval and puerulus settlement processes in nine settlement seasons, from 2000/01 to 2008/09. The model satisfied four key criteria associated with the spatial and temporal distribution of the larvae and the puerulus settlement throughout the average duration of 9-11 months. The assessment of the annual variation of the puerulus settlement abundance and distribution will be the focus of the stage two model with another four criteria proposed to assist in fine-tuning the model.

As was found in previous oceanographic modelling of the WRL larval processes, advection alone did not produce a model that satisfied the four criteria, particularly the spatial distribution of the settlement. The increased growth and subsequent increased survival of the larvae associated with higher water temperature was an important component of the model to satisfy the model criteria.

The modelling indicates that early larval release (mid-October to early December) results in a greater chance of survival to puerulus compared to late release (mid-January to February). Early-release phyllosoma larvae experience a longer period of warmer temperatures during the summer, which enable them to grow faster and hence increase their survival. The model results also indicate that there tends to be a much higher settlement success rate associated with phyllosoma releases in 60 and 80/100 m depths compared to 40 m. This is probably a reflection of the additional mortality associated with shallower released phyllosoma, staying on the shelf for a more extended period compared with those released in deeper water.

The modelling showed that, on average, there is a declining trend of the likely success of settlement from larval releases from Abrolhos (28°S) to the Fremantle region (32°S), indicating that the more northern sources are likely to be more important in most years. The larvae released in the north tend to experience higher temperatures and therefore tend to have shorter overall pelagic larval duration compared to those released further south. The area north of Shark Bay appeared (superficially) to potentially be a relatively important source of successful larvae, but as these results were based on equal larval releases at all latitudes, given that the breeding stock levels in this region are minimal it will be much less important than the Abrolhos region. The limited assessment of variations in the source-sink relationship among years did highlight that the north-south trend can vary significantly with the southern areas more important than the northern regions in some years. The initial results therefore suggests that while the breeding stocks in the northern areas, including the deep-water Big Bank stocks may be particualry important, the breeding stock in all regions need to be maintained at appropriate levels.

The upcoming three-year project will focus on further development of the model to better reflect the recorded interannual variability in settlement and to enable an examination of the factors that could be affecting settlement success.

KEYWORDS: Western rock lobster, source-sink, oceanographic modelling

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- The Bluelink (BRAN) model developers in CSIRO and Bureau of Meteorology
- The Satellite data providers e.g. NASA
- WW3 model.
- WAMSI and CSIRO Wealth from Oceans National Research Flagship
- The internal reviewers at CSIRO and DoF
- Huijie Xue and Alejandro Sanchez for sharing some programming codes
- Jenny Moore for editorial and administrative work on the project.

Background

The unusually low puerulus settlement in 2006/07, 2007/08 and the particularly low numbers in 2008/09 was the initial impetus to developing this project to urgently examine the individual based larval tracking modelling of the larval stage so as to undertake a preliminary assessment of the source-sink relationships of 9 month larval and puerulus stages. This FRDC tactical research project is complementary to a more comprehensive three-year project which will examine the relative importance of environmental factors and breeding stock to the recent low settlements (FRDC 2009/018).

Understanding the cause(s) of the low settlement has been identified as a high priority by Low Puerulus Settlement risk assessment workshop in April 2009. The future management of the fishery is dependent on understanding whether the cause of low settlement is due to short-term environmental factors and/or long-term climate change effects and/or from changes in overall breeding stock levels or in specific parts of the fishery.

Need

The puerulus settlement in 2008/09 was the lowest in 40 years and follows two years of below-average settlements. Previous studies have shown that environment factors such as the Leeuwin Current and storms affect the abundance and spatial distribution of puerulus settlement. However it is important to identify if there are some changes to these environmental factors contributing to the low recruitment. The very low 2008/09 settlement occurred despite the Leeuwin Current being above average this year. This event was unexpected based on previous settlements during years of strong Leeuwin Current and has serious implications for the management of the fishery. The breeding stock overall is believed to be within historic ranges and so is not expected to have contributed to the recent decline in settlement. However it is possible that the breeding stock in certain parts of the fishery may be more critical than others and this could have changed over the years due to climate change effects. Advances in quality of satellite data in the 1990s measuring sea surface topography (altimeter satellites) have enabled significant improvements in our understanding of the environmental factors, with the assistance of oceanographic modelling. Previous oceanographic models were focused on the open ocean circulation off the continental shelf. Recent advances enable the development of high-resolution models at 10 km spatial scale which resolve the dominant processes on the shelf. Understanding the cause of recruitment variability and their long-term trends has important implications in the stock assessment and management of the fishery. The management response would be significantly different if the cause of the series of low recruitment was due to egg production or environmental factors. An adjustment to the sustainable harvest rate may be required if there are long-term environmental trends that affect the average recruitment of the western rock lobster.

Objectives

1. To determine the relative contribution of larval production from different areas to the abundance and spatial distribution of puerulus settlement over 15 years using a larval advection model.

1.0 Introduction

1.1 Introduction

The recent low puerulus settlements in 2007/08 and 2008/09 for the Western Rock Lobster fishery have indicated the need for an improved understanding of the spawning stock-recruitment processes. In particular there is a need for an increased understanding of relative significance of spawning stocks through each of the three management zones for the fishery (i.e. source-sink relationships) and the environmental processes affecting larval processes leading to successful settlement.

For this purpose an update of the previous larval advection model by Griffin DA, Wilkin JL, Chubb CF, Pearce AF and Caputi N (2001) -- Ocean currents and the larval phase of Australian western rock lobster, Panulirus cygnus. (Mar. Freshwater Res., 52, 1187—99) for the fishery is being undertaken during 2009. This short-term project "Evaluating source-sink relationships of the western rock lobster fishery using oceanographic modelling" is supported by Tactical Research Funding from the FRDC during 2009. This project is to be followed by a more extensive three-year FRDC funded project "Identifying factors affecting the low western rock lobster puerulus settlement in recent years".

The approach adopted in this preliminary assessment of the source-sink relationship of the western rock lobster (WRL) was to (a) develop a preliminary larval tracking model that could be used to model the larval behaviour of the WRL; (b) review the literature relevant to the larval behaviour of the WRL; (c) develop appropriate model parameters reflecting larval behaviour that could be input into the oceanographic model; (d) evaluate potential source-sink relationships.

This stage 1 individual-based model was developed and assessed against a series of criteria associated with the spatial and temporal distribution of the phyllosoma larvae and the puerulus settlement. The further development of the model (stage2) to reflect and then assess the causes of annual variation of the puerulus settlement abundance and distribution will be the focus of the following more comprehensive three-year modelling project.

1.2 Previous models for larval advection

The Griffin *et al.* (2001) paper described the first comprehensive biophysical model for the larval phase of the western rock lobster stock. This model incorporated for the first time satellite-based oceanographic observations to drive the ocean currents needed to transport the hatching larvae offshore into the Indian Ocean before returning them to settle along the coast as puerulus about a year later. The outputs from this model showed that the combination of larval behaviour and observed ocean circulation was capable of moving significant numbers of larvae offshore from the fishery zone and returning them to the west coast as puerulus some 9—11 months later. The model was a major step forward in the oceanographic sense, however the authors noted that their model of necessity involved a number of simplifications and was not able to fully replicate the observed geographic distribution of settlement or the inter-annual variability in settlement. The model focused on the advection of the larvae and assumed constant survival each year irrespective of the temperature or other environmental conditions. Sensitivity testing to assess which biological parameters were likely to be affecting the model puerulus settlement was therefore carried out and a number of suggestions for future modelling research were made. This chapter has therefore focussed on reviewing and updating the biological parameters from those used in the original model, and takes into account the authors' suggestions on factors that may have limited the ability to match the observed puerulus settlement.

The updated biological parameters developed in this report have been used as inputs to the 2009 model, which has been rewritten using more current software and incorporates the more recent oceanographic modelling systems.

1.2.1 Biological parameters used in the Griffin model

In summary, the Griffin model used the following biological parameters as inputs to the model and to generate the larval movements:

1. Hatching: Constant numbers released every 5 days from 1 Nov to 28 Feb between latitudes 27 to 34.20^{o}S. Hatching phyllosoma larvae were released from outer part of the continental shelf.

2. Categories of larvae: The model uses 3 classes of larvae, which all have set ages/durations except Class 3 where 2 scenarios were used.

3. Duration of larval stages: Class 1 = Early stages I, II, III and has set duration of 50 days. Class 2 = mid stages IV—VI were assigned a set duration from 35 days. Class 3 stages VII—XI were assigned a duration of 185 days for a total of 270 days.

4. The duration of Class 3 larvae was also extended up to 300 days where an alternative scenario for metamorphosis to puerulus was tested.

5. Depth strata for diurnal movements of larvae: The model used three depth strata, Upper/Surface: 0—10 m, mid-depth: 10—50 m, and deep 50—90 m.

6. Vertical migration of larvae: Class I larvae were in upper layer at night [2100—0500hrs = one model step] and middle layer during daylight [0500—2100hrs]. Class II larvae were in upper layer at night and descended to the deep layer during the day. Class III larvae remained in the deep layer in daylight and ascended to the middle layer at night, except within 3 days either side of the new moon when they came to the surface at night.

7. Metamorphosis to puerulus: Two scenarios were used to trigger the moult to puerulus. Scenario 1: All class 3 [stage 9] larvae moulted to puerulus on day 270 [9 months] or Scenario 2 where any class 3 larvae would moult to puerulus at any age between 270 and 300 days, if the larvae encountered the edge of the continental shelf [depth less than 2000 m], but only when this occurred within 3 days of a new moon. Under scenario 2 the maximum larval duration appears to be about 300 days or 10 months.

8. Puerulus movements: Following the moult to puerulus at either 270 days [scenario 1] or when triggered by interaction with 2000 m depth contour [scenario 2], all puerulus swam east at 0.1 m/sec [360 m/ day] plus the current velocity [and direction] in the surface layer at night and in the middle layer during the day.

9. Puerulus duration: The maximum period that puerulus survive appears to be 30 days, after which they die if not settled.

10. Puerulus settlement triggers. Any puerulus reaching a depth of 100 m within 3 days of a new moon was deemed to have successfully settled on the coast.

1.2.2 Review of larval behaviour parameters in Griffin et al. 2001.

The main behavioural parameters used to generate movements of phyllosoma and puerulus in the Griffin model have been listed to assess where changes may improve the performance of the 2009 model being developed in this project. The relevant statements from Griffin *et al.* (2001), listed in italics, are followed by review comments where relevant to indicate where revised parameters could be useful.

1. *Class 1 larvae move to the north and west under easterly wind driven current influences.*

   The 'trade wind belt' of southerly/south-easterly winds moves south in summer to cover the main spawning distribution i.e. Cape Naturaliste to Kalbarri/Big Bank during the summer hatching season. These wind-driven surface currents are likely to transport most early stage phyllosoma offshore, however any strong southwesterly winds coupled with the north westerly direction of the coastline north from could result in significant numbers of phyllosoma being retained on the shelf in some years.

2. *Class 1, 2, 3 phyllosoma in the model have durations of 50, 35 and 185 days respectively.*

   The approximate durations for these phyllosoma classes from Phillips *et al* 1979, are Class 1 = 90 days [Dec. – March], Class 2 = 60 days [April-May] and Class 3 = 150 days [June – October] giving a total of about 300 days, from peak hatching in December to peak settlement in October. The model use of the shorter durations for classes 1 and 2 will have interacted with the diurnal behaviour parameters, to impact on model phyllosoma distributions off the coast.

3. *Any larvae that move north of 23 degrees South in the model have little chance of returning to fishery area.*

4. *The distribution of model larvae by July was consistent with observed general distribution recorded by Phillips et al. (1979), i.e. off the centre of the fishery.*

   This observed distribution, centred off Geraldton in the centre of the fishery, was largely the result of the 1970s CSIRO survey area, which was constrained for cost and logistic reasons, relative to the wider area covered by the 1960s Navy surveys. These earlier surveys showed a wider and potentially more northern distribution of larvae through the year.

   Secondly, separating out the late stage IX larvae in terms of catch rate (CPUE) from the Rimmer and Phillips (1979), indicates that stage IX larvae were more abundant in the northern part of the survey area i.e. off the Kalbarri/Shark Bay and out to 105 degrees E, with fewer south of Geraldton. Although the distribution of all stages combined provided a distribution slightly further south, significant numbers were still being recorded at the NW edge of the survey area suggesting that there could have been additional late stage larvae further west and to the north.

   In summary, a more north western distribution of late stage larvae and particularly stage IX would put larvae in a location which would allow subsequent settlement to be more influenced by the Leeuwin Current (LC) and therefore potentially more closely aligned with the geographic distribution of puerulus collector catches. That is, the revised model needs to better replicate this more north westerly distribution of late stage phyllosoma to enable the model puerulus to be positively influenced by the variations in the LC and distributed in a pattern closer to the recorded settlement.

5. *The September distribution phyllosoma is affected by westerly winds south of 30 deg S, and weakening of SE winds north of 30 deg S. The distribution of model phyllosoma was also*

found to be overly affected by LC through winter, with the result that too many were being lost around Cape Leeuwin.

This is a consistent problem in the model outputs recognised by the authors and suggests there may be a problem with the model parameters for the diurnal larval behaviour and/or the model generated current flows at different depth strata. The model puerulus distribution may also be due to environmental effects on growth/mortality not being factored into the model.

6. The movement of larvae, both successful and otherwise, was heavily influenced by the LC eddy field, typically situated off the centre of the fishery near the Abrolhos Islands. Despite the consistent position of the eddy field and shoreward jet south of the Abrolhos, the model larvae/puerulus settled all along the coast, and particularly further south than where the eddy flow generally interacted with the coast.
7. This circulation/mixing of the model larvae prevented any relationship in the model between the hatching location and final settlement position.
8. Authors suggest that settled individuals were mostly hatched near the Abrolhos Is.

   Data or model outputs to support this observation aren't apparent in the paper, but are likely to be a function of the model having larger numbers released on this section of the coast to reflect the high proportion of the breeding stock present in this area.
9. *Settlement timing was not apparently related to hatching date in the model.*
10. *Inter-annual variability was very low and not related to the observed puerulus settlement, which showed a 5-fold variation from 1993 to 1996, although there was a general correlation in numbers of model puerulus settling with the flow of the LC.*
11. *The timing and pattern of model settlement within the year was roughly related to the timing of pattern of observed settlement.*

    This is probably due to the model hatching period being fixed as 1 Nov. to 28 Feb with constant numbers released every 5 days, and relatively fixed duration of the model phyllosoma life at 9 – 10 months. These factors are likely to dictate that the availability of larvae to settle will peak around September/October.
12. *The only large inter annual variability in model settlement was generated by the proportion of larvae lost [both north and south] out of the system.*
13. *The model also produced a negative correlation between the strength of the LC [high Fremantle sea level] with losses to the north, while losses to the south corresponded positively to strong LC years/ high Fremantle sea level years.*
14. *The authors tried varying the deeper current flows in the model i.e. at 300 m and 1000 m, however this didn't improve settlement.*
15. *Increasing the surface wind drift factor from the standard 3.5% to 5% (as proposed by Chittleborough and Thomas 1969) resulted in more larvae being lost to the north and west, while decreasing the wind factor to 2%, increased numbers being lost to the south/east, but neither made an obvious difference to inter annual variability of settlement.*
16. *Increasing the depth to which mid and late stage larvae descended during the day from 70 to 100 m, had no impact probably because the model was not able to fully resolve the current shear with depth.*
17. *Varying the time larvae spent on the surface at night from 8 hrs to 0 hrs or to 16 hrs had significant impact. 0 hours on surface resulted in half of the larvae [relative to 10%] being*

lost to the south by July under influence of LC. 16 hrs on the surface caused 50% of the larvae to be lost to the north/west by April [relative to 15%]. The model was found to be sensitive to time larvae spend on surface at both early and mid stages.

The time larvae spend at the surface used in the model, appears to be less than the time found in the most extensive field sampling data set available (Rimmer and Phillips 1979). The biggest difference appears to be in the late stage larvae [7-9], where the model larvae only ascend to the surface layer [0—10 m] for 3 days either side of the new moon i.e. 6 [or 7] days per month. Rimmer and Phillips (1979) summarised data shows a reduced percentage i.e. about 30% of larvae in the top 10 m on full moon compared with about 60% on new moon, but most of the larvae were within the first 30 m in all cases.

A second significant issue is that the vertical position of the majority of the larvae in field samples is also a function of prevailing sea state/ weather conditions. With the dominant weather conditions offshore being moderate to rough, the Rimmer and Phillips (1979) paper indicates that all larval stages are likely to exhibit their pattern 'C' suggesting a high degree of mixing in the surface layer at night. That is, the larvae are distributed fairly uniformly from the surface down to about 50 m at night but with an approximate mean depth of about 30 m. This more uniform nighttime distribution of larvae with average depth of 30 m, regardless of moon phase may be more useful as a starting point for the 2009 model.

Although daylight distribution was not sensitivity tested, there is a reasonable expectation that the reported increased swimming ability with size/age could result in increasing depths during daylight hours with age, and faster attainment of the preferred depth. The deeper depth distribution with age used in the model is therefore considered to be reasonable, but could be adjusted to allow greater daylight depths for the late stage larvae compared with the mid stages.

18. *Varying the parameters for triggering the metamorphosis to puerulus and for settlement didn't make significant changes to inter annual variation. It was also noted that the swimming speed of 0.1 m/sec to the east gave the puerulus a 50% chance of reaching the 100 m isobath within a week.*

    The concept of the continuous active swimming by the puerulus to the east, is not well supported by the literature, and assumes some sophisticated navigational ability. Directional swimming by other crustacean larvae is often triggered by significant environmental cues, such as tidal changes, however these behaviours typically only occur in near shore areas. Such distinct environmental cues are unlikely in the open sea off the shelf.

19. *The authors suggest that advection does not appear to be the major problem in the model leading to the lack of significant inter-annual variability. They conclude an unknown factor(s) not included in the model, but correlated with the LC [sea level] are the likely causes of the lack of inter annual variability in model settlement. An example suggested of such a factor is an effect of temperature that could allow the larvae to hatch earlier and grow faster so that they escape the influence of the LC.*

    The above conclusion assumes that the biological parameters/behavioural factors used must be generally correct and the model hydrodynamics are a reasonable reflection of reality. An alternative scenario from other sensitivity tests is that minor changes in the diurnal behaviour of model larvae would be capable of moving more of the model larvae to the northwest i.e. offshore from Shark Bay to NW Cape, and such a shift in location particularly for the mid to late stage phyllosoma would position them to allow the LC flow to assist their return movements. This location would allow more of the late stage phyllosoma to metamorphose and puerulus to settle in the centre of the fishery in average years.

20. *Sensitivity testing of the parameters controlling metamorphosis and settlement were not found to make significant changes to the inter-annual variations in model settlement.*

The two scenarios tested i.e. metamorphosis occurring at 270 days or after 270 days when they encountered the continental shelf (200 m depth contour) within 3 days of a new moon. This limited period for metamorphosis to puerulus appears to be very restrictive. Similarly, the model parameter that has the pueruli swimming eastwards at 10 cm/second (plus the surface current velocity at night) is linked to the suggestion of a very short duration for the swimming stage (Lemmens 1994), based on the energy requirements for continuous swimming. These aspects of the model, which limit puerulus settlement to very short periods around the new moon and involve continuous swimming by the puerulus prior to settlement are not well supported by the literature on the species, and are aspects of the model were alternative scenarios may provide significant improvements.

1.3 Development approach for 2009 model

As a result of the greater computer power now available, the strategy adopted for the 2009 model was to incorporate most of the known biological and behavioural characteristics the phyllosoma and puerulus, which influence the transport and advection of individual larvae as fixed parameters into the initial model runs for each year. These fixed biological parameters were then used to interact with the oceanographic model to generate model larval trajectories for a series of years, including both very high and low settlement years. This process involved the release of equal numbers of hatching larvae throughout the known latitudinal range of the spawning stock, and equal numbers hatching at each location, each day throughout the hatching season. Some limited sensitivity testing of the basic biological input parameters i.e. for hatching depth, aspects of phyllosoma behaviour, etc was carried out during this phase, where time permited. Due to the complexity of these combined biological/oceanographic advection model runs, they take one or more days to complete a single year.

Testing to assess the impact of factors such as hatching location or time, natural mortality etc on subsequent settlement i.e. source sink relationships was then carried out through ‘post model’ analysis using the database tracks of model phyllosoma/puerulus for each year modelled. As this process does not require refitting the model, it requires relatively little computing power and can efficiently provide rapid outputs and assessments of the influence of a range of factors (eg changes in hatching pattern, breeding stock abundance etc) which influence ‘model’ settlement. These outputs are then compared to known phyllosoma distributions and actual puerulus settlements along the coast, and for each of the years modelled.

In addition, a number of aspects of the biology where more complex parameters may be useful, but could not be incorporated in the current model within the time available have been noted. These are listed for consideration in the subsequent modelling project, to be undertaken from 2010 to 2012.

2.0 Oceanographic model

2.1 Summary

In this project, daily outputs from two hydrodynamic models, the Bluelink ReANalysis (BRAN) and Hybrid Coordinate Ocean Model (HYCOM) as set out in Section 2.2, are used to provide the 3-dimensional wind and density driven horizontal velocity fields. While the two models have similar performance in terms of linear correlation with observation data, HYCOM is slightly biased in that it generates stronger than required southward flows off the west coast of Australia (not shown). For this reason, only outputs from BRAN have been used in the individual based modelling component of the project.

Hydrodynamic models (e.g. BRAN and OceanMAPS) also tend to underestimate wind driven velocity at surface layer, especially on the continental shelf when the model does not have enough horizontal and vertical resolution. A correction term has threrefore been applied to the surface layer (0-20 m) velocity of the hydrodynamic model outputs, using scatterometer satellite (e.g. QuikScat) derived wind fields.

Surface wave induced Stokes drift is another important mechanism of larval transport when the larvae stay in the near-surface layer, i.e. mostly at night time. Because the Stokes drift is not taken into account in the hydrodynamic model, the Stokes drift velocities in the surface layer (0-20 m) off the west coast of Australia have been separately derived from a wave model (WW3 – Wave Watch 3) and the outputs added to the velocity profiles from BRAN at each grid cell.

2.2 Oceanography models

In this section, we provide some detailed information on the oceanographic model outputs used to drive the individual based model.

2.2.1 BRAN

Bluelink ReANalysis, or BRAN, is based on a global ocean model, OFAM (Ocean Forecasting Australia Model), and has been developed as part of the BLUElink partnership between CSIRO, the Bureau of Meteorology, and the Royal Australian Navy (Schiller *et al*., 2008). BRAN is forced by the European Centre for Medium-Range Weather Forecasts (ECMWF) wind stress, and heat and freshwater flux forcing at sea surface, assimilating (corrected by) satellite (including altimeter) and in-situ data (Oke *et al*., 2008).

In this project BRAN was used to create a 1993 to May 2008 archive of daily values of ocean properties including ocean currents, salinity and temperature in 3 dimensions – resolved at 10 km horizontally and 10 m vertically (in the upper ocean) in the Australian region (http://www.marine.csiro.au/ofam1/om/index.htm). The BRAN model domain and bathymetry are shown in Figure 2.1. The shallowest water depth in BRAN is 20 m and in most regions there are more than 3 grid cells to resolve the width of the continental shelf, except where the shelf is narrow i.e. off the Northwest Cape and off Cape Leeuwin along the west coast.

BRAN has been used to perform operational short-term forecasts in the Bureau of Meteorology's OceanMAPS system on the same spatial grid as used in this project (Gary Brassington, personal communication). Because BRAN was only available up to May 2008, equivalent forecast data have been used in place of BRAN after May 2008, to allow a preliminary assessment of the critical 2008/09settlement year. A newer version of BRAN is currently being developed by CSIRO Marine and Atmospheric Research, and will be used in a subsequent project.

2.2.2 HYCOM

HYCOM, the Hybrid Coordinate Ocean Model, has been used as it has a vertical coordinate that is isopycnal (a surface of constant density of water – because of the action of winds and currents, isopycnals are not always level) in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas (Bleck and Boudra 1981; Bleck and Benjamin 1993). The HYCOM hindcast system is configured for the global ocean with HYCOM 2.2 as the dynamical model. Computations are carried out on a Mercator grid between 78°S and 47°N (1/12° equatorial resolution). Daily outputs from 2004 to present, which were interpolated to data at fix levels, have been downloaded from:

(http://hycom.rsmas.miami.edu/hycom-model/overview.html) for use in this project.

2.2.3 QuikScat

QuikScat (http://winds.jpl.nasa.gov/missions/quikscat/index.cfm) satellite-derived wind data has also been used in the particle tracking aspects of this project. The twice-daily global data at ¼ degree by ¼ degree resolution from 1999 to present was downloaded. The data are averaged into daily values and smoothed in time using a 7-point Hanning filter, and then interpolated onto the BRAN ~10 by ~10 km velocity data grid.

The correction terms of the wind-driven surface current was calculated using 1% of the wind speed and 20 degrees to the left of wind direction in the southern hemisphere (Jenkins 1987) for areas deeper that 200 m. To compensate for coastal wind effects, 3% of the wind was used as a correction factor for waters on the continental shelf i.e. within the 200 m isobath.

2.2.4 WW3

Significant wave height, wave period and direction from Wave Watch 3 model (WW3) data (http://polar.ncep.noaa.gov/waves/wavewatch.shtml; Tolman *et al.* 2002) were used to derive Stokes drift velocity for the particle tracking. 8-hourly global WW3 data at 1-degree longitude by 1.25 degree latitude resolution from 1997 to present were downloaded for this purpose. The WW3 data were then converted to daily means, and then interpolated onto the ~10km x ~10km BRAN velocity grid between 90E - 130°E and 1°N – 61°S.

In the wave propagation direction, the Stokes drift velocity can be calculated as

$$U_s = \frac{(ak)^2 C_P \cosh[2k(z+H)]}{2\sinh^2(kH)}$$

Here, $C_P = \sigma / k$, is the phase speed of the waves (m/s), $\sigma^2 = gk\tanh(kH)$, where a is the wave height (m), k is the wavenumber, z is the depth which is zero at sea surface and positive upward, and H is the water depth. Using the WW3 data, $a = H_S / 2$, and $\sigma = 2\pi / T_S$, where H_S is the significant wave height, and T_S is the significant wave period (Monismith and Fong 2004). The Stokes drift velocity is derived for the upper 20 m at 1-m resolution. Figure 2.8 shows the seasonal wave induced drift of the Western Australian coast. As with the wind-induced component, the data for the winter months show the importance of the Stokes drift component in the return flows needed for phyllosoma transport and puerulus settlement.

2.3 Seasonal cycles of model outputs

BRAN captures the average seasonal variations of the Leeuwin Current and Capes Current along the west coast of Australia (Figure 2.2). The modelled currents and ocean temperature on seasonal and sub-seasonal (from days to weeks) time scales have been validated with shipboard and mooring observations off the coast and show significant skills (Feng *et al.* 2008: An assessment of surface kinetic energy variability off the North West Cape of Western Australia, Project Report to Woodside North West Cape project; Alan Pearce, personal communication). However, BRAN may have underestimated the surface wind-driven currents, especially those on the continental shelf (e.g. Capes Current).

Figure 2.3 shows the average seasonal meridional flow along 32°S from BRAN. It shows a coherent year-long Leeuwin Current (southward flowing) with the core velocities above 25 cm/s in the upper 50-100 m, relative to current meters anchored at the shelf break. The Leeuwin Current peaks during the austral autumn and winter and weakens in spring and summer, consistent with observations. The Capes Current (northward flowing along the coast) in the model is strongest in spring and summer, however with weak magnitude. The core of the Leeuwin Current in BRAN is slightly more offshore during the summer period.

Figure 2.4 shows the seasonal variations of zonal flow field along 110°E. Onshore (eastward) flows exist generally north of 32°S, to feed the Leeuwin Current. In most seasons, the onshore flows tend to have a banded structure, such as during July-September, the onshore flows mainly occur north of 25°S, near Abrolhos, and north of Perth (32°S) and there is a dominantly offshore flow near 26°S off Shark Bay. These intense onshore flows may provide pathways for phyllosoma to move back to the shelf regions.

During the austral spring and summer seasons, northward wind fields are important to drive northward and offshore (westward) surface transport (Figures 2.5 and 2.6). This coincides with lobster larvae release period, when the pelagic lobster larvae need to move offshore to develop and to avoid potential predation and mortality on the shelf. Conversely in the late winter season, the westerly winds may facilitate the movement of late stage phyllosoma back to shoreward for them to metamorphose to puerulus and settle in the coastal habitats (Figures 2.5 and 2.6). The sensitivity of the model larvae to the magnitude of the wind-driven surface current correction will be assessed in the future project.

The open ocean waves (swells) off the west coast of WA mostly arrive from southwest and south-southwest directions, due to storm activities in the Southern Ocean, as derived from the WW3 outputs (Figure 2.7). The significant wave heights are less than 3 m off the coast in January-March, and are strongest (4-5 m) during the July-September season when puerulus start to settle off the west coast (Figure 2.7).

These seasonal variations are reflected in the wave-induced Stokes drift velocities, averaged in 0-20 m (Figure 2.8). In the summer months, the Stokes drift velocities off the west coast are weakly northward. From April-June, the Stokes drift velocities show a strong northeast component off the lower west coast, and typically peak in July-September period.

BRAN also captures the seasonal variations of the temperature structure in the Leeuwin Current region (Figure 2.9). However in using the sea surface temperature (0-20 m average) to calculate the growth rate and mortality of phyllosoma, we acknowledge that during the austral summer, there are 2-4°C differences between the surface and 100 m temperatures, as shown in BRAN model outputs (Figure 2.9), which could have significant impacts on model larval growth and survival. This is an issue that will need to be futher investigated in the subsequent longer-term modelling project.

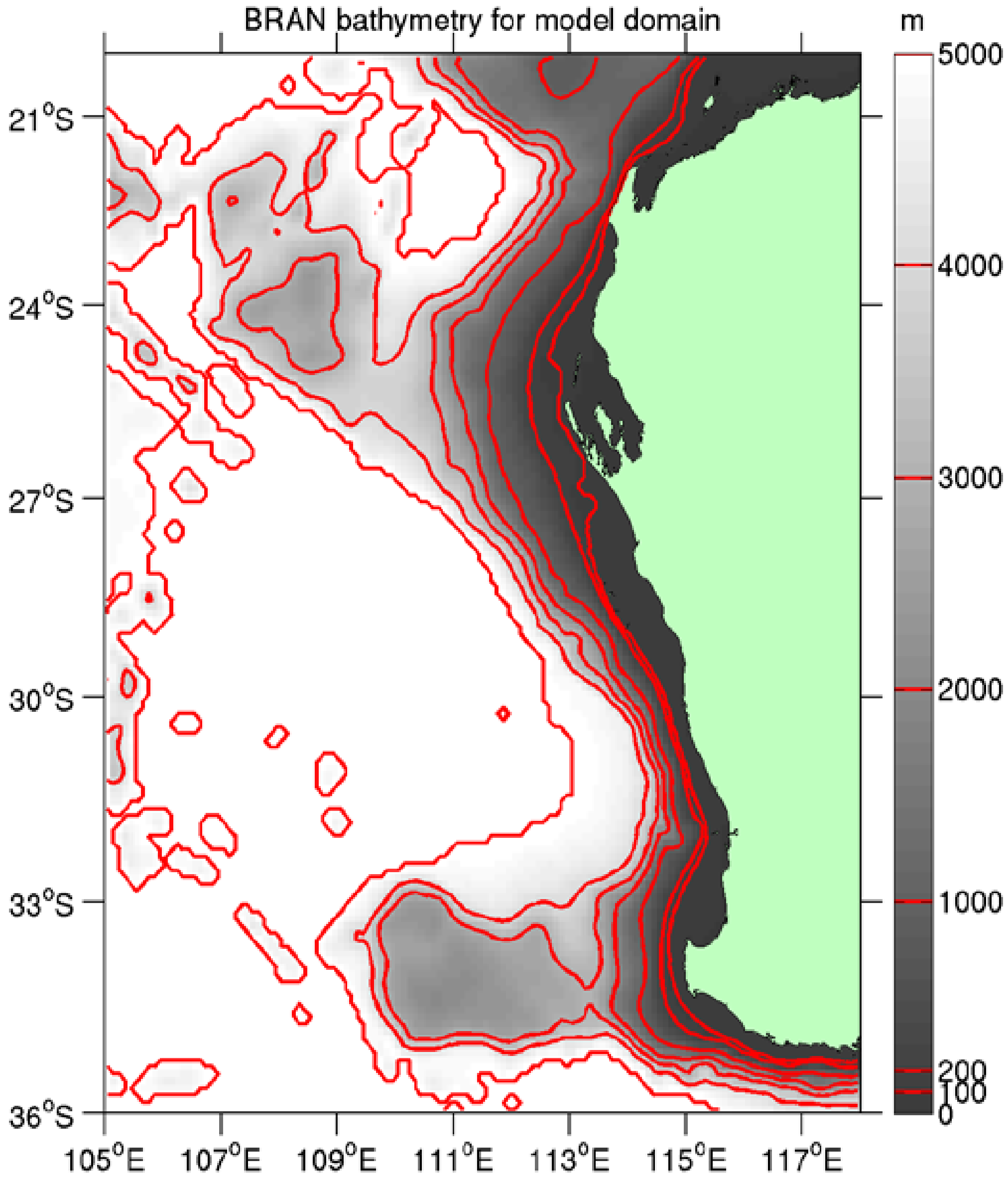


Figure 2.1. BRAN model domain and bathymetry off the west coast of WA.

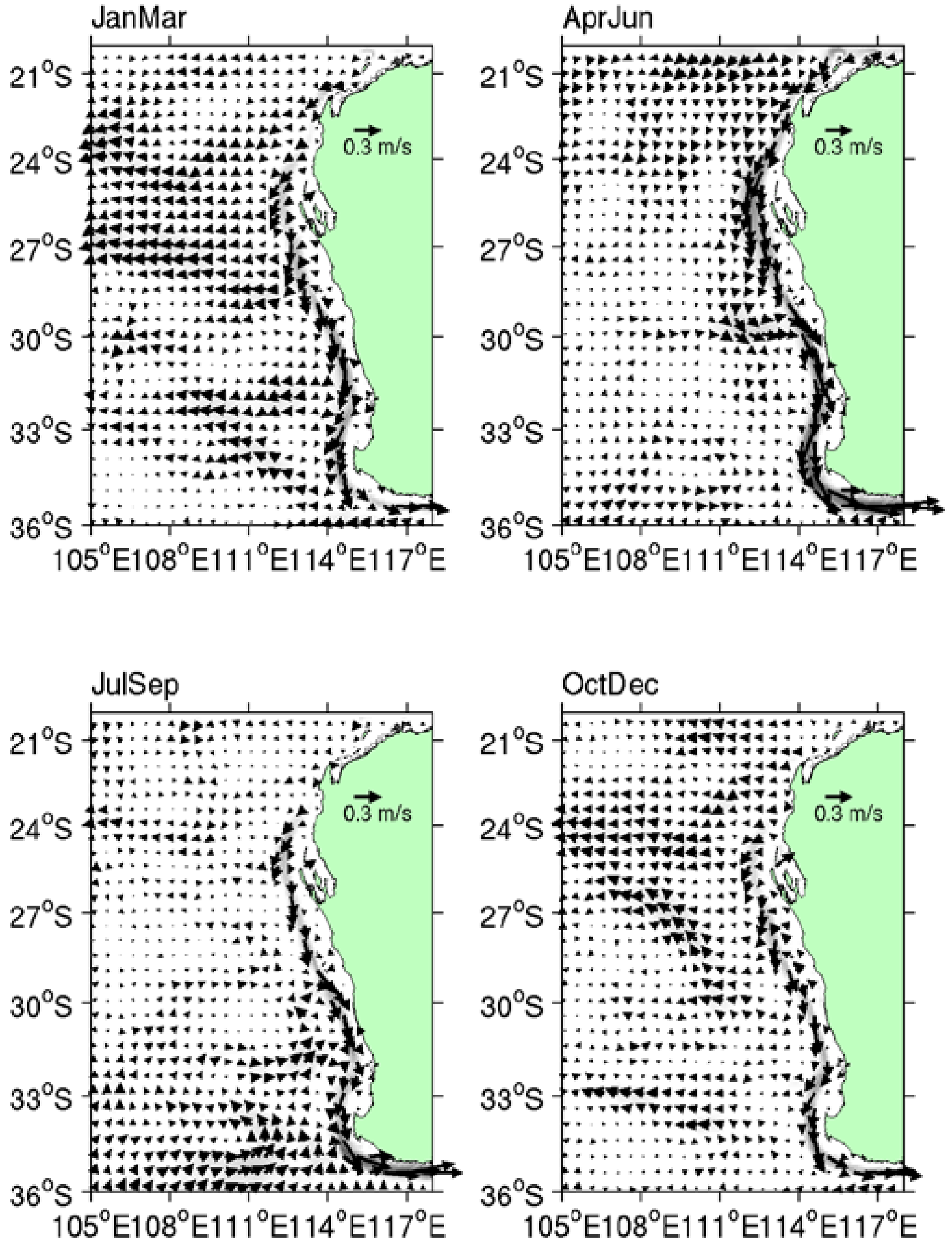


Figure 2.2. Seasonal cycle of BRAN surface (0-20 m) velocity field averaged over 1993-2008.

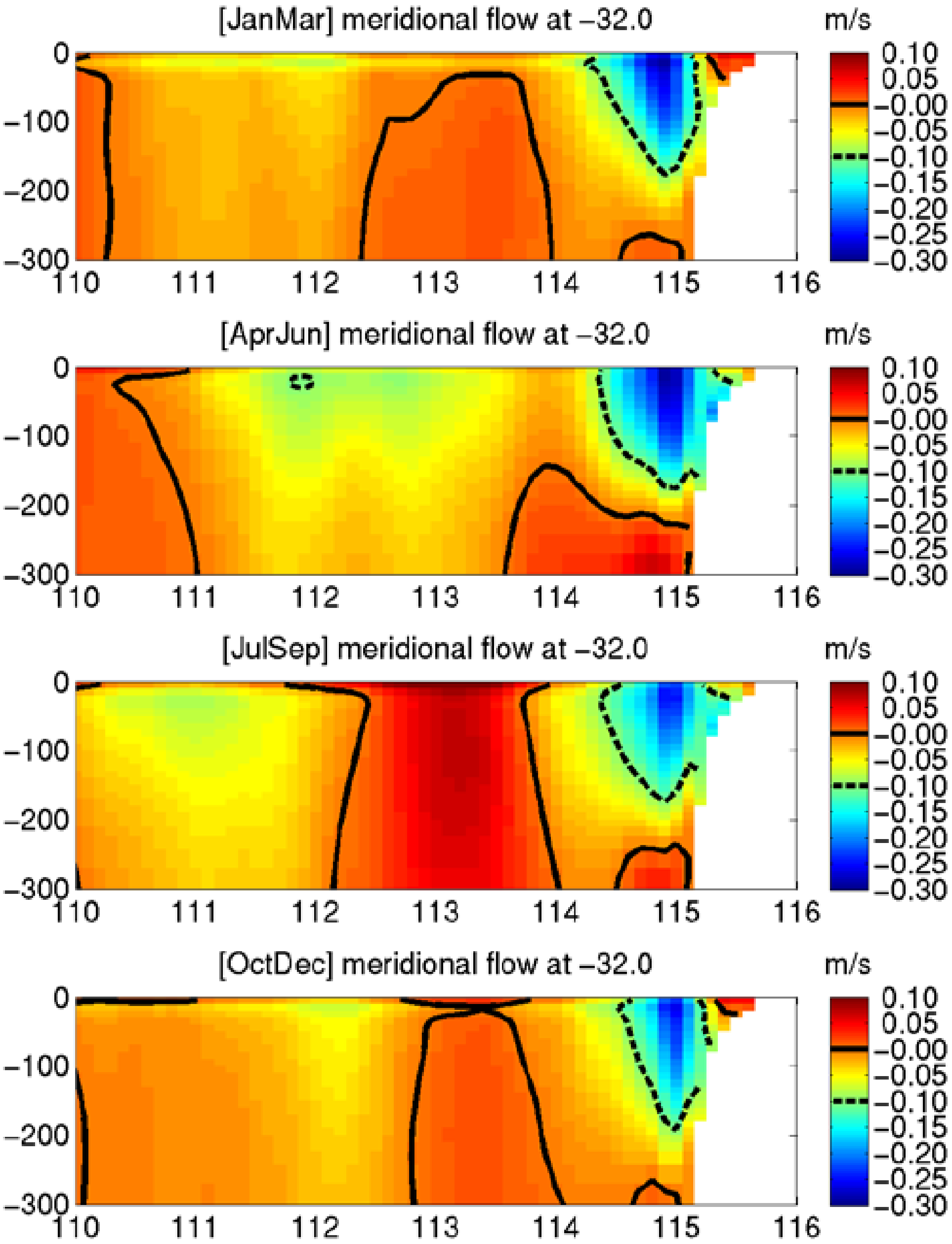


Figure 2.3. Seasonal cycle of BRAN meridional current at 32ºS (0-300 m) averaged over 1993-2008. Positive values are northward velocities.

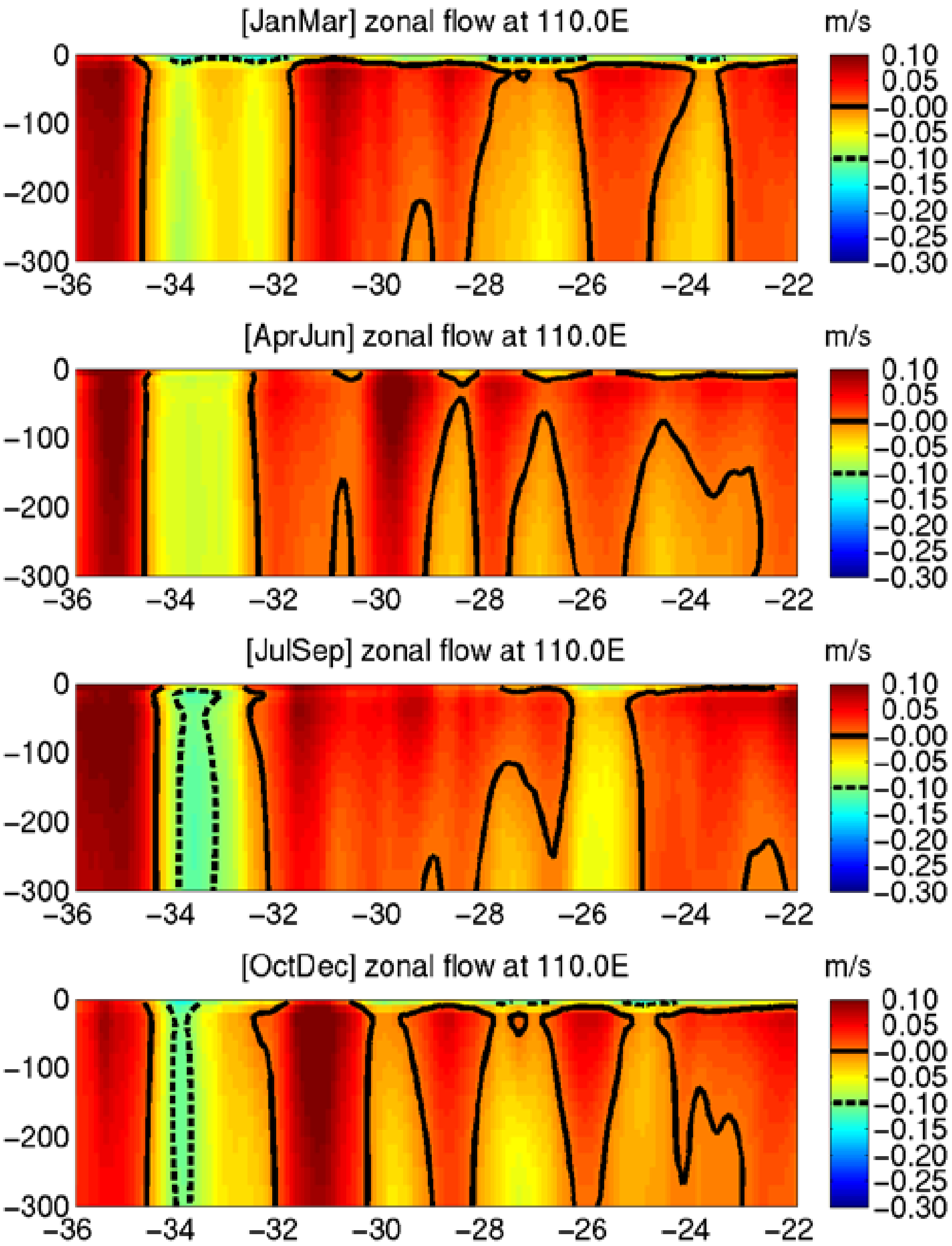


Figure 2.4. Seasonal cycle of BRAN zonal current at 110ºE (0-300 m) averaged over 1993-2008. Positive values are eastward velocities.

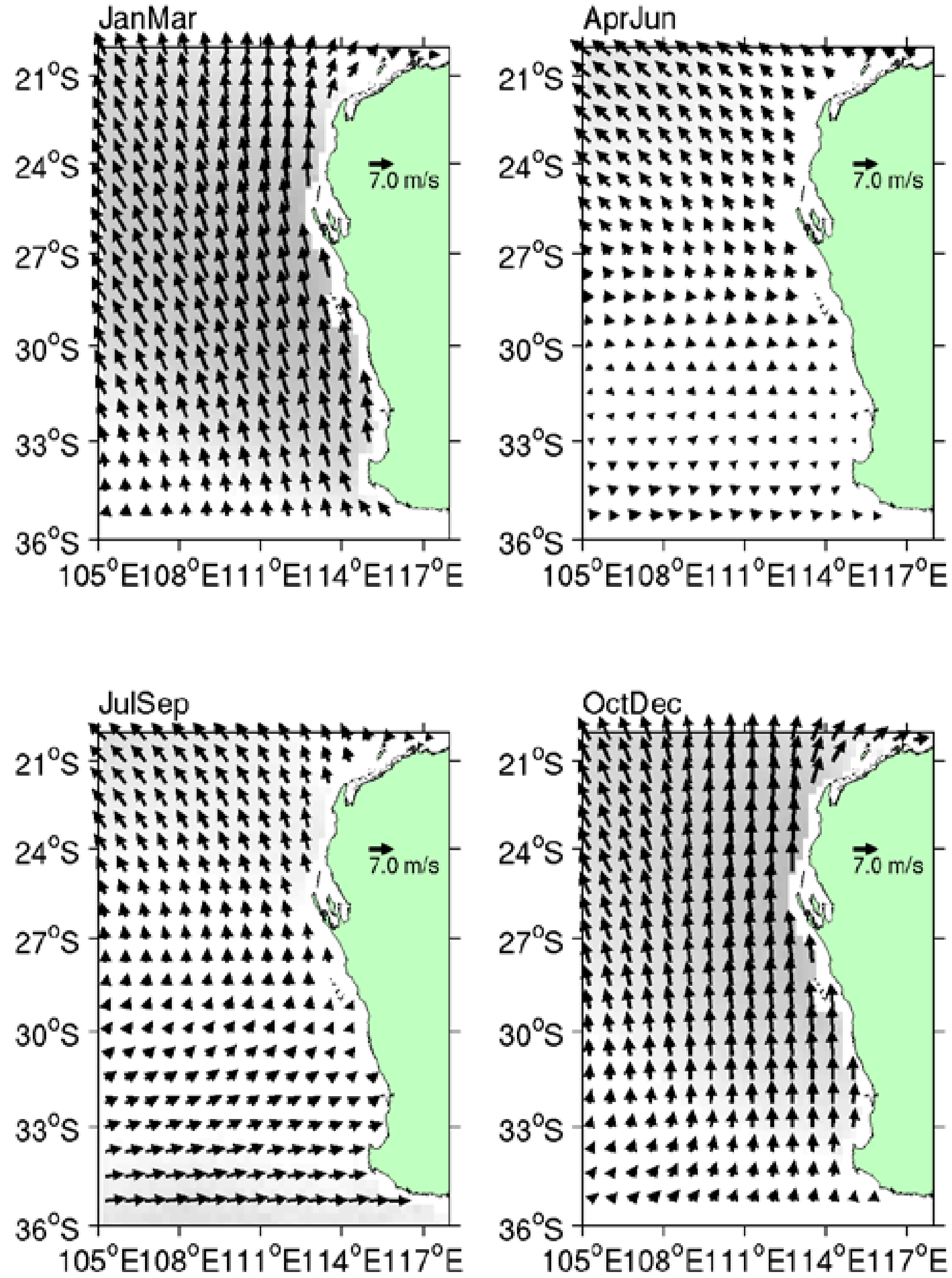
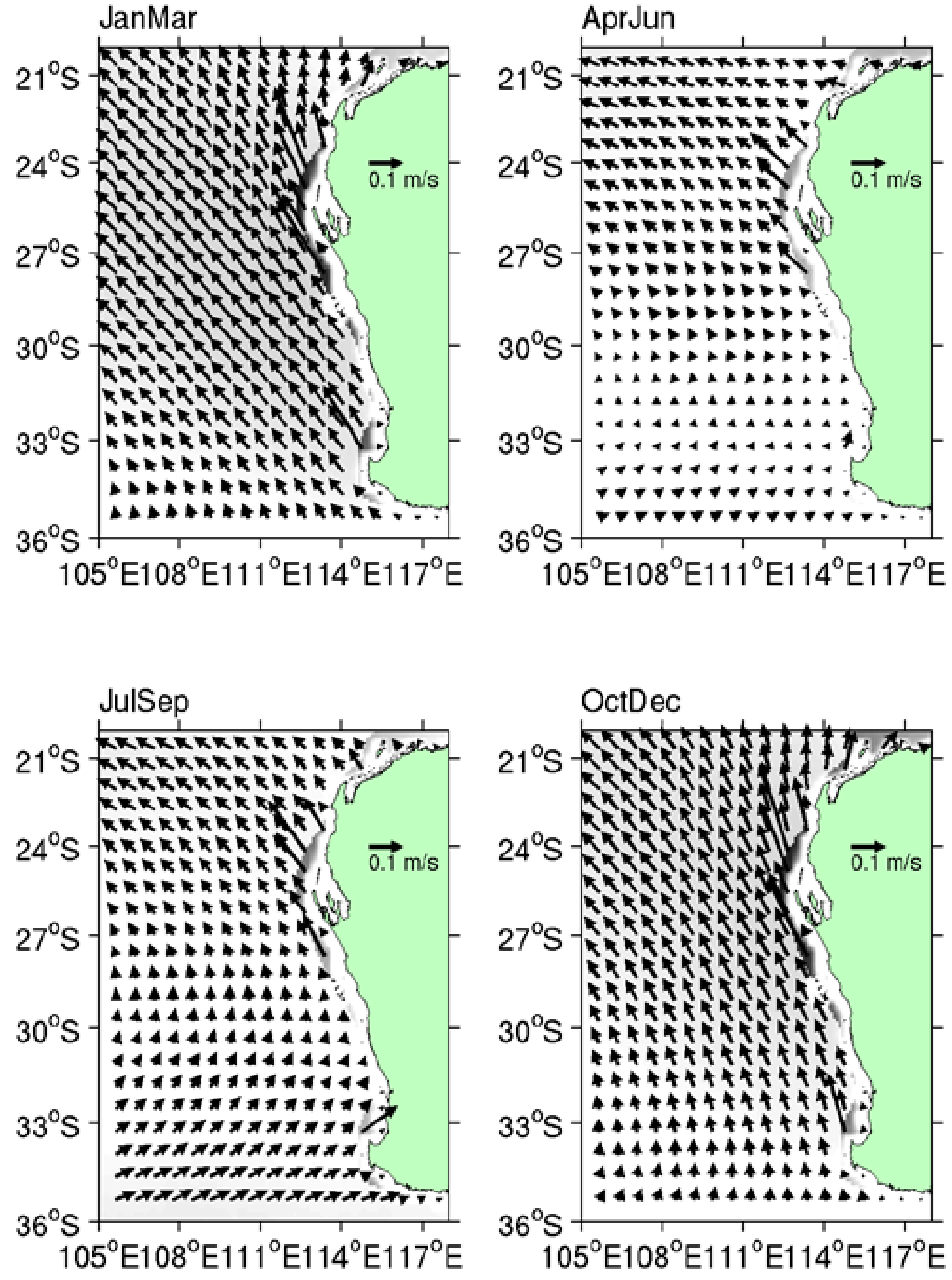


Figure 2.5. Seasonal cycle of Scatterometer winds averaged over 1999-2008.



JanMar

AprJun

JulSep

OctDec

Figure 2.6. Seasonal cycle of Scatterometer wind-derived surface current averaged over 1999-2008.

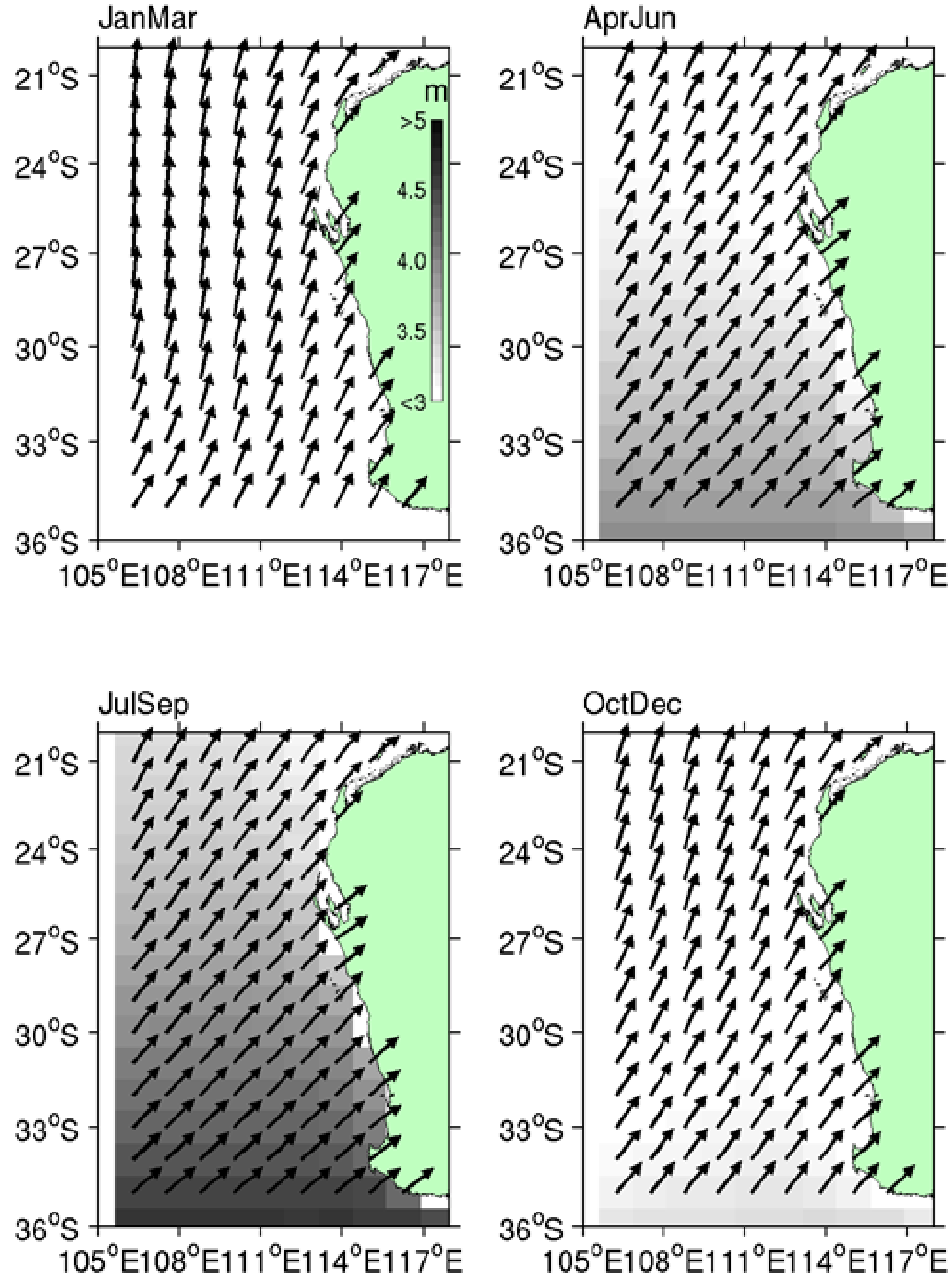


Figure 2.7. Seasonal cycle of WW3 significant wave height and direction averaged over 1999-2008.

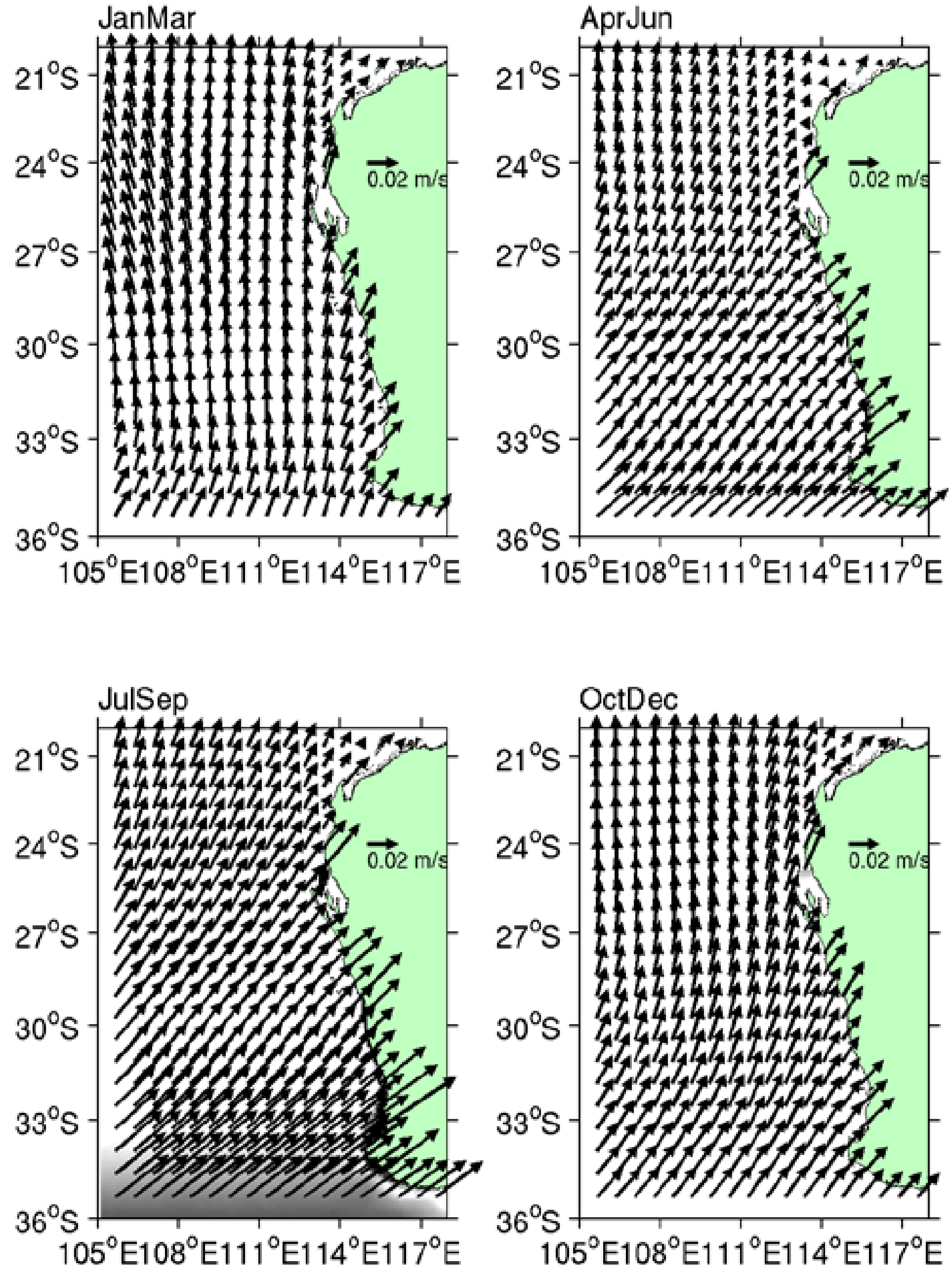


Figure 2.8. Seasonal cycle of wave-induced Stokes drift current (0-20 m) averaged over 1999-2008.

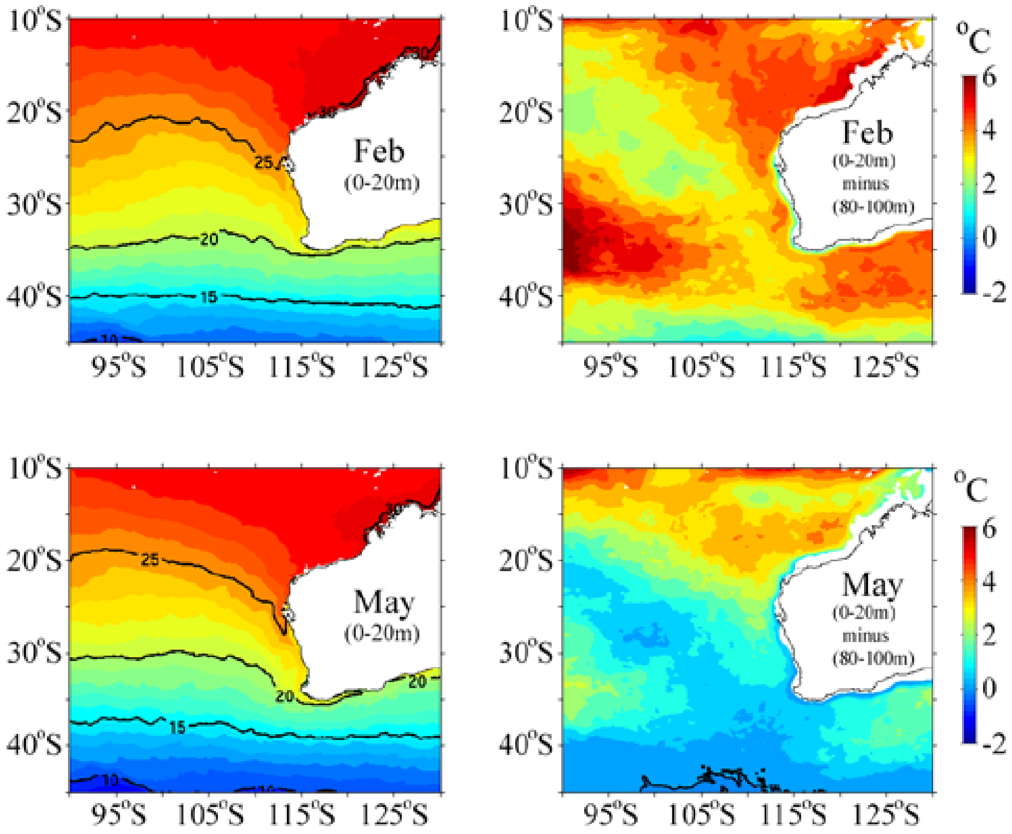


Figure 2.9. BRAN surface temperature (°C) in 0-20 m in February and May averaged over 1993-2008 and their difference with 80-100 m average temperatures.

3.0 Individual-based larval model

The purpose of this section was to review the relevant literature and data available on rock lobster spawning stocks, the phyllosoma larvae and puerulus, and from this review to develop improved biological parameters for the 2009 larval advection model (referred to as the stage 1 or 2009 model), which is an updated version of the previous Griffin *et al.* (2001) model. This chapter also includes some suggestions for additional biological parameters and ranges of parameter values, which could be incorporated in future more complex models.

3.1 Hatching of phyllosoma

3.1.1 Phyllosoma hatching pattern/season

The most comprehensive data on the monthly pattern of spawning is from Chubb (1991), which provides a full year snapshot of spawning activity from a site in each Zone of the fishery. Some data from the following year is also presented, which suggests that significant yearly variation may be occurring. This difference between years is also likely to include some sample variation in the monthly catch rates at each site.

The Chubb data on monthly catch-rates of berried females, lagged by a month, does however provide a reasonable first approximation for a pattern of larval hatching for each zone. An average across the whole fishery has also been created (Table 3.1) to provide a general fishery wide pattern. This use of a one-month lag to convert the observed pattern of berried female abundance to larval hatching/release, assumes that the berried females observed are on average, part way through the cycle, which takes about 6 weeks to complete.

While the Chubb data is useful for the general spawning and hatching patterns, further investigation of the annual variability in the spawning/hatching period, is required. This potential for significant annual variability in the timing of the spawning/hatching season was first suggested by Chittleborough and Thomas (1969) who reported significant year to year variation in the presence of early stage larvae and suggested that early hatching in some years may explain the presence of more advanced stages i.e. V and VII early in the year [i.e. Feb 1968]. There is also likely to be significant variations in the timing of the hatching season in the different sections of the fishery, as suggested by the above data from Chubb (1991). Further data on annual variation in hatching may be required, particularly if the initial revised model proves sensitive to this factor.

2009 model development

The phyllosoma are being released in the model at a constant daily rate from 16 October to the 15 March, to cover all of the typical spawning/hatching period (Chubb 1991). This approach increases the efficiency of the model process and allowed for the seasonal hatching pattern to be incorporated and varied through the post model analysis.

Post model analysis

In post-model analysis the model outputs were weighted by the fishery-wide monthly hatching percentages (Table 3.1), to reflect the fishery-wide averaged monthly hatching rates.

Future model development

While the data on spawning for each zone from Chubb (1991) do not give any information on inter annual variability, it would be reasonable as a first step to allow the peak for hatching in model to variy by two weeks in either direction for the purposes of sensitivity testing. This level of variation is in keeping with preliminary analysis of fishery monitoring data (S. de Lestang pers. comm.), which suggests that the onset of spawning and hatching is related to the preceding winter temperature.

Sensitivity testing using post model analysis, could also be used to further assess the impact on model settlement of the annual variations in the pattern and timing of the peak of release in each zone. For this purpose the timing of hatching each year may be able to be estimated from the independent breeding stock survey (IBSS) data sets (for the start of the hatching season) and data from commercial monitoring time series (for the end of the hatching season).

3.1.2 Phyllosoma release depths

Spawning female lobsters through the main coastal fishing areas are typically found on offshore reef bottoms which generally occur in depths from about 40 to 80 m (Melville-Smith R, de Lestang S. and Thomson A. 2009). These reef areas are narrow bands corresponding to old fossil shorelines, which occur at varying depths out to about 80 m, although in some offshore locations north of the Abrolhos, reefs occur down to about 140 m (i.e. in the Big Bank area, Chubb *et al*. 1994). The exceptions to this general depth distribution of spawners is at the ends of the species distribution and at the Abrolhos Islands. In these sections of the coastline, spawners are found on shallow reefs including some very close to the coast, as well as on reefs in the normal depths further offshore (J. Penn pers. comm.). These areas include the Cape Naturaliste-Leeuwin coastline, throughout the Abrolhos Island groups, along the cliffs from Kalbarri north to the islands off Shark Bay and from Quobba to Ningaloo.

The spawners in the shallow waters of the Abrolhos Islands (Melville-Smith *et al*. 2009) and along the cliffs north of the Kalbarri also have a lower size at maturity i.e. below legal size. Detailed data is not available on reproductive sizes for the other shallow water spawning areas i.e. Shark Bay north or Cape Naturaliste South, however anecdotal reports suggest that spawning females in these areas are typically large and similar to the general offshore coastal stock. Some larger spawning females have been reported from shallower water closed areas around Rottnest Is. Many of these sections of the coastline are co-incidentally areas heavily influenced by the Leeuwin Current in winter.

2009 model development

In the 2009 model, western rock lobster larvae are released uniformly along the coast i.e. at every 0.1° (10 km) along the coast between latitudes 22°S and 35°S covering the range of the stock. At each 0.1° of latitude, larvae are also released at three depths, 40, 60, and 80 m, except in the Big Bank area north of the Abrolhos Islands, where they are released in about 100 m, instead of 80 m (Figure 3.1). That is, 10 larvae are released daily at each of the grids (crosses or pluses in Figure 3.1).

Post model analysis

The post model analysis has been used to compare the model puerulus settlement success rates for each of the three release depths.

Future model development

As the current model outputs appear to be sensitive to the depth of release, specific fishery data on the relative abundance of spawners with depth may be required for incorporation in future models. Later models may also need to be adjusted to allow for release depths below 20 m (shallowest water depth in BRAN) for the coastline above Kalbarri and below Cape Naturaliste, where spawning has been observed very close to the shoreline.

3.1.3 Phyllosoma releases by latitude

Catches of lobsters have been recorded from about NW Cape in the north to Cape Leeuwin/ Windy Harbour in the south (Chubb 1991) and spawning females can be expected through out this range. While commercial catches have taken historically from about 22°S (Coral Bay) to 34.5°S (Cape Leeuwin), the catches from areas south of Cape Naturaliste and North of South Passage, Shark Bay have historically been low and very variable relative to the main area of the fishery i.e. between 27°S and 34°S. This suggests that breeding stocks in these outer areas are unlikely to have significantly contributed to population egg production on a regular basis.

2009 model development

In the 2009 model, hatching phyllosoma are released every 0.1° (10 km) along the coast (22-35°S), at each of three depths, 40, 60, and 80/100 m (Figure 3.1). At each of these grids in the model, 10 larvae are evenly released daily (i.e. at each of the grids shown as (crosses or pluses in Figure 3.1).

Post model analysis

Post model analysis has been used to compare the impact on model settlement, of latitudinal position of release and from each of the three management zones as part of the source-sink assessment.

Future model development

In the follow up project, detailed data on the latitudinal pattern and numbers of phyllosoma released each year could be a useful addition to the model. This data could bederived from the historical logbook data base records and from population dynamic model outputs for the fishery, and used to more accurately scale the model outputs for the post-model analysis process.

3.2 Phyllosoma/puerulus durations

As a result of the numbering system, stages I to IX used to describe the nine development stages in the phyllosoma phase of the life history (Braine *et al.* 1979) and the use of 'stage' to describe the 3 broader categories of phyllosoma [Stages I—III, IV—VI, VII—IX] by Griffin *et al.* (2001) there is increasing potential for confusion in the numbering terminology i.e. relating to what a larval stage number represents in the models. To avoid this potential problem, in this modelling project the grouping of phyllosoma larval stages are referred to as Category A, B, and C phyllosoma, with development stage numbers used to distinguish stages in the model where needed, i.e. A1 for newly hatched phyllosoma (i.e. stage I). Similarly, the two stages for the puerulus i.e. natant [or swimming] have been designated as category D1 and the settled stage as D2.

The main data for assessing the duration of each phyllosoma stage and puerulus is from Chittlebrough and Thomas (1969) and Phillips *et al.* (1979). The modal progression data throughout the year in each of these papers has been used to show the approximate times spent in each phyllosoma stage (I to IX) and to suggest that the typical time from hatching to puerulus settlement was about 9 to 11 months. In using these two data sets, more reliance has however been attached to the average times shown in the Phillips *et al*. (1979) data, as the Chittlebrough and Thomas (1969) sampling was not able to cover December, and late-hatched larvae i.e. from February, and did not appear as expected in their samples in March, April or May. The combination of 5 years data from more regular sampling reported in Phillips *et al* (1979) is therefore considered to provide the more reliable average timing for phyllosoma development.

These data together with the monthly pattern of puerulus settlement in those years (Phillips and Hall, 1978) also provides useful data on the possible range of times taken from hatching to settlement. That is, the earliest and latest significant puerulus settlement in those years was typically from August to February or March, which would correspond to a minimum and maximum development times ranging from 8 months (240 days) to about 14 months (420 days). This potential for an extended larval duration is also supported by the presence of some late stage IX phyllosoma and puerulus between July and March in the Chittlebrough and Thomas (1969) samples, relative to the relatively fixed hatching period December to March.

These survey data (Chittleborough and Thomas 1969, and Phillips *et al*. 1979) also suggest that the growth period for each stage may be quite variable, particularly the duration of stages VII to IX (Note: stages V and VI were rarely caught). That is, stages I to IV are present in the survey samples over about 3 months, which corresponds to the duration of the spawning season, while stages VI, VII, VIII and IX occur in the samples for 5, 7, 6 and 4 months respectively. These variations in the numbers of months that each stage is present, suggests that individual phyllosoma may also spend a variable amount of time in each stage to create the observed monthly distributions. Alternatively the increasing spread of stages with time may simply reflect annual variability and the use of combination data presented covering five years. If the variability is real, it would most likely relate to the timing of hatching and the effects of temperature on growth during the autumn period.

For this project, it has also been assumed (based on the work of Lemmens 1994) that about 21 days are required from metamorphosis to puerulus settlement on the coast. This survival time assumes that the puerulus are swimming intermitently rather than continuously after metamorphosis.

In addition, category A phyllosoma in the model have been separated into A1 (stage I) and A2 (stage II and III) to allow for different behaviour by the newly released phyllosoma. A1 being one of three stages is also assumed to take one third of the time to develop.

2009 model development

In the 2009 model, the phyllosoma/puerulus stages are divided into five categories: three for phyllosoma and two for puerulus. The average duration or growth periods for each phyllosoma stage in the model approximate to the field observations from Chittlebrough and Thomas (1969) and Phillips *et al*. (1979). The phyllosoma durations are also made temperature dependent (see Section 3.4) in the model. For the swimming puerulus (D1), which do not feed or grow, the model duration has been fixed at a maximum of 21 days.

The specific average durations used in the 2009 model (Table 3.2), are as follows:

- Category A larvae (stages I, II, III phyllosoma in classification) have an average development period of 90 days;
    - Sub-category A1 has an average period of 30 days (stage I)
    - Sub-category A2 has an average period of 60 days (stages II and III)

- Category B larvae (stages IV, V, VI phyllosoma) have average development period of 60 days;
- Category C larvae (stages VII, VIII, IX phyllosoma in classification) have development periods of:
  - Sub-category C1 has an average period 120 days (stages VII and VIII);
  - Sub-category C2 represents stage IX larvae after finishing C1, can live up to 150 days, giving a total phyllosoma duration of 420 days;
  - At C2, the larvae are capable of metamorphosing into puerulus, if they cross continental shelf break (less than 200 m)
- Model puerulus: can live up to 21 days after metamorphosis, or until they settle in near shore areas in the model, i.e. enter water depths shallower than 40 metres.

(Note: the above periods are different to those used in Griffin *et al*. (2001), which were 50 days, 35 days and 185 days for Categories A, B, and C respectively. These, shorter periods were an attempt to take into account the expected faster rate of development by an individual, compared with the average development time estimated from modal progression, which would be biased by natural mortality (D. Griffin pers. comm.).

Post model analysis

A comparison of the rate of successful settlement between puerulus with average development durations and those with delayed development times has been undertaken.

Future model development

In future models the constraint on the maximum phyllosoma duration of 420 days could be relaxed further and the effect assessed through sensitivity testing. Similarly the 21-day survival for puerulus could also be further assessed.

3.3 Phyllosoma/puerulus behaviour

3.3.1 Phyllosoma vertical diurnal movements

For the diurnal vertical migration patterns of phyllosoma, the most comprehensive data set for *P. cygnus* is from Rimmer and Phillips (1979). This paper provides diurnal depth profiles for early, mid and late phyllosoma stages based on detailed 24-hour depth stratified samples taken at times of new and full moon. Very useful data on the impact of sea conditions on vertical distributions, although not a controlled variable in the study, is also provided.

From a review of the *P. cygnus* literature it appears that Stage I phyllosoma may have a different response to daylight and spend more time close to the surface than stages II and III (Ritz 1972, Rimmer and Phillips 1979). A more detailed assessment of the field data on the early stage phyllosoma (Rimmer, 1980), suggested that the stage I phyllosoma are on the surface at night and descend to 30-60 m during the day. Offshore movement by this stage was estimated to occur at a rate of about 5 km per day and easterly wind driven surface currents were suggested as the mechanism. To accommodate this behaviour of the stage I phyllosoma and its potential to interact with wind-driven surface currents, it would be preferable to treat these larvae as a separate category from stages II and III in the model. The above papers also report that phyllosoma vertical movement speeds increase with stage/age and the development of swimming appendages.

The above literature also indicates that all phyllosoma categories move into the very surface layers [less than 20 m] at night, and tend to concentrate in the upper few metres, particularly under calm conditions. This nocturnal pattern was however, also found to bo be affected by moonlight and sea conditions Rimmer and Phillips (1979). For the modelling of larval advection the influence of both moonlight and sea conditions on the pattern of larval depth distribution, particularly at night, ideally needs to be factored in to the phyllosoma depth distributions.

The approximate day and night depth ranges and depth of peak abundance appropriate to each model category set out in the Table 3.1 have been generated from the figures presented in Rimmer and Phillips (1979), using the combined data from both dark and moonlight samplin.. From the Rimmer and Phillips (1979) information it also appears that the phyllosoma descent and ascent during the daylight follows an arc reaching a maximum in the middle of the day. However for modelling purposes, it may be necessary to consider the ascending and descending phases as four-hour periods, and assume that the transition depths for the model animals will simply link the estimated day and night depth ranges as shown in Table 3.3 and Figure 3.2 (adapted from Griffin *et al*. 2001).

2009 model development

For the 2009 model it has been assumed that the larvae will spend 8 hours on the surface at night (2100hrs to 0500hrs), 4 hours descending to daytime depth (0500hrs to 0900hrs), 8 hours at depth during the day (0900hrs to 1700hrs) and 4 hours ascending in the evening (1700hrs to 2100hrs). This simplification used to reduce complexity and computing time also involved an assumption that the depth transition was taking place evenly during the 4-hour period.

The exception to this is model category A1, which spend all of their time in the surface 20 m-layer (Table 3.3) to approximate a positive phototactic response (Ritz 1972). A diagram illustrating the diurnal migrations of the model larvae in the different Categories is presented in Figure 3.2.

Three vertical profiles of larval distributions in the upper 20 m are also used when applying wave-induced Stokes drift movements (Figure 3.3). Distribution I assumes evenly distribution of larvae in the surface-20 m layer, while Distributions II and III have exponential vertical distributions by assuming larvae have skewed distribution towards the sea surface.

The 8-hour/4-hour block distribution approach to depth simplifies the model, but may underestimate the daytime depths. Also to simplify the model the potential effects of changing moonlight levels, which are also significant during full moons (Rimmer and Phillips 1979), but unpredictable due to cloud cover, have not been incorporated in the diurnal movement patterns (see future model development section).

Post model analysis

Not applicable

Future model development

In future models the daytime depth trajectory would ideally follow an arc from dawn to dusk, rather than a step function. Also for future models the effects of moonlight on phyllosoma could be directly incorporated. However, because there are limited data on moon light effects on phyllosoma depth distribution in Rimmer and Phillips (1979), i.e. only for categories A, C, and puerulus catches were very low, these changes in model depth distributions during the lunar cycle will be used in a sensitivity analysis.

While the theoretical moonlight levels may be able to be predicted directly from lunar tables incorporating moonrise / set times, they will need to take into account cloud cover. Sea state effects on the model phyllosoma categories may also be incorporated using the wind or wave predictions from the model and the behaviour 'typical' depth distribution patterns suggested by Rimmer and Phillips (1979). As these patterns were only recorded for category A and C, some assumptions will be required to incorporate category B and D animals in the model.

3.3.2 Phyllosoma diurnal behaviour- moonlight effects

The effect of moonlight level on the night-time phyllosoma depth distribution has been explored in detail by Rimmer and Phillips (1979). This paper showed that moonlight had little impact on early stages (category A), but significant effects on category C phyllosoma (category B data were insufficient to assess). Category C phyllosoma were distributed close to the surface, mostly above 10 m (pattern A) when moonlight was <5% of full moon level, and distributed deeper i.e. from 10 to 40 m when moonlight was >5%. Depth distribution was also found to be affected by sea state, with the deeper more uniformally dispersed patterns also being linked to both moderate seas and moonlight >5%. As high moonlight levels occur only during full moons periods which account for less than 25% of days, and are reduced by cloud cover and moon rise times etc., this effect on phyllosoma depths at night will have a relatively limited impact and only during the full moon periods.

2009 model development

As the effect of moonlight on phyllosoma depth distributions is likely to be limited to the short full moon periods each month and is likely to have a relatively constant effect across years, it has not been incorporated in the 2009 model to simplify development.

Post model analysis

Not applicable

Future model development

The potential impact of moonlight on model phyllosoma distributions should be further assessed through sensitivity testing. Although moonlight level could be relatively easily incorporated in future models as it is predictable, it would need to be adjusted for cloud cover. Incorporation of moonlight level in the models has the potential to move the phyllosoma depth distributions to slightly deeper levels at night but may also result in the daytime depth arc being moved downward during the full moon periods. However these deeper distributions during full moon periods are likely to be consistent from year to year and therefore unlikely to contribute significantly to interannual variability in model settlement.

3.3.3 Phyllosoma diurnal behaviour-sea state effects

The sea state has been shown to have an impact on phyllosoma depth distributions (Rimmer and Phillips 1979). This appears to be most significant at night when the larvae are concentrated near the surface. Because sea state was not a 'controlled' factor in the field surveys, less data on sea state effects is available compared with the effect of moonlight. Rimmer and Phillips (1979) were however able to show that moderate to rough seas at night resulted in some mixing of the larvae through the surface layers, which were typically distributed from the surface down to about 40 m, under these conditions. This effect of sea state was most evident for category A. phyllosoma. The effect of sea state, in redistributing the larvae away from the surface at night appears to be due to turbulence from wave action simply redistributing the phyllosoma through the turbulence zone. Because this effect appears to be less on the later stages (category C), it is likely that their increased mobility allows them to maintain their preferred surface depth distribution against the water movements.

As an approximation for average sea state, the numbers of samples under the different sea conditions obtained by Rimmer and Phillips, during their extensive survey is suggested as an approximation for typical sea conditions experienced by the phyllosoma over a year. For example, the sea state conditions encountered during their surveys were: calm-70, samples, moderate-75 samples, and rough seas-57 samples. These data suggest that sea conditions from hatching [Dec.] to peak settlement [Sept/October] are more often in the moderate to rough categories i.e. approx 65% of the time. Secondly, the estimated 65% is likely to be a minimum, as sampling would only have been curtailed during rough seas. The larval night distributions are therefore more likely to be affected by moderate/rough sea conditions. For this reason it is suggested that the initial model trials could as a first step, assume that all larvae spend the night in upper 50 m [average at 30 m depth] rather than try to incorporate the moonlight effect in calm seas which brings them closer to the surface. Later modelling could attempt to incorporate both moonlight/cloud cover and sea state effects on depth distribution. Future modelling could also consider incorporating variable day/night length to match the annual changes in day length.

A further issue to be considered in the model is the daylight depth distribution. The field survey data suggests that the phyllosoma follow an arc pattern from dawn to dusk and that the reported swimming speeds would allow maximum depths to be reached of about 110 m, 140 m and 160 m for early, mid and late stages respectively. These maximum depths are below the maximum depths shown for the bulk of the phyllosoma caught in the field surveys, but correspond approximately to the bottom of the main distribution of the phyllosoma in the field surveys based on an assumed average starting depth of about 10 m at dawn. Because the maximum depths achieved are dependent on the starting depth at dawn, which varies with sea state, the daytime depth distribution is one aspect of the phyllosoma behaviour in the model that could usefully be sensitivity tested. If the average dawn starting depth is 30 m due to moderate/rough sea conditions, then the phyllosoma may reach depths of 130 m, 160 m and 180 m at early mid and late stages. The survey data is more likely to reflect calm seas noting that rough seas are likely to have limited sampling.

2009 model development

Although the sea state cannot be easily predicted or incorporated in the model, the typical phyllosoma depth patterns for different sea states in Rimmer and Phillips (1979) suggest that the surface distribution for all stages at night should be pattern C, reflecting the moderate to rough sea state most typically encountered. These night depth distributions are used to reflect wave driven turbulence in the surface layers. The depth distributions assumed in the model for each phyllosoma category are presented in Table 3.3

Post model analysis

Not applicable

Future model development

In future models the sea state may be able to be predicted from the wind/wave inputs to the oceanographic models, and used to directly adjust the depth distributions in line with the patterns reported in Rimmer and Phillips (1979).

3.3.4 Phyllosoma metamorphosis triggers

A recent review (Phillips and McWilliams, 2008) of the process and locations where phyllosoma metamorphose to puerulus, has suggested that most puerulus are found near or on the shelf break, although some were caught out to several hundred kilometres. This suggests, that either the moult/metamorphosis to puerulus is triggered when the late stage [IX] phyllosoma are carried close to the shelf break, or that moulting occurs more widely but the resulting puerulus if they are well offshore, are quickly lost through natural mortality, and only those moulting close to the shelf are likely to survive.

Based on the information from both the field and laboratory [mostly aquaculture] studies, the most likely hypothesis for the trigger for metamorphosis to a ‘successful’ puerulus is the nutritional state of the late stage [probably VIII and IX] larvae. That is, the late stages have encountered sufficient food to feed and build up energy reserves [lipids] that will sustain the puerulus for the duration of the period needed to travel across the shelf and settle in a nursery habitat. This hypothesis leads to the suggestion that successful metamorphosis for *P. cygnus* is linked to and mostly occurs in areas with a high biomass of plankton such as the edges of the Leeuwin Current [(Phillips and Pearce, 1997]). This paper shows a reasonable association between late stage phyllosoma, biomass of food species and puerulus in the area off Geraldton. More recent data on chlorophyll levels from satellite monitoring, suggests that these levels are highest in the late winter/spring period when puerulus settlement is peaking. At this time the levels are also greatest on and along the edge of the shelf (200 m) (Feng *et al*., 2009), which would fit in with the food trigger hypothesis and metamorphosis occurring close to or on the outer shelf.

In the previous model (Griffin *et al*., 2001) very precise criteria for the stage IX phyllosoma to metamorphose [moult] to puerulus were applied. Two scenarios were used for the trigger, the first being for all phyllosoma to moult to puerulus at 270 days, while the second scenario allowed the phyllosoma to metamorphose after 270 days, but only when they encounter the 2000 m depth contour [edge of continental slope]. Once metamorphosed, the Griffin model puerulus swim east at 10 cm/sec, in addition to being transported by the surface current at night and middle layer during the day. If they reached water shallower than 100 m within 3 days of a full moon, they were counted as settled. If the currents carried them offshore, they were allowed a further month to settle i.e. to reach the 100 m depth contour, or would die.

However the limited range of ages i.e. between 270 and 300 days as the window that stage IX larvae can successfully metamorphose to puerulus used by Griffin *et al*., (2001), appears to be overly limiting on survival/settlement. Based on the presence of *P. cygnus* puerulus in most months of the year, despite the restricted hatching season from about November to March. This suggests that the maximum larval duration can be extended to about 14 months. The extended larval time is most likely to occur in the later phyllosoma stages while the animal builds up reserves for metamorphosis, if the current hypotheses for the trigger are correct.

The hypothesis that successful metamorphosis to puerulus relates to a ‘factor’, which occurs at the outer shelf edge, is the model mechanism which was used by Griffin *et al.* (2001) i.e. the trigger for metamorphosis was the intersection with the 2000 m depth contour. While either the 2000 m or 200 m depth contours could be used as a proxy for the edge of the coastal high productivity zone on the continental shelf, the 200 m depth line is more closely aligned to the high productivity area of the shelf (Figure 3.5) than the 2000 m line, which extends much further offshore along some sections of the coastline particularly off Shark Bay and off Cape Naturaliste.

2009 model development

The triggers for metamorphosis to puerulus in the 2009 model are assumed to be both age and location related.

Age trigger: metamorphosis in the model is permitted at any age from 240 days to a maximum of 420 days after which any phyllosoma, which have not reached a trigger location would perish. These times correspond approximately to the minimum and maximum periods for phyllosoma survival estimated from the field survey based figures in Phillips *et al*. (1979).

Location triggers: All model phyllosoma at C2 are triggered to metamorphose to puerulus if they intersect the 200 m depth contour, i.e. providing they meet the above age criteria.

Post model analysis

No applicable

Future model development

In later models, the C2 phyllosoma could be allowed to metamorphose to puerulus before 240 days to allow for more rapid development of phyllosoma, which have encountered optimal temperatures through out their model life. Similarly, the 420-day limit on C2 could be relaxed further, as some puerulus are recorded on the collectors in most months of the year and may therefore survive beyond 420 days.

Sensitivity testing to assess the impact of alternative triggers for metamorphosis, i.e. based on proxies for food availability/nutritional status would be useful. Possible alternate triggers for C1 phyllosoma are:

1. Crossing the 1000 m or 2000 m depth isobaths,
2. A set period within a high chlorophyll zone, or in the Leeuwin Current or in a significant eddy.

3.3.5 Puerulus diurnal behaviour/migration

As a non-feeding stage it is generally (and reasonably) assumed that the puerulus does not need to move into the surface layers at night like the phyllosoma, which follow the zooplankton to the surface to feed.

Diurnal movements: Although relatively few puerulus have been taken in plankton tows, Phillips *et al*. (1978) have reported that puerulus were present at night during new moons off the shelf in depths from 0 to 90 m, but were most often caught at a depth of about 20 m. In equivalent night sampling on the shelf [seafloor depth about 25 m] they were caught in similar numbers (to offshore stations) during new moon and these were mostly taken at depths around 15 m. During full moon very few [2 only] were caught on the shelf and those were at similar depths to those caught on new moon. These low numbers of puerulus on the shelf during the full moon could be equally be explained by them remaining on the bottom during these periods, and probably during daylight. Attempts to bottom trawl for puerulus during the day were however unsuccessful leaving the question of daylight location open.

Inshore migration: The Griffin *et al*. (2001) model assumed that all puerulus would swim east at 0.1 m/sec, plus the current velocity in the surface layer at night and the middle layer by day. These parameters were simplifications of puerulus movement ability and survival times derived from lunar settlement information in Phillips and Olsen (1975) and from laboratory trials on nutritional reserves by Lemmens (1994). The hypothesis that puerulus swim continuously and directionally to the east, has led to Lemmens' suggestion of a very short duration of the natant [swimming] puerulus stage due to limited energy reserves. However, if the puerulus were not continuously swimming, Lemmens' work suggests that the survival would be much longer i.e. about 21 days compared with about 5 to 11 days under continuous swimming activity.

Active swimming to the surface, followed by transport by surface currents at night, and resting at depth or on the bottom during the day is therefore a realistic hypothesis to explain their shoreward transport and movement across the shelf to the near shore settlement areas over a longer period. This transport hypothesis would also accommodate the one observed very high catch of 24 puerulus on the surface at night during storm conditions, in a depth of about 100 m reported by Ritz (1972). Such a behavioural mechanism is also compatible with the puerulus catch rates recorded during a series of nights by Phillips and Rimmer (1975). Active swimming behaviour observed in Phillips and Olsen (1975) close to shore and near settlement habitats, is also in keeping with the hypothesis that puerulus are intermittently active [at night] rather than undertaking continuous swimming. Such a scenario would allow the puerulus to survive for much longer periods and to utilize the surface wind driven currents at night for migration purposes. During the settlement 'season' from August to November, the winds are typically southerly or onshore westerly, providing wind-driven surface currents, which would assist the puerulus to migrate across the shelf to the main settlement areas near the shoreline. Spring rainfall as a proxy for westerly wind fronts, has been shown to correlate positively with puerulus settlement (Caputi *et al.*, 2001) further supporting this hypothesis that wind-driven surface currents assist the puerulus shoreward migration.

It has also been suggested by a number of authors, that puerulus may have some directional swimming ability, which allows them to actively migrate across the shelf towards the coastline. This hypothesis has been investigated, (Jeffs *et al.* 2005), however no mechanism could be identified, which would allow the puerulus to navigate in the direction of the coastline. Directional swimming therefore remains a possibility, but needs to be further investigated before being accepted as part of migration process.

2009 model development

The diurnal depth ranges for D1 puerulus used in the 2009 model, are listed in Table 3.3, and are an approximation based on Phillips *et al.* (1978). In addition, the model puerulus are also assumed to swim toward the coast (i.e. 26 degrees north of east) during each 8-hour night, at a speed of 15 cm/s. This equates to about 4.3 km in 8 hours or 90 km in 21 days. These movements are modified in the model by the on shelf currents occurring during the 21-day period after metamorphosis. Any model puerulus, which does not cross the 40 m-depth contour to 'settle' during the 21-day period, will also perish.

Post model analysis

Not applicable

Future model development

Because the puerulus depth distributions in the literature are based on very small numbers caught in the surveys, some sensitivity testing of variations in the day and night depth distributions may be useful. The hypothesis that the swimming stage puerulus actively move to the surface at night during strong wind conditions should also be further investigated through linking time at the surface at night in the model to higher wind speeds.

3.4. Phyllosoma growth

3.4.1 Temperature growth relationships

Some basic information on the effects of temperature on the growth rate of the early larval stages [Category A or stage I—III] *P. cygnus* is available from Marinovic (1997). This study is mostly applicable to assessing the growth of the early stages (I to III), because of the difficulties experienced in growing the phyllosoma beyond that stage. That is, the 'health' of the later stages appears to decline and experimental data from growth trials at different temperatures appears to have become unreliable after about 40 days, when high levels of mortality typically began to occur in all treatments. Data from this thesis suggests that:

1. Growth from stage I to III took about 30 days at 25° C and increased to about 40 days at a temperature of about 20° C.
2. Survival was also higher at 25° C i.e. about 95% after 20 days, relative to 75% at 20° C.

More recent data on the growth rates of early stage P. cygnus is available from Liddy *et al.* (2004) who compared growth rates at 19, 22 and 25°C, with sufficient live food available that food did not alter/limit growth at any of the temperatures tested. Overall experimental mortality rates were similar to those reported by Marinovic (1997), although the experimental design did not involve holding batches of larvae continually through all three stages. The Liddy *et al.* results suggest that growth from hatching to stage III took about 60 days at 19°C, 36 days at 22°C and 28 days at 25°C. However while the difference in growth rate/moult interval between 19°C and 22°C was large, there was little difference between 22°C and 25°C. The post-moult size of the phyllosoma at both 22°C and 25°C were also similar but smaller than at 19°C. This growth data and the tendency for higher mortality to occur at stage III held at 25°C, led the authors to suggest that the optimal growth temperature for the species was around 22°C.

These two data sets differ in that Liddy *et al.* (2004) used individual phyllosoma while Marinovic (1997) used groups of phyllosoma, which would have suffered some mortality, and may have biased the estimated growth times. For the model the individual growth rates are more appropriate, but cannot be estimated from field data. This issue of the difference between growth times for individual phyllosoma and times estimated from the modal shift from field samples which can be biased by the effects of extended recruitment interacting with natural mortality led to the shorter phyllosoma durations than those adopted in the Griffin *et al.* (2001) model.

From these studies, the optimal temperatures for growth appear likely to be in the range 22° to 23°C, which is in keeping with the SST recorded in the area off the mid west coast where the phyllosoma spend much of their time (Phillips *et al.* 1979). These suggested optimal temperatures are also supported by Caputi *et al.* (2001) who showed that peak puerulus settlement was associated with SST of about 22.5°C in February-April and low settlement with 20.7°C in the areas occupied by the phyllosoma.

2009 model development

The 2009 model has allowed for growth to vary with temperature from the average durations set out in Table 3.2. These listed durations for each phyllosoma category approximate to the timing of the various stages from Phillips *et al.* (1979). That is, at the nominal temperatures of Table 3.2 (average 21.65°C), the larvae are assumed to reach Category C2 after 270 days. If the average temperature encountered is greater than the nominal temperatures, the growth rate is above average so that it takes less than 270 days to reach C2 (e.g. at an average temperature of 23°C it takes about 240 days to reach C2), while if the average temperature is lower than nominal temperatures, the growth will be slowed down (e.g. at an average temperature of 20°C it takes about 315 days to reach C2) (Figure 3.4). Other restrictions in the model are that there is no growth if the temperature is below 15°C, and the growth rate plateaus if the temperature is above 26°C. Constant growths are assumed for Category C2 larvae and puerulus.

Within the model, an age variable, STAGE, is used to keep track of larval growth, which are updated daily ($\Delta t = 1$ day):

$$STAGE = STAGE + G_s \times \Delta t$$

STAGE = 1 when the larvae are released in the model domain as Category A1. The larvae are moved one category up after spending a total of 1 of their STAGE at each category. Temperature-dependent growth rates are implemented according to their stages:

$$G_s = \frac{(T - T_0)}{P_s(T_1 - T_0)}, \text{ when } T > 15°\text{C}$$

$$\text{While } G_s = 0, \text{ when } T \leq 15°\text{C}$$

- $1 \leq STAGE < 2$ for Category A larvae: $P_s = 90$ days; $T_1 = 21.5$°C; $T_0 = 10$°C;
- $2 \leq STAGE < 3$ for Category B larvae: $P_s = 60$ days; $T_1 = 22.4$°C; $T_0 = 10$°C;
- $3 \leq STAGE < 4$ for Category C1 larvae: $P_s = 120$ days; $T_1 = 21.4$°C; $T_0 = 10$°C;
- $4 \leq STAGE < 5$ for Category C2 larvae: $G_s = 1/(420-270)$;
- Puerulus: $G_s = 1/20$;

where T is the average temperature (for 0 to 30 m estimated in the model) that phyllosoma larvae experience and T1 is taken from Table 3.2. Phyllosoma and puerulus are assumed to die once they reach STAGE = 6 and have not reached the correct depth for settlement.

Post model analysis

Not applicable

Future model development

In the 3-year project, non-linear growth models taking into account the limited laboratory data for *P. cygnus* and data for similar species, should be used to generate a more realistic growth-temperature relationship. These relationships would then be used to sensitivity test the effect of temperature on model puerulus settlement.

3.4.2 Food supply/nutritional growth dependency

The eastern Indian Ocean has historically been regarded as an area of very low productivity. Field survey data (Tranter and Kerr, 1969) indicated that chlorophyll A peaked in the region in May/June, with zooplankton peaking two months later in August/September. The more recent satellite monitoring data has confirmed this general seasonal pattern that chlorophyll levels are highest in winter months, suggesting that zooplankton will peak in spring, assuming the lag in zooplankton abundance by Tranter and Kerr (1969). The variations in abundance of zooplankton, which are the likely food for phyllosoma, are assumed to follow the satellite observed chlorophyll patterns. In addition the SeaWIFS satellite monitoring data also shows that chlorophyll is generally low throughout the region, except for the shelf waters, where consistently higher levels are recorded (Figure 3.5).

The low productivity of the off shelf area, where the *P. cygnus* phyllosoma spend most of their development time (Phillips *et al*., 1979), suggests that growth may be food limited. Similarly it is likely that availability of food/zooplankton, may limit the nutrition levels needed for successful metamorphosis to puerulus (Phillips and McWilliam, 2009) unless the late stage phyllosoma are near the shelf edge.

2009 model development

The impact of variations in food supply has not been able to be incorporated in the 2009 model, except for the use of the 200 m shelf edge as a proxy for the trigger for metamorphosis. In this case the use of the 200 m contour, as the typical edge of the high productivity zone, is assumed in the model to represent a phyllosoma high growth zone.

Post model analysis

No applicable

Future model development

In future it may be possible to incorporate the time phyllosoma spend in high chlorophyll A areas (from satellite monitoring) into the models to both increase phyllosoma growth and to trigger metamorphosis. This process would however need to lag the growth response by about two months to approximate to the presence of zooplankton, as this is the food for phyllosoma rather than the phytoplankton. Because of the need to incorporate a lag, it is unlikely that productivity will be able to be incorporated in future models at a local level, but may be usefully incorporated as a year to year variable to increase growth generally in high years.

3.5 Phyllosoma/puerulus mortality through oceanic phase

Following hatching, the numbers of phyllosoma surviving over time will be a function of the level of ‘natural’ mortality occurring. This ‘natural’ mortality will be generated by a range of factors such as: temperatures outside of the species range (both high and low), lack of food (low productivity in the area is likely to result in some starvation losses), predation (likely to be high on the shelf, where the density of predatory fish is likely to be greatest) and from being unable to successfully metamorphose (i.e. they are carried away from coast such that metamorphosis occurs away from any settlement area and the puerulus do not survive).

Although the phyllosoma appear to be able to survive a wide range of oceanographic conditions having been taken in surveys between latitudes 11 and 35°S, i.e. from the NW Shelf to well south of Cape Leeuwin (Chittlebrough and Thomas 1969), survival is likely to be influenced to some extent by temperature.

Noting that P. cygnus juvenile/adult distribution decreases significantly above NW Cape, where maximum coastal temperatures in the order of 28°C can occur, this would be a reasonable first guess for the upper temperature limit for survival of puerulus and therefore phyllosoma. Similarly, 15°C is about the minimum temperature for the Albany area, which is about southern/eastern extent of the species distribution i.e. where puerulus have settled and juveniles are regularly found in low numbers. The relatively low numbers of phyllosoma found south of 32°S by Chittleborough and Thomas (1969), and the lack of significant puerulus settlement along this section of the coast (Caputi *et al*. 2001), suggests that there may be a significant mortality of phyllosoma, which are moved to this colder southern area by the currents. This lack of survival may be due to temperature directly, or indirectly due to an inability to actively feed and therefore starvation (or slower growth) at the cooler temperatures in this region.

For *P. cygnus*, detailed information on the predators of the phyllosoma stages is not available, but are most likely to be plankton feeding fish species. This hypothesis is supported by the observation that few phyllosoma apart from the hatching stage I (or late larval stages) are ever found on the shelf. This area corresponds to the highest areas of fish abundance in WA, as the low productivity of more offshore waters corresponds to low pelagic fish abundance.

The other likely source of mortality is from the phyllosoma being carried away from the coast by the current systems and never returning to areas where successful metamorphosis occurs. This mortality is most likely to occur for phyllosoma, which are carried west out into the central Indian Ocean and south into the Southern ocean. The same situation can occur to the north, although in this area the general southward flow has a greater possibility of return of the phyllosoma. The existence of phyllosoma in these areas well away from the coastal settlement zone has been demonstrated by the survey data of Chittleborough and Thomas (1969).

While there is no direct measure of natural mortality in total, for this or any other similar species, the larval numbers taken in the standardized surveys conducted by Rimmer and Phillips (1979) provide a very basic indicator of changing phyllosoma abundance through the year, which might correspond to natural mortality or survival rates. These data show that in January 76, there were 3025 categories A larvae [early stage I—III] caught, in May there were 1934 Category B [mid stage IV—VI] larvae caught, in Sept 76 there were 287 larvae Category C [late stage VII-IX] caught and in November 76 there were 521 Category C [late stages VIII and IX] caught. This decline in numbers by about 85 to 90% over the 9-month period provides a rough indication of phyllosoma survival rates from stage II to VIII, suggesting that the numbers surviving from hatching to settlement is likely to be considerably less than 10%.

2009 model development

In the 2009 model three specific causes of mortality have been incorporated.

1. *On shelf mortality:*

This has been incorporated as follows:

a larval survival index, SI, is assigned to 1 to the Category A larvae when they are released. Mortality is applied to larval category A, B, and C1:

$$SI = SI - M_s \times \Delta t$$

i. For Category A larvae, M_s = 1/15 days when found on the shelf, that is, allowing 15 days for the early stage larvae to move offshore from shelf.

ii. For Categories B and C1 larvae, instant mortality is applied when they are found on the shelf.

iii. Note: for category C2 phyllosoma entry to the shelf waters triggers metamorphosis, and for category D (Puerulus), no on shelf mortality is applied.

2. *Temperature-dependent mortality:*

In the 2009 model, for Category A to C phyllosoma a mortality rate is applied as, Ms = 1/14 days, if phyllosoma larvae experience a temperature less than 16°C; and mortality rate Ms =

1/7 days, if the phyllosoma larvae experience temperature less than 15°C. For this purpose the temperature used is the model sea surface temperature that the phyllosoma encounters. If *SI* becomes less than zero, the larvae are dead and not longer tracked.

3. *Out of domain mortality:*

Where phyllosoma larvae move out of the model domain i.e. above 18°S or west of 101° E or below 40°S, they are also assumed to be have died.

In addition to the above specific sources of 'natural' mortality of phyllosoma in the model a general natural mortality rate has been applied to all phyllosomas after they reach an age of 300 days. This mortality is applied in the model through post model analysis as set out below.

Post-model analysis

General natural mortality occurs to all model phyllosoma with pelagic durations between 300 and 420 days. This mortality is applied in the model through post model analysis, using the e-folding time scale of 1 month for larvae with total larval periods greater than 300 days (Figure 3.6). This process results in a mortality of about 63% during the 30 additional days (300 to 320 days) taken to reach the puerulus stage and reaches 100% by age 420 days.

Future model development

In the 3-year project, variations to the temperature-dependent mortality rate should be considered and assessed through sensitivity analysis in the post-model analysis. In addition, variations to mortality generated by the phyllosoma leaving the model domain should be further explored by expanding the model boundaries. This may be a critical issue for the northern border of the domain as these phyllosoma have most potential to be transported by the currents back to locations on the coast where settlement is recorded. This area to the north of the model domain is also an area where *P. cygnus* phyllosoma were regularly recorded in surveys by Chittleborough and Thomas (1969) although the species identity of these northern phyllosoma was an issue at that time.

3.6 Successful puerulus settlement

Puerulus settlement most commonly occurs in shallow protected reef areas close to the coastline typically in depths of less than 5 m (Phillips *et al*. 2003). Although occasional puerulus are reported by commercial fishers on lobster pots/ropes further offshore, collectors set through this area i.e. out to 140 m depth, failed to catch any puerulus except in the locations less than 5 m (Phillips *et al*. 2003). This result suggests that puerulus caught offshore were probably still in transit to the coastal reefs.

In the Griffin model, puerulus which intersected the 100 m isobath within 3 days of the new moon were counted as successfully settled. However, if the currents carried them offshore they could remain alive for another 30 days during which time they successfully settle if they reached the 100 m isobath within 3 days of a new moon. These criteria for model puerulus settlement and timing were simplifications and appropriate to the modelling process being undertaken at the time, but can now be revised and better tailored to the information available.

Specifically, the previous model requirement for settlement to only occur within 3 days of a new moon appears to be very restrictive relative to the literature available. Although there are limited published observations on settlement relative to lunar phase, the available data shows a spike in numbers within a few days of the new moon but also some settlement occurring over a much longer period (Phillips 1972). This suggests that the time from metamorphosis to settlement, including the period needed for cross shelf migration, could take several weeks.

2009 model development

In the 2009 model, puerulus have been regarded as settled if they encounter the 40 m isobath at any time of the lunar cycle.

Post model analysis

Not applicable

Future model development

In future models, puerulus could be regarded as settled when they reach the 20 m depth zone, which corresponds to the outer perimeter of the coastal reef system, and which contains the preferred settlement habitats. This would allow the model to better take into account the transport effects of the coastal current systems i.e. the Capes Current, which may, for example, be a factor in the delayed settlement peak at the Abrolhos Islands.

3.6 Particle tracking method

An individual based model (IBM), Lagrangian particle tracking method, is used to transport WRL larvae after they are released from the hatching area. Both ocean current and wave-induced current (only affecting 0-20 m depth) are included in calculation. The advection scheme is 4th-order Runge-Kutta, in which the position of a particle at time step $n+1$, (x_{n+1}, y_{n+1}) is given by

$$x_{n+1} = x_n + u_{n+1/2}\Delta t + R\left[2r^{-1}K_m\Delta t\right]^{1/2}$$

$$y_{n+1} = y_n + v_{n+1/2}\Delta t + R\left[2r^{-1}K_m\Delta t\right]^{1/2}$$

where (x_n, y_n) is the position of the particle at the previous time step, Δt is the time step, and ($u_{n+1/2}$, $v_{n+1/2}$) is velocity at the predicted position at time $n+½\,\Delta t$. The third term on the right-hand side represents sub-grid scale processes unresolved by the BRAN data. It is a model of diffusion by random-walk, with R a random number having zero mean and variance of 1, and K_m (=1 m^2s^{-1}) the horizontal diffusivity. 1-hour time step is used to calculate the larvae movement.

The records of the position of each partice in the model are stored in a database and used in post model analysis.

3.7 Performance criteria for the models

There are a range of field data sets, which can be used to provide performance criteria for the 2009 and later models. The model phyllosoma stages and distributions at various points in the annual cycle can for example be compared to the field survey data to assess the performance of the model components. However there are relatively few years with field surveys, so these data can only be used to assess the general spatial distribution of the model phyllosoma. In contrast, the extensive puerulus settlement database can be used to assess both the general patterns during a year, but also the yearly variations in puerulus settlement. The following performance criteria are proposed as a means to evaluate the realism of the model:

1. The model phyllosoma stage distributions should generally match the monthly abundance patterns for each stage from the combined surveys for the years 1973 to 1977 in Rimmer and Phillips (1979).
2. The spatial distributions for late stage [VI to IX] phyllosoma should generally match the mid year [June/July] spatial distributions from Rimmer and Phillips (1979) - figure 4. Specifically, the bulk of the phyllosoma should be at stages VII and VIII at this time and the highest numbers should be between 26 and 30°S and out to at least 105°E offshore. Noting that reasonable numbers were found along this offshore limit to sampling effort, model phyllosoma to the west of 105°E and north of 30°S should be also expected.
3. The general monthly pattern of settlement, i.e. with a peak around October.
4. The general distribution along the coast i.e. with a peak between 29 and 31°S, or with uniformly high settlement from 31 to about 25°S [this would reflect the hypothesis that the low settlement north of Geraldton, is atypical or a shadow effect from the Abrolhos Islands]

For yearly variations in model settlement the outputs should be able to generally match:

5. The effect of the Leeuwin Current on the overall annual level of settlement.
6. The variation in the timing of the peak settlement by location (north-south variation and Abrolhos variation) during high and low years.
7. The effect of Leeuwin Current Leeuwin Current on the position of the peak in the distribution of settlement.
8. Effect of SST in Feb-April on puerulus settlement (this may be useful to tune the temperature-mortality relationship)

Meeting criteria 1 to 4 should be the primary target for the 2009 model. Criteria 5 to 8 may be more applicable to the later model.

Table 3.1. Approximate monthly hatching rates for *P. cygnus* based on Chubb (1991) [Note: CPUE data to convert to percentages was taken from the publication figures].

	Abrolhos Zone A	**Dongara Zone B**	**Two Rocks Zone C**	**Fishery wide Average**
MONTH	1984/85	1986/87	1985/86	NA
September	0%	0%	0%	0%
October	0%	0%	9%	3%
November	9%	16%	19%	15%
December	25%	37%	47%	36%
January	30%	25%	14%	23%
February	27%	22%	11%	20%
March	9%	0%	0%	3%

Table 3.2. Average larval duration (days) of different phyllosoma and puerulus categories and the average temperatures they experience in the model.

	Category A		Category B	Category C		Category D
	A1	A2		C1	C2	D1
Larval duration (days)	30	60	60	120	<150	<21
Average temperature (°C)	21.5		22.4	21.4		N/A

Table 3.3. Depth ranges of diurnal vertical migrations. The near surface profiles are as in Figure 3.3.

	Category A		Category B	Category C	
	A1	A2		C1	C2
Day time (9:00-17:00)	0-20m	10-100m*	30-100m#	Below Leeuwin Current%	
Transition time (17:00-21:00 and 05:00-9:00)	0-20m	0-100m	0-100m	Surface to below Leeuwin Current%%	
Night time (21:00-05:00)	0-20m	0-60m**	0-40m##	0-20m	
Near surface profile	I	I	II	III	

*50% of the larvae are in 10-50 m and 50% in 50-100m
**50% in 0-20 m and 50% in 20-60 m
#50% in 30-60 m and 50% in 60-100 m
##50% in 0-10 m and 50% in 10-40 m
%Stationary
%%use one third of 0-100 m BRAN velocity to transport larvae

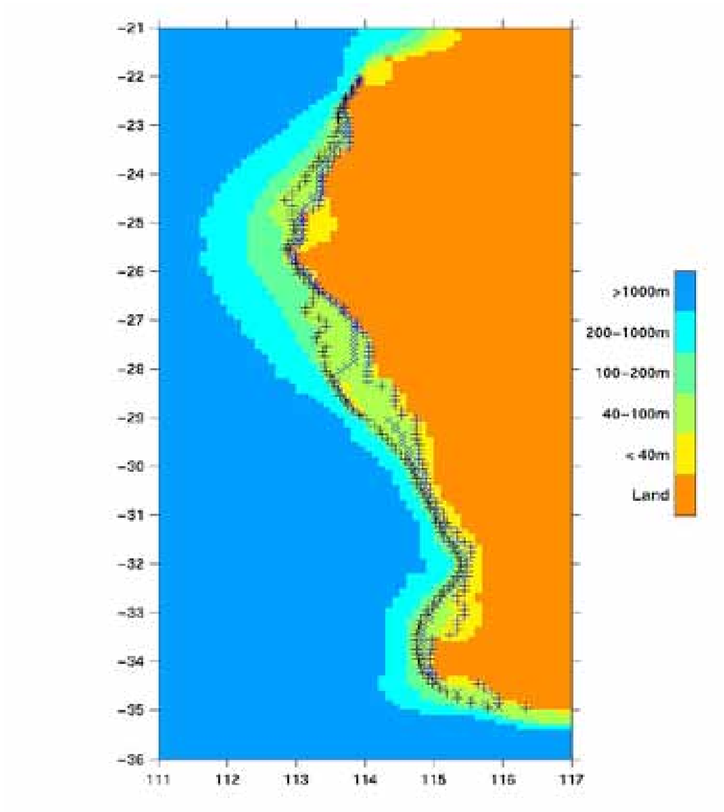


Figure 3.1. Bathymetry of the BRAN model and the larval release locations on the shelf (nominally 40, 60, and 80 m). Note that the 40-100 m depth range of the shelf has been widened inside of Abrolhos (~29°S).

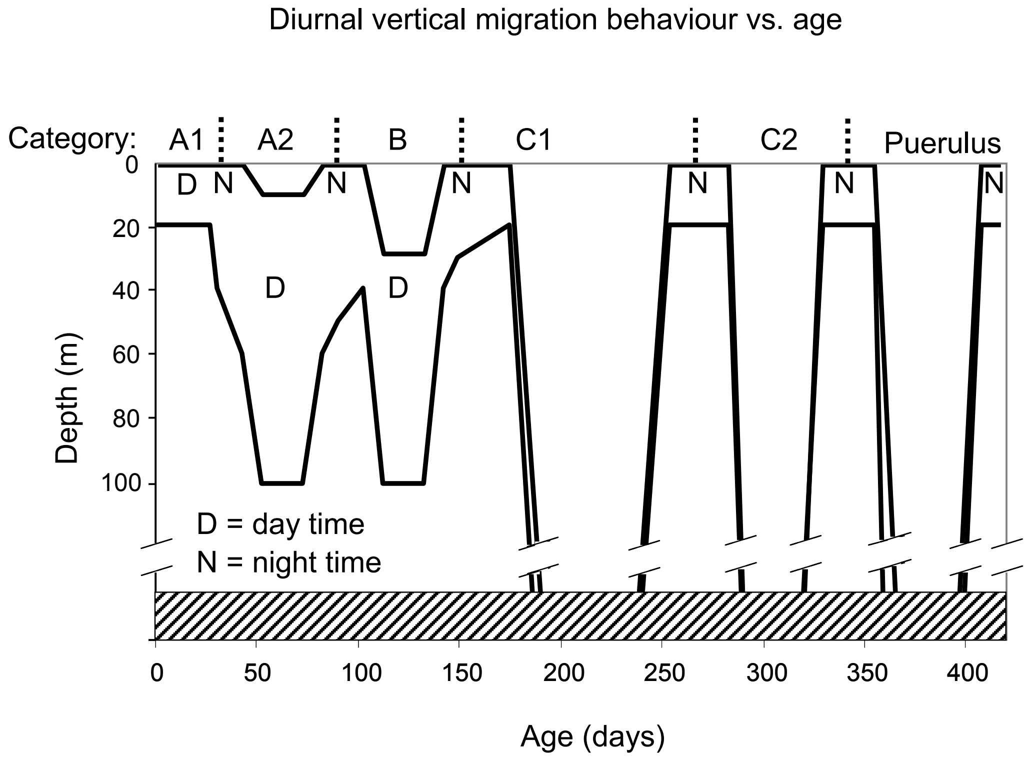


Figure 3.2. Diagrams on vertical migration phyllosoma in different categories and puerulus in the 2009 model. D denotes daytime and N denotes night time. The stippled area denote below the Leeuwin Current or shelf bottom.

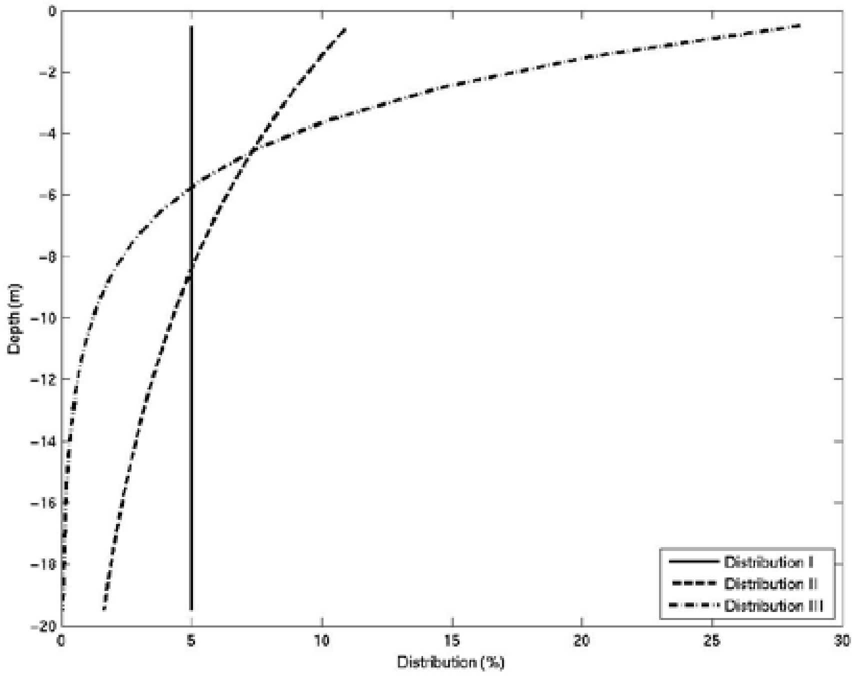


Figure 3.3. Three vertical profiles of larval distributions in the upper 20 m in different larval Categories as denoted in Table 4.3. The horizontal axis denotes the percentage of total larvae. Distribution I applied to Category A, II applies to Category B, and III applies to Category C.

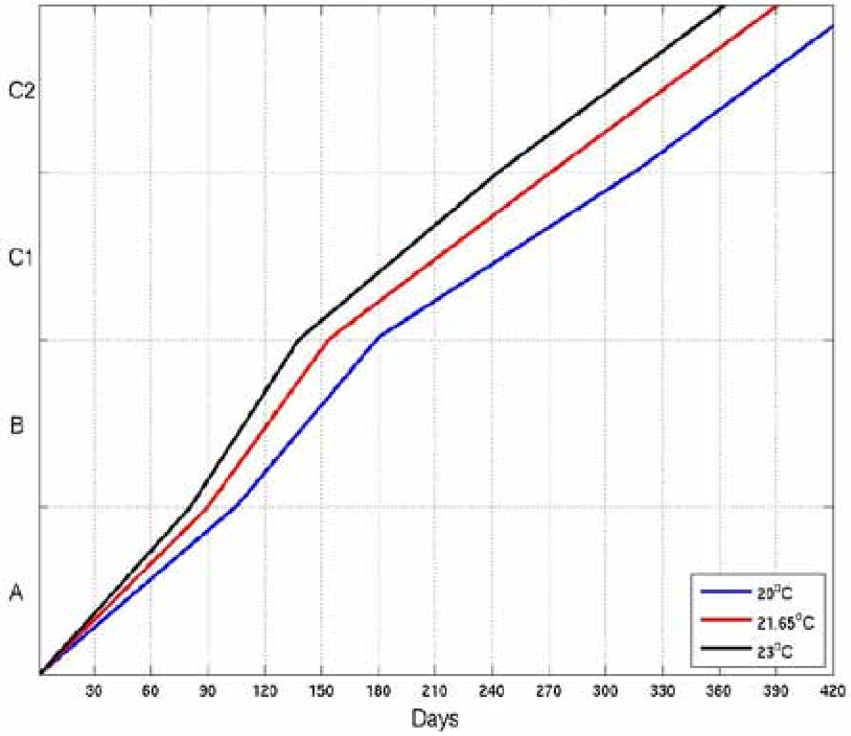


Figure 3.4. Diagram of the growth of WRL larvae at three constant temperatures in the 2009 model.

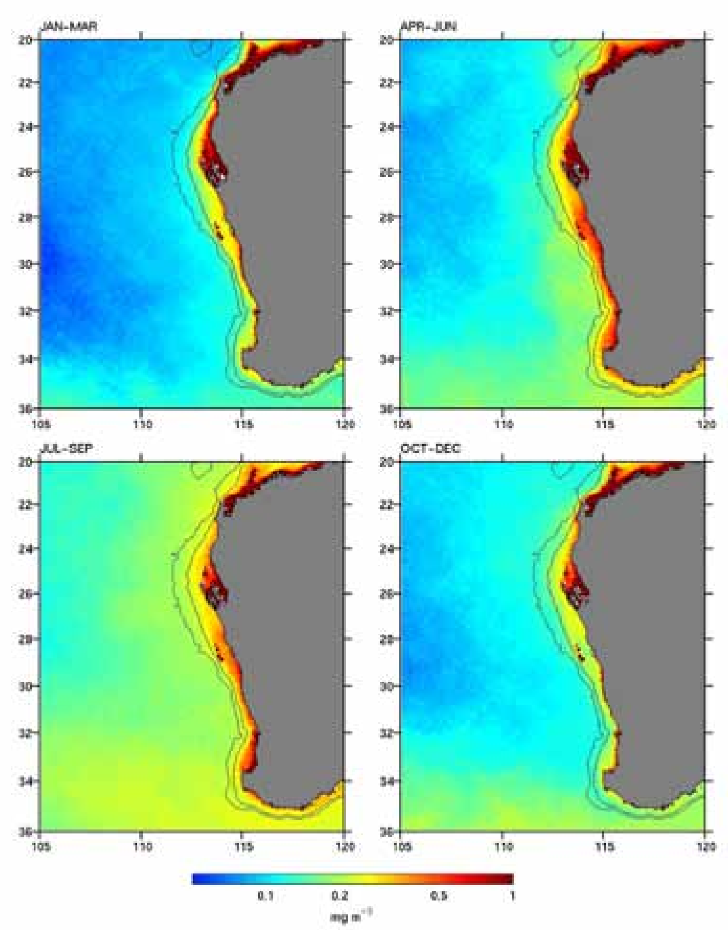


Figure 3.5. Seasonal variations of sea surface chlorophyll a concentration derived from SeaWIFS satellite data. The contours denote 200 and 1000 m bathymetry depths.

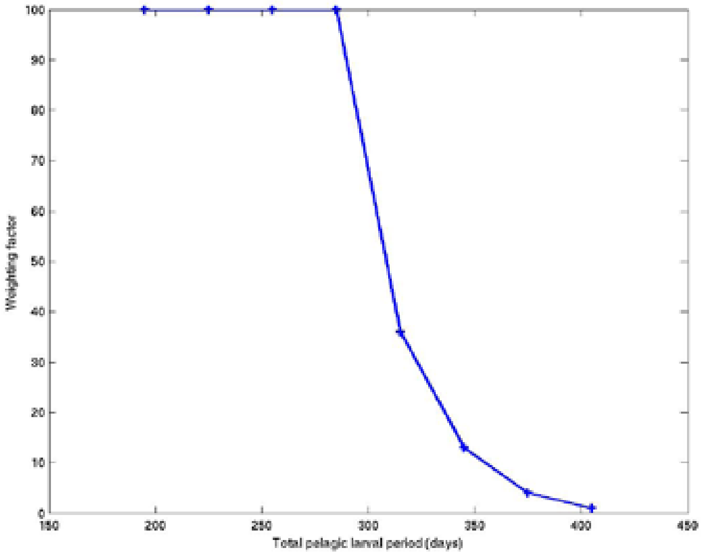


Figure 3.6. General natural mortality rates of WRL larvae as derived from the total pelagic larval period, which are applied as weighting factors in post-model analysis showing the rate of increased mortality if above 300 days are required to reach the puerulus stage. Note this mortality is in addition to other mortalities e.g., on shelf, temperature related and out of domain mortalities, which are applied during the phyllosoma phase.

4.0 Results and Discussion

4.1 Overview

The 2009 model focuses on simulating WRL puerulus settlement processes during nine settlement seasons, from 2000/2001 to 2008/2009, for which the data used in wind and wave induced surface current corrections are available. For each settlement season, the model simulation is carried out for the period of 16 October of year-1 (start of hatching) to 31 March of year+1 (end of puerulus settlement). The model domain the waters off the WA coast between 18-40°S, and between 101-129°E.

During the hatching period of each season, a total of 585,000 larvae are release into the model domain from North West Cape to Cape Leeuwin. On average, 415 model puerulus settle to the west coast each year, or about 0.071% of the larvae released in the model, up to March of year+1 in the settlement season. Only a smaller number of model puerulus, 19 on average, settled onto the south coast each season.

The main purpose of the following sections (4.2 to 4.8) is to assess the general performance of the model, relative to the available information on the distribution and abundance of the various life stages.

See movie of Larvae dispersal tracks of the 2005/06 settlement season to graphically illustrate the functionality of the 2009 model: http://www.per.marine.csiro.au/staff/Dirk.Slawinski/FRDC/TRF_2008/

4.2 Development of WRL phyllosoma/puerulus

To assess the overall performance of the model, the monthly patterns of occurance of each category of of phyllosoma and puerulus have been presented in Figure 4.1. This figure shows the 9-year average monthly counts for each category from November (year-1) in the spawning season to March (year+1) near the end of the settlement season. These model distributions have then been compared to average monthly patterns of phyllosoma stages from 1973 to 1977 (Phillips *et al*., 1979). Although the growth parameters used to generate development of the phyllosoma through the model categories were also based on the modal progression from this study, it is important that the final model outputs have similar distributions to the original field data. These comparisons with the data from Phillips *et al*. (1979) are reported below.

4.2.1 Category A phyllosoma

On average, the peak numbers of Category A phyllosoma occur in February in the model domain, near the end of the hatching season, and Category A phyllosoma in the model domain have largely disappeared after May (Figure 4.1), which is consistent with field observations.

4.2.2 Category B phyllosoma

The peak numbers of category B phyllosoma occur in April, though its dominance in total phyllosoma numbers is during April-May (Figure 4.1). Very few of these stages were taken in the field survey, however their occurrence ceased at about the same time as the model Category B phyllosoma i.e. they had largely disappeared by September.

4.2.3 Category C phyllosoma

The peak sub-category C1 phyllosoma occurs in June-July, and sub-category C2 phyllosoma, which are capable of metamorphosing into puerulus (as they cross the shelf) starts to occur in June and reach peak numbers in October-November (Figure 4.1). Category C phyllosoma become dominant in the distribution from June-July, which is consistent with field observations.

4.2.4 Category D puerulus

In the 2009 model, small numbers of D1 puerulus start to appear in the model domain in June and their peak occurrence is in September (earlier than the peak of C2 phyllosoma). The peak in model settlement corresponds to peak at the central coastal site of Dongara, however the overall period of model puerulus settlement is closer to that recorded for the Abrolhos, which typically has a later settlement (Phillips *et al.* 1979). After September, the oceanographic conditions are generally less favourable to transport the phyllosoma shoreward (Fig 2.2).

4.3 Spatial distribution of phyllosoma

To show the general patterns of model phyllosoma distribution through a season, the 9-year averaged latitudinal distributions of combined sub-category C1 and C2 phyllosoma in the whole model domain, between April and November, have been presented in Figure 4.2. These distributions have not been weighted by the spawning stock levels along the coastline.

In April, category C phyllosoma have a peak distribution off North West Cape (22°S), and the distribution tapers towards the south (Figure 4.2). This north-south trend reflects the temperature-dependent growth rate – the model larvae grow faster in the north as they usually experience warmer temperatures.

In June/July, the central distributions of the category C phyllosoma have shifted southward and are centred at around 30-32°S (Figure 4.2), due to more of the southern larvae, which have been subject to colder temperatures having reached late stages. The June/July distribution also reflects the strengthening of the Leeuwin Current which moves some of the northern model larvae southward.

From August to November, the centre distribution of category C phyllosoma slowly moves northward (Figure 4.2). This is mostly due to the weakening of the Leeuwin Current and the wave-induced Stokes drift (northeastward) starting to increase (Figure 2.7).

These unweighted phyllosoma distributions suggest that the model larvae are responding appropriately to the major transport mechanisms along the west coast.

See movie of monthly larval distributions of the 2005/06 settlement season http://www.per.marine.csiro.au/staff/Dirk.Slawinski/FRDC/TRF_2008/.

4.4 Factors affecting successful model puerulus settlement

To provide a preliminary assessment of 'source-sink relationships' in the rock lobster fishery, we have used the model to compare the settlement success of phyllosoma released at various points throughout the range of the species, and at different times through the hatching season.

At this stage the model reasonably replicates the typical monthly pattern and general latitudinal distribution of puerulus settlement, but has not yet been developed to the point where it reasonably represents the historical annual variability in the puerulus settlement. For this reason, the model outputs have been combined for the 9 years modelled to date to provide a general indication of phyllosoma tradjectories and settlement success.

For the assessment of factors, the data is provided in the form of unweighted statistics to provide an indication of the relative likelihoods of successful settlements. In addition, two weighting factors are applied to derive more realistic results from the 2009 model run. The first weighting factor is the average monthly hatching rates from Table 3.1, that is, for all successful settlements derived from October hatching, a multiplying factor of 3 is applied, for those derived from November hatching, a factor of 15, etc., so as to reflect the average distribution of hatching (percentage) per month. The second weighting (multiplying) factor is the relative survival associated with the total pelagic larvae durations of the successfully settled puerulus, as shown in Figure 3.9. That is, for settled larvae with pelagic larval durations (PLD) less than 300 days, a multiplying factor of 100 is applied, for those with PLD between 300-330 days, a factor of 37 is used, etc.

4.4.1 Timing of the larval releases

Based on the unweighted data, the amalgamated distribution of release dates for the successfully settling model puerulus, suggests that phyllosoma hatched/released earliest in the hatching season i.e. from mid-October have the highest chance of coming back to the coast (Figure 4.3a). Apart from a small peak in December the chance of successful settlement declines consistently from October to March. It appears that early-released larvae experience the warmer temperatures during the summer season, which enables them to grow faster and be at a stage able to metamorphose to puerulus, when the strongest onshore flows occur during the winter to early spring months.

When the model settlements are weighted (scaled) by the average monthly hatching rate, the most successful settlements are derived from releases in November and December, with the December releases slightly more important (Figure 4.3b).

When the settlements are weighted by both monthly hatching rate and the pelagic larval duration mortality, there is a slight reduction of the proportion of successful releases in the latter half of the spawning season (Figure 4.3c).

4.4.2 Latitudes of the larval releases

To assess the impact of latitudinal position on the probability of successful settlement, the unweighted (amalgamated) distribution of the release latitudes for the success of model puerulus settlement has been examined (Figure 4.4a). These data suggest that three release regions have a higher likelihood of successful settlement – North of Shark Bay, Abrolhos (28-29°S), and Geographe Bay, although there is also a moderate level of settlement between the Abrolhos and Geographe Bay. These data however are not adjusted for the abundance of breeding stock in each area. While detailed and fully comparable breeding stock measures have not been applied for each release location in the model, the Abrolhos region is known to have a high abundance of breeding stock and provides the major contribution to egg production from the stock as a whole (Chubb 1991). Taking the general abundance of spawning stock into account suggests that there is a declining trend of the likely settlements from releases from Abrolhos to the Perth region (32°S), indicating that the more northern source is likely to be more important. The significant decline of likely settlers from releases off Shark Bay (26-27°S) probably reflects the modelled location of the releases being close to the coast in this region (see Fig 3.1).

Using the monthly hatching pattern to weight the release latitude (Figure 4.4b) suggests that the sources of successfully settled larvae are not sensitive to the timing of the release.

In contrast, when the release latitudes of successfully settled larvae are further weighted with the pelagic larval duration mortality, it generates a linear gradient from north to south (Figure 4.4c). It appears that the larvae released in the north tend to experience high temperatures and therefore tend to have shorter overall pelagic larval duration, while larvae released in the south tend to experience cold temperature and then longer larval duration. Under this situation Geographe Bay region is no longer a significant source of successful larval settlement.

4.4.3 Timing of settlements

The unweighted outputs from the 2009 model (Figure 4.5a) have been compiled to examine the pattern and timing of model settlement relative to the puerulus collector database. These data show that the average and peak settlement both occur in September, which is reasonably consistent with puerulus collector data, and most of the settlement occurs before December.

When weighted with monthly hatching rate, relatively more model settlement occurs in November and relatively less settlement in July-August, while the peak settlement is still in September (Figure 4.5b). This is expected as the weighting has scaled down the October-November releases.

Using the additional weighting of pelagic larval duration mortality, there are significant increases in about August and reductions in settlement after November, reflecting the relative advantages of fast growth (Figure 4.5c).

4.4.4 Latitudes of settlements

The unweighted data showing the latitude of model puerulus settlements suggests that the mean latitude for successful settlement is at about 30.4°S, with the main settlement region centred from Abrolhos in the north and Perth region in the south (Figure 4.6a). There are also three other regions where peaks occur i.e. Coral Bay, South of Shark Bay, and near the Capes region. Although this distribution bears some similarity to the spatial distribution derived from puerulus collectors, it must be noted that these results are based on equal releases along the coast and do not take into account the significant differences in spawning stock levels between locations. If this adjustment was included it would significantly alter the relative size of each peak.

Weighting the model settlements with monthly hatching rate does not modify the settlement pattern significantly (Figure 4.6b). When adding the weighting factor of pelagic larval duration mortality, the likelihood of successful settlement in the north has increased, while the successful settlement in the south has reduced (Figure 4.6c). The overall settlement structure under this arrangement has more resemblance to the spatial distribution from puerulus collector observations which may indicate the importance of environmental effects of growth/survival on the puerulus settlement.

4.4.5 Pelagic phyllosoma/puerulus duration

To assess the phyllosoma/puerulus durations of the model the durations for the settled puerulus over the 9-year period have been amalgamated. These unweighted data show a mean model duration to settlement of 307 days, or about 10 months (Figure 4.7a), which is consistent with observed period from peak hatching (December) to the peak of puerulus settlement (September). The peak distribution of model settlement occurs between 270 and 330 days, or 9-11 months.

Weighting the model larval duration by the monthly hatching rate does not greatly alter the situation, although there is a slight increased settlement at shorter durations (Figure 4.7b).

The addition of the effects of the pelagic larval duration mortality (Figure 4.7c) shortens the average duration as expected and also creates a step function after about 300 days at 30-day intervals which is an artefact created by the mortality weighting algorithm.

4.5 Model source-sink projections

In this report, we focus our assessment on the average source-sink situation for puerulus settlement off WA coast, while the interannual variations will be assessed in the 3-year project, given the need to take into account the annual variation in breeding stock, the timing of the spawning, and the location of the spawning. It should also be noted that the results are based on equal larvae released along the coast. That is, the outputs provided relate to the likelihood of successful settlement (relative to release timing and location of release), rather than stock wide sources and sinks.

From the 2009 model outputs averaged for the 9 year period, the model suggests that the two areas which are major sources of successful puerulus settlement. These were the area between Coral Bay and the north of Shark Bay, and the Abrolhos region (Figure 4.8). The model also suggests that the phyllosoma released off Coral Bay – north of Shark Bay are likely to supply successful settlements all along the coast, i.e. from North West Cape to Cape Leeuwin but with a peak around Coral Bay and in the Abrolhos/Dongara section of the coastline. The model larvae released off Abrolhos region were more likely to result in a broad area of settlement mainly south of Shark Bay, but also with the peak occurring in the Abrolhos region.

Model phyllosoma released between Abrolhos and Fremantle region were more likely to return to the same region than settle in the north. Model releases from the regions off the North West Cape, off Shark Bay, and near the southern Capes were relatively less important as sources of successful model puerulus settlements.

The model results (Figure 4.9) further suggest that for the Coral Bay area, self-recruitment is likely to be the main possibility for successful settlements. South of 25°S (northern Shark Bay), the data suggest there is a greater mixing of populations, due to dispersal by ocean current and eddies. For model settlements off Shark Bay, the most important source is further north, while at Abrolhos, sources from the north of Shark Bay and from local recruitment are both important. Moving further south, northern sources become more important, though roles of local sources cannot be underestimated.

Because these model outputs are not adjusted for breeding stock abundance, they should not be viewed as indicating relative source-sink performance for the stock as a whole. For example the very low breeding stock abundance from Shark Bay northwards indicates that the model settlement contributed from this area, will not be particularly significant to either the local or more more southern areas in the main fishery. Conversely, the contributions from Abrolhos area and parts of C zone, which have relatively high breeding stock indices, are likely to be more important overall.

4.6 Interannual variations in model settlement

While predicting interannual variations in puerulus settlements and the source-sink relationship will be studied in more detail in the 3-year project, some preliminary results for different settlement seasons based on the 2009 model have been presented in an attempt assess its performance in replicating the year-to-year variations in the field puerulus collections.

Here we present the interannual variations of total model settlement and average settlement latitude for phyllosoma equally released along 26-29°S (the northern sector of the main fished stock (Figure 4.9).

These data show that the 2000/01 season (designated as 2000 in Figure 4.9) had the highest model settlement numbers, more than double the rest of the settlement seasons during the other 8 years, 2001-2008. This high model settlement is reflected in actual settlement for 2000/01 which was the highest of these 9 years, suggesting the model may have now included some of the factors influencing the above-average settlement. In contrast, the low model settlements in 2003/04 and 2004/05 seasons and average settlements in 2007/08 and 2008/09, suggest that the model has yet to capture the factors contributing to below-average settlement. The significant year-to-year variation in the model settlement latitudes i.e. by more than 2 degrees of latitude (Figure 4.9b) also indicates an improvement from the previous model, as they are closely related to the strength of the Leeuwin Current, which is a known influence on actual settlement distribution.

These variations in model settlement are also reflected in the variations in the projections for source-sink areas. Figure 4.10 shows the model source-sink outputs for a high year (2000/01) and an average settlement year (2003/04). These two outputs show that when there was high model settlement (2000/01), the settlement occurred at more southern locations, the northern release sites such as the Abrolhos/Big Bank were more important. In contrast, when settlement was low (2003/04) the settlements occur at more northern locations, but the release sites in the south were as important as the Abrolhos area. While these results are limited by the current functionality of the model, they suggest that the source and sink areas are likely to vary between years in response to the oceanographic conditions.

4.7 Relative larval mortality

In assessing the performance of the 2009 model the fate of the phyllosoma and puerulus that do not survive to settle is also of interest. Among the unreturned larvae, about 442,500 larvae, or 75.6%, died at Category A1, as ocean currents on the shelf were unable to move them offshore within the 15 days allowed. The total relative mortality on the shelf/land for larvae in all categories is about 90.8%. Further, the mortality rates on the shelf/land were not evenly distributed by latitude of releases. The regions with higher relative mortality rates were off the North West Cape, off Shark Bay, and near the Capes region (Figure 4.11), which therefore were not important as sources of successful model settlement.

Also, about 3.7% of the model phyllosoma are lost by drifting out of the model domain and a further 4.0% of the phyllosoma do not reach a position to undergo metamorphosis to puerulus within 420 days. For phyllosoma that have drifted out of the model domain, the majority of them cross the northern and western boundaries (with slightly higher numbers crossing the western boundary).

About 1.4% of total released phyllosoma are still within the model domain on 31 March at the end of the model simulation.

4.8 Sensitivity to release depth

Among particles (phyllosoma) released at 40, 60 and 80/100 metre depths along the west coast, there tend to be higher successful rates for 60 and 80 m releases compared with those in 40 metres (Figure 4.12). The model suggests that particles released in waters greater than 40 meters are about four times more likely to return to the coast as puerulus than those released at 40 m. This is probably a reflection of the shallower released phyllosoma taking longer to exit the shelf and therefore subject to additional mortality associated with staying on the shelf beyond 15 days. The 40 m releases were only important contributors north of Shark Bay and in the southern Geographe Bay where the continental shelf is relatively narrow.

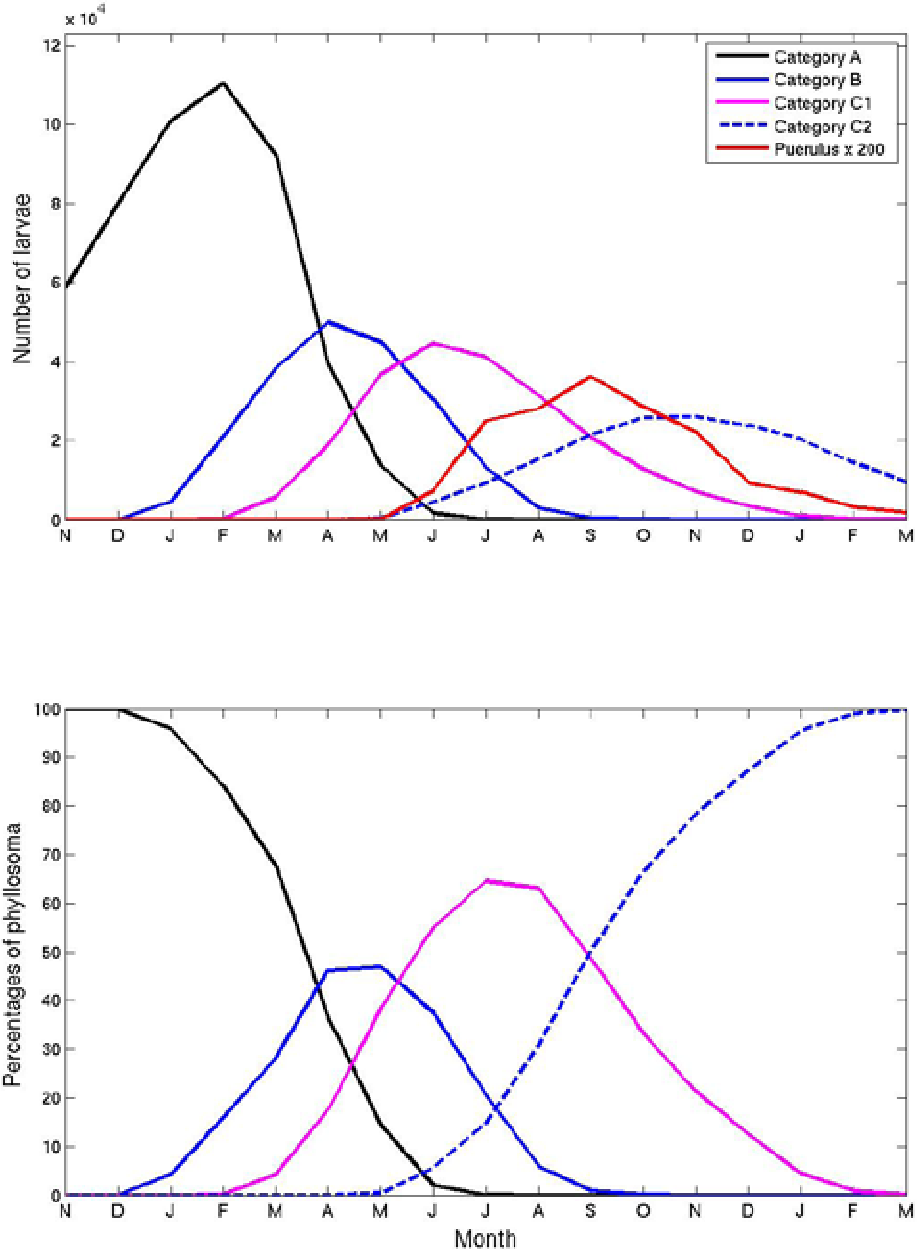


Figure 4.1. (top panel) 9-year average monthly counts of phyllosoma of different categories and puerulus from November near the start of the spawning season to March near the end of settlement season, and (lower panel) the average percentage of phyllosoma of different categories in the 2009 model. Note that the puerulus counts in the upper panel have been multiplied by 200.

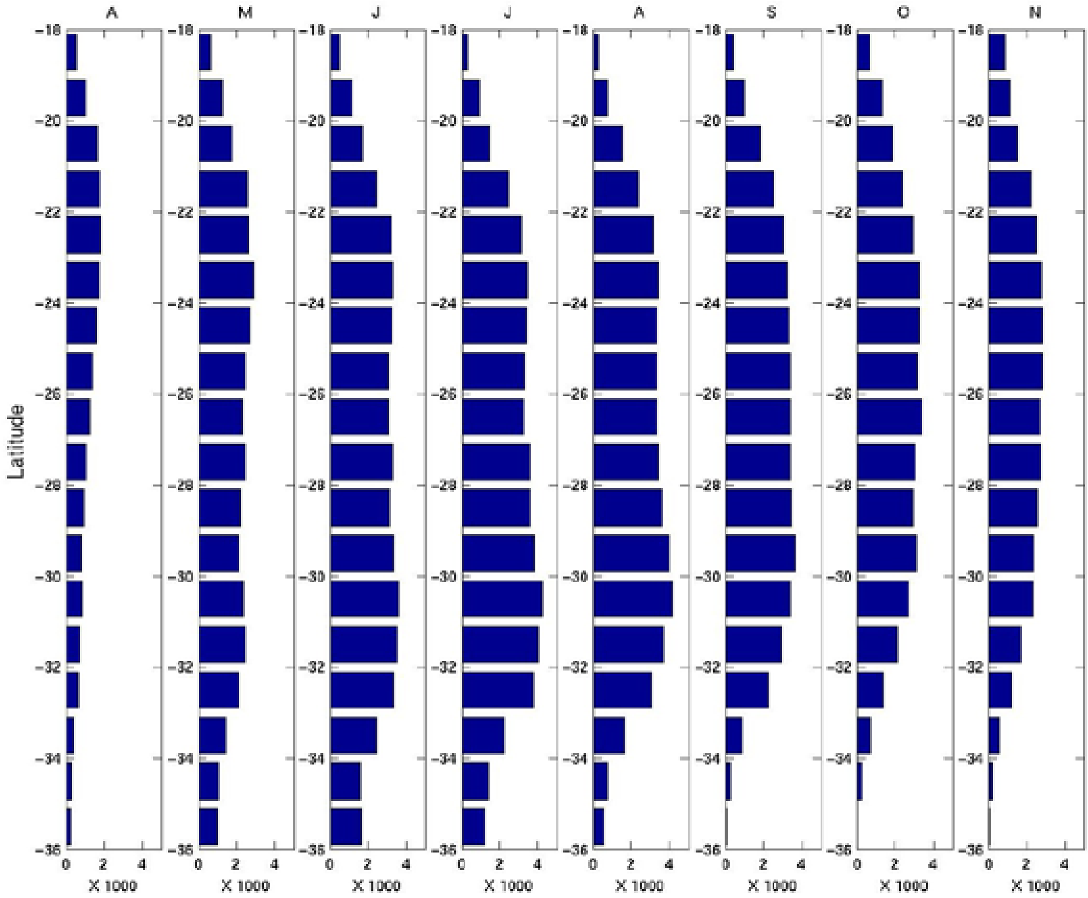


Figure 4.2. Modelled latitudinal distribution of late stage phyllosoma (Category C) in different months (April to November) off the west coast of Australia in the 2009 model.

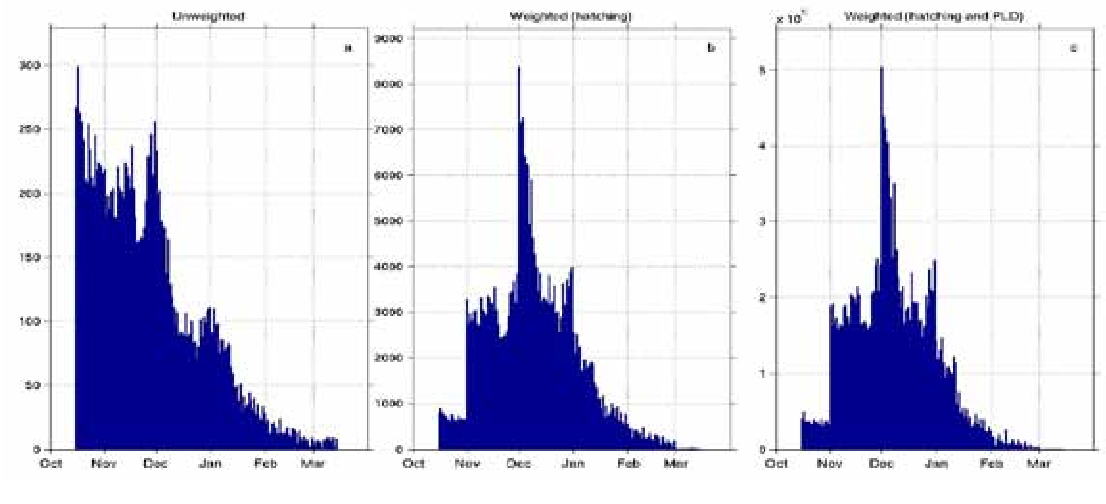


Figure 4.3. 9-year amalgamated distribution of the release dates of the returned larvae: (a) unweighted, (b) weighted with monthly hatching rate, and (c) weighted with monthly hatching rate and pelagic larval duration.

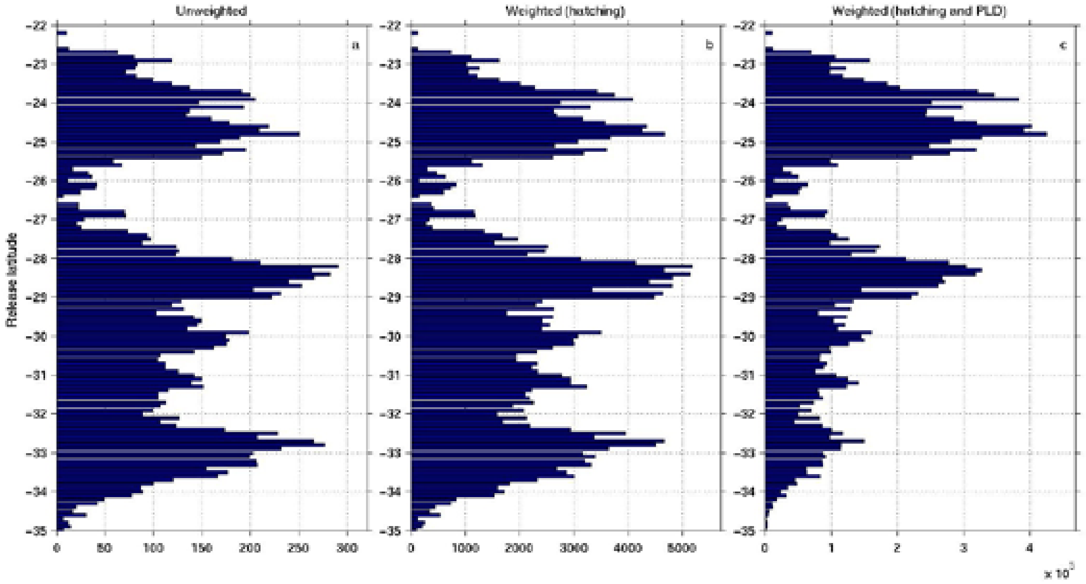


Figure 4.4. 9-year amalgamated distributions of the release latitudes of the returned larvae: (a) unweighted, (b) weighted with monthly hatching rate, and (c) weighted with monthly hatching rate and pelagic larval duration.

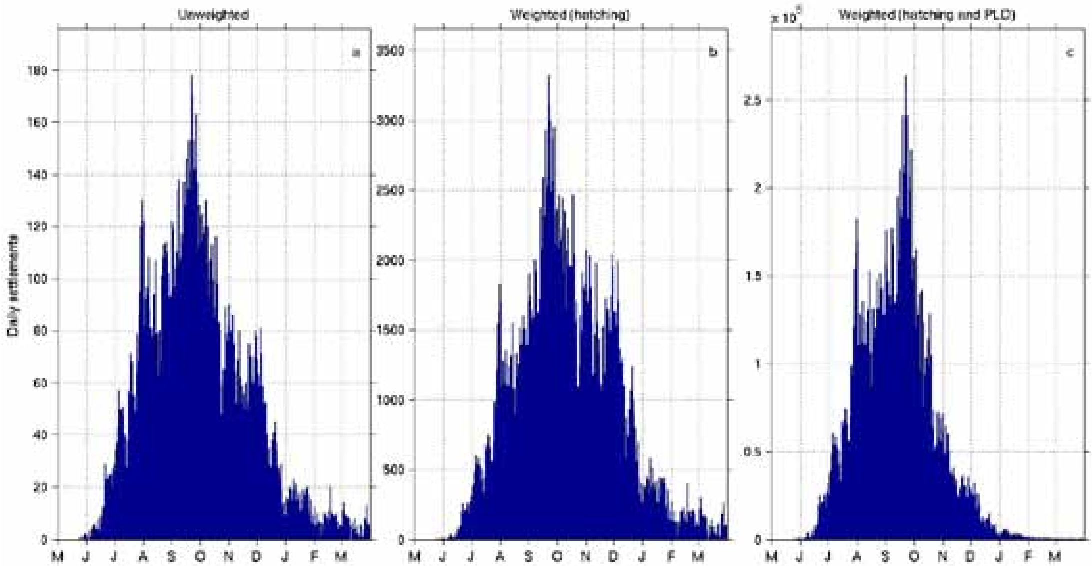


Figure 4.5. 9-year amalgamated distributions of the daily settlement of the returned larvae: (a) unweighted, (b) weighted with monthly hatching rate, and (c) weighted with monthly hatching rate and pelagic larval duration.

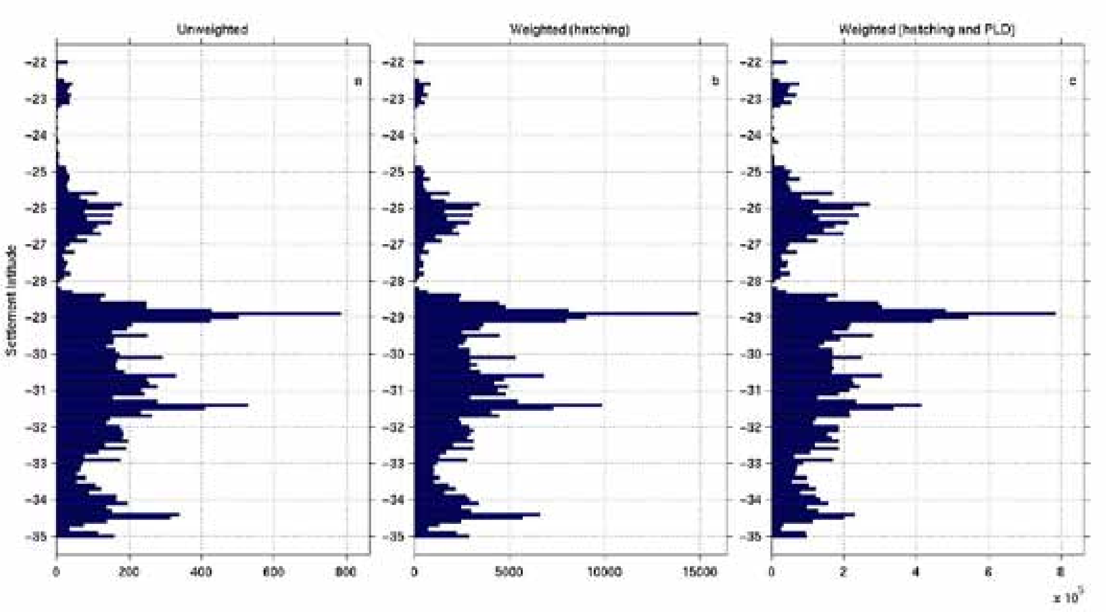


Figure 4.6. 9-year amalgamated distributions of the settlement latitudes of the returned larvae: (a) unweighted, (b) weighted with monthly hatching rate, and (c) weighted with monthly hatching rate and pelagic larval duration.

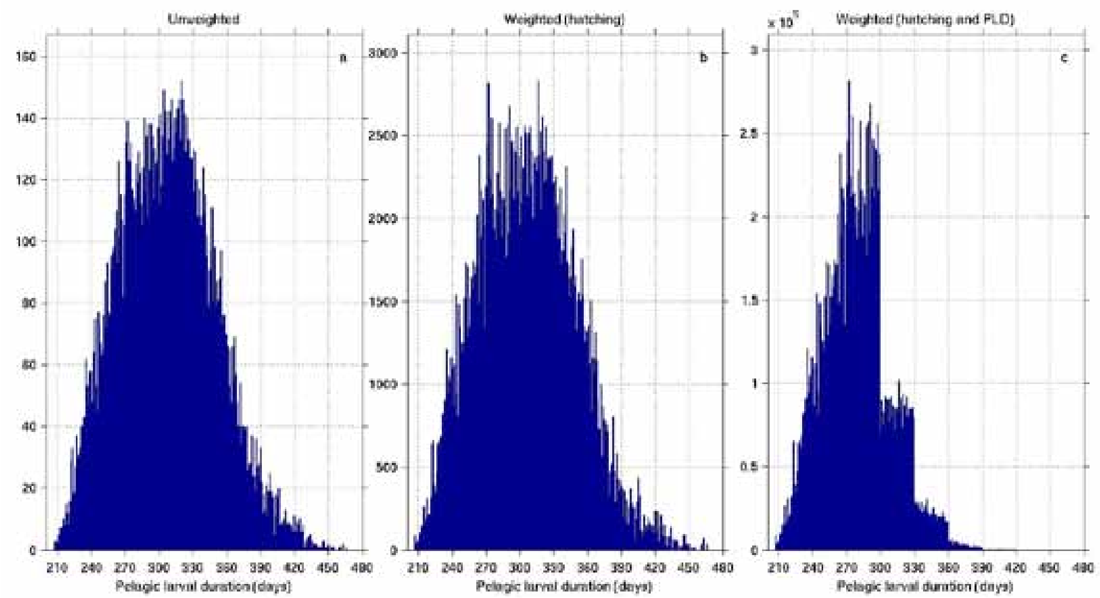


Figure 4.7. 9-year amalgamated distributions of the pelagic larval duration of the returned larvae: (a) unweighted, (b) weighted with monthly hatching rate, and (c) weighted with monthly hatching rate and pelagic larval duration.

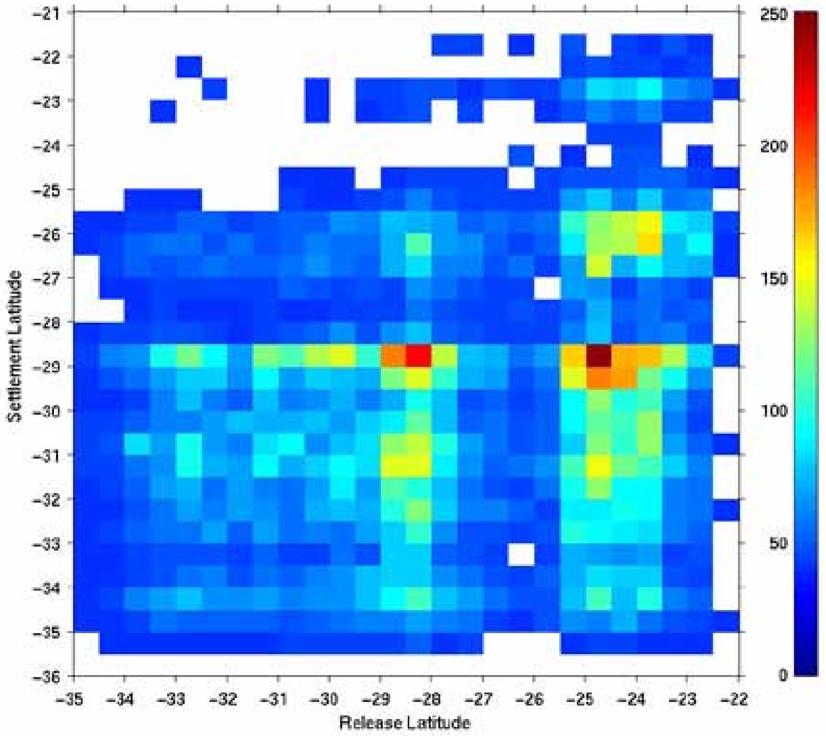


Figure 4.8. 9-year averaged likelihood of source-sink relationship for puerulus settlements off the west coast. The relationship is derived from the weighted (by monthly hatching rate and pelagic larval duration) release latitudes and settlement latitudes of successfully settled larvae as in Figure 4.4c and Figure 4.6c for every half degree boxes, that is, the amalgamated numbers of larvae released from each half degree segment into all the other half degree segments. The weighted numbers are divided by 1000 for this plot.

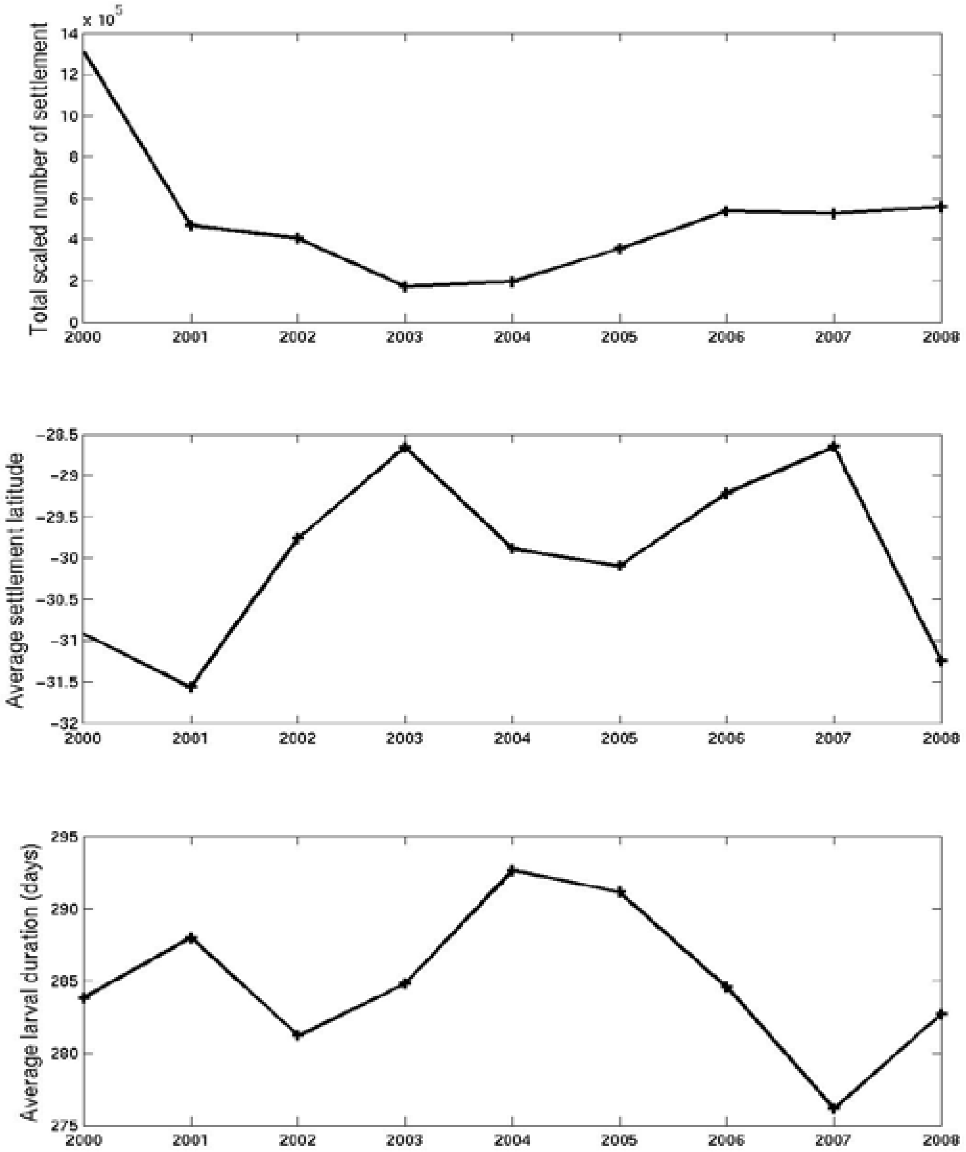
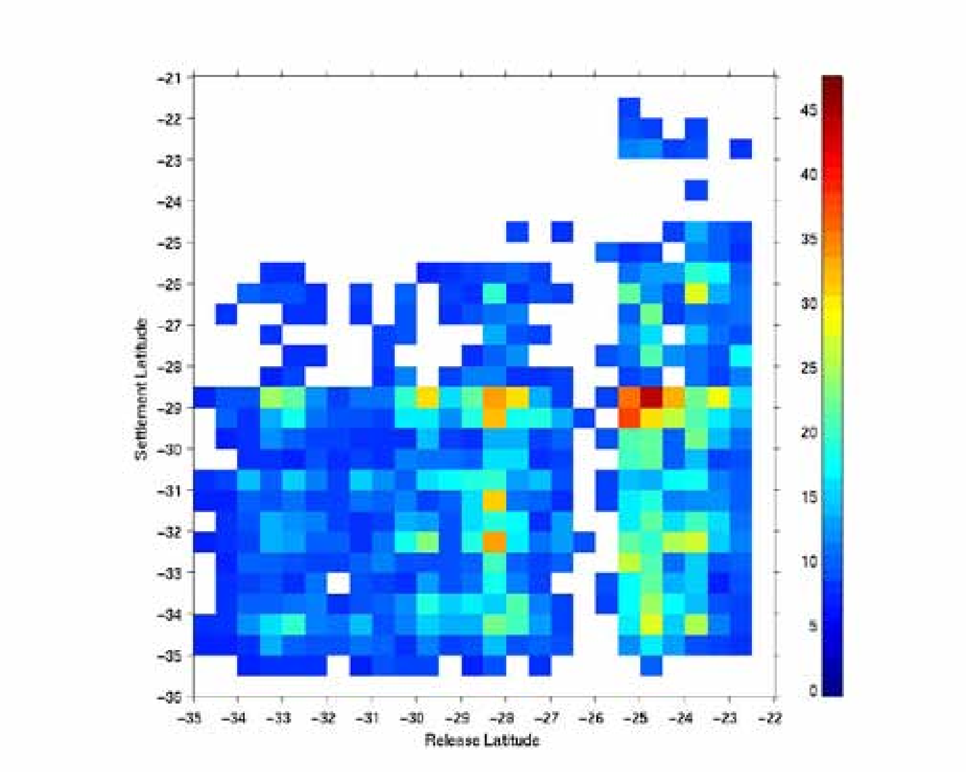


Figure 4.9. (a) Interannual variations of weighted numbers of successfully settled larvae and (b) the average settlement latitudes, for larvae released between 26-29°S.

(a)



(b)

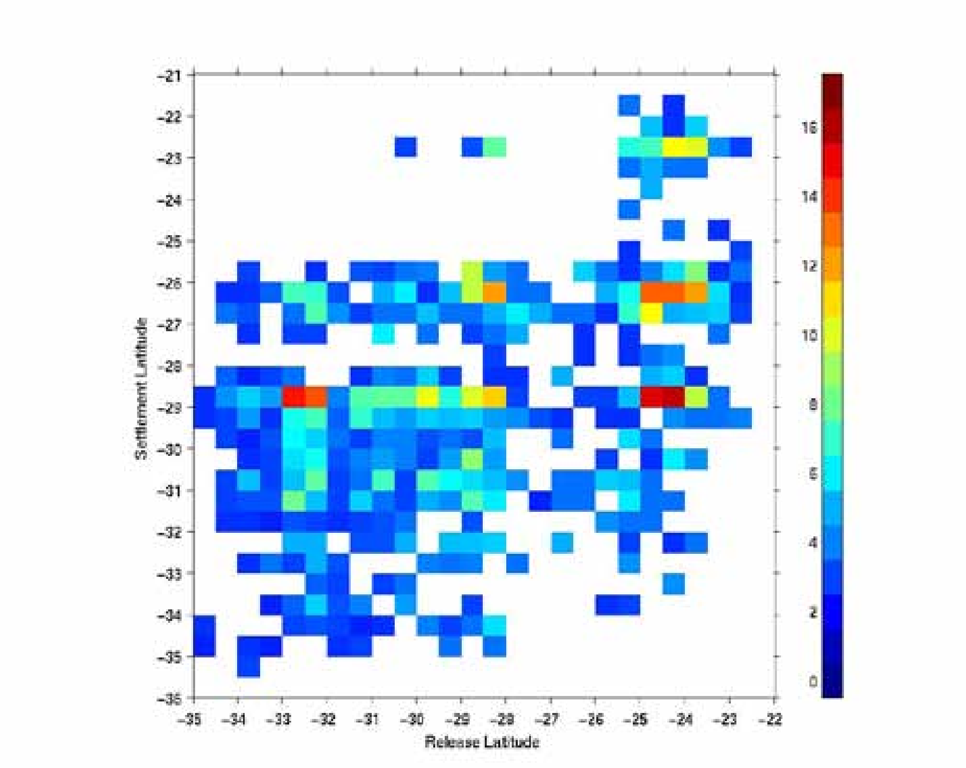


Figure 4.10. Source-sink relationship as per Figure 4.8 for settlement seasons (a) 2000/01 and (b) 2003/04.

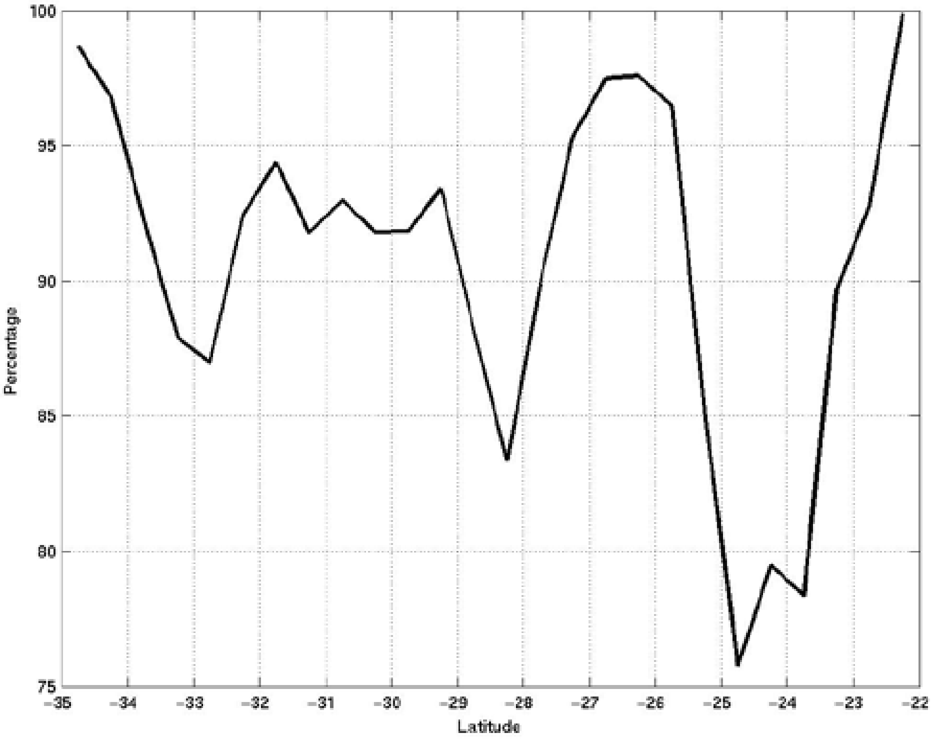


Figure 4.11. Mortality rates on the shelf/land at different latitudes of releases.

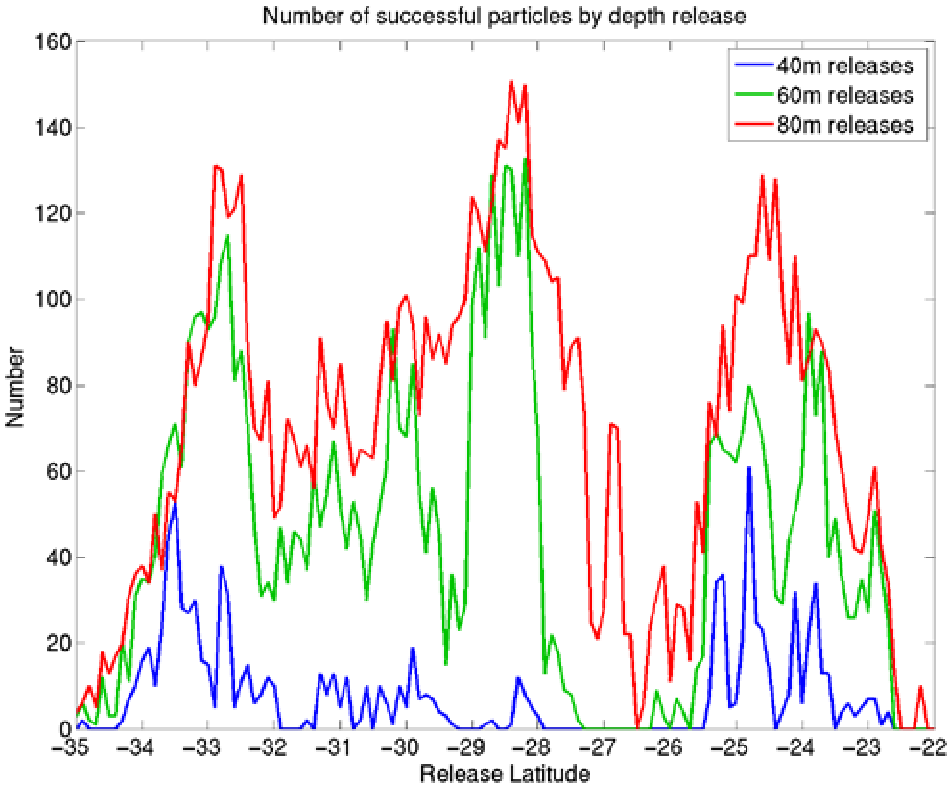


Figure 4.12. 9-year amalgamated release latitude and depth of successful settled particles (puerulus).

5.0 Benefits

The project has produced an improved model which has provided a preliminary understanding of the factors affecting source-sink relationships along the coastline, as well as demonstrating how physical environmental factors interact with spawning areas. Specifically, the project has provided an improved understanding of how physical factors interact with phyllosoma behaviour and provided initial relative assessments of the way spawning location (depth and latitude) is likely to contribute to the successful settlement across the geographic range of the stock. It has also indicated that the source-sink relationship is likely to vary between years suggesting that spawning stocks in all regions should be regarded as being important until a more complex model capable of predicting interannual variability in settlement is developed. This project is the basis for developing the more complex model as part of the FRDC project 2009/087 Identifying factors affecting the low western rock lobster puerulus settlement in recent years.

6.0 Further Development

Further development of the individual based models for puerulus settlement will be focused on three areas:

1. Use the 2009 model to assess the sensitivity of the puerulus settlement to environment variability, which will aid the statistical analyses currently being employed. Some examples are:
    a. Increase (decrease) the effect of the water temperature to shorten (lengthen) the pelagic larval duration of phyllosoma
    b. Increase (decrease) the surface wind corrections to the hydrodynamic model
    c. Increase (decrease) later winter onshore winds
2. Improve the phyllosoma/puerulus behaviour module from the 2009 model, to:
    a. Include proper representation of the influences of lunar cycle and the sea state
    b. Provide a better representation of phyllosoma durations during different development stages
    c. Include improved growth rate and mortality parameters.
3. Fully utilize the new advances in hydrodynamic modelling – there will be a new version of Bluelink model (Spinup6) by the end of 2009. The performance of the new model will be assessed in different WAMSI and Wealth from Oceans Flagship projects. The 2009 larval tracking model and the improved model will be migrated to the new hydrodynamic model once the assessments of the improved Bluelink model are carried out.

7.0 Planned Outcomes

The project has provided a preliminary assessment of factors likely to influence the source-sink relationship. This has suggested that larval releases in the north part of the fishery are more likely to result in puerulus successfully settling on average than those further south. The model suggests that phyllosoma released in the north will tend to experience high temperature and therefore have a shorter overall pelagic duration, compared with those released in the south which tend to experience cooler temperatures. However, the model also suggests that in some years the southern release sites may also be important to the settlement further north in the fishery. These results suggest that breeding stocks in all sectors need to be maintained, but that the highest risk to the fishery is likely to come from depletion of the breeding stock in the more northern regions, including the more offshore release sites at the Abrolhos and Big Bank.

8.0 Conclusion

This project has been successful in the development of an improved oceanographic model that enabled the individual-based model of western rock lobster phyllosoma/puerulus transport and survival from hatching to settlement. Daily outputs from the hydrodynamic model, BRAN (Bluelink ReANalysis), were used to provide the 3-dimensional wind and density driven horizontal velocity fields. A correction term was applied to the surface layer (0-20 m) velocity of the hydrodynamic model outputs, based on scatterometer satellite (QuikScat) derived wind fields. The Stokes drift was taken into account in the hydrodynamic model surface layer using the wave model (WW3 - Wave Watch 3) outputs and added to the velocity profiles from BRAN at each grid cell.

The individual-based model simulated larval and puerulus settlement processes in 9 settlement seasons, from 2000/01 to 2008/09. The model satisfied four key criteria associated with the spatial and temporal distribution of the larvae and the puerulus settlement throughout the average duration of 9-11 months. The assessment of the annual variation of the puerulus settlement abundance and distribution will be the focus of the stage 2 model with another four criteria proposed to assist in fine-tuning the model.

As in the Griffin *et al.* (2001) model, advection alone did not produce a model that satisfied the four criteria, particularly the spatial distribution of the settlement. The increased growth and subsequent increased survival growth of the phyllosoma associated with water temperature was an important component of the model to satisfy the model criteria. In particular, the puerulus settling in the southern part of the fishery generally experienced cooler temperatures during their oceanographic phase which resulted in slower growth and hence lower survival to puerulus. These improvements to the previous model enabled a more realistic distribution of puerlus settlement along the coast.

The modelling indicates that early larval release (mid-October to early December) results in a greater chance of survival to puerulus than late release (mid-January to February). Early-release larvae experience a longer period of warmer temperatures during the summer, which enable them to grow faster and hence increase their survival.

The potential positive effect of warmer water temperature and/or early hatching of larvae on the model puerulus settlement is supported by the negative relationship between the annual level of puerulus settlement and average day of the year that settlement occurs (Caputi *et al.* 2001). That is, good settlement (e.g. 50% above average) in a year is associated with an earlier peak in settlement of about a month compared to a low settlement year.

The model further indicates that there is a trend for much higher settlement success rates associated with larval releases in 60 and 80 m depths compared to 40 m. This is probably a reflection of the additional mortality associated with larvae staying on the shelf for an extended period. That is, phyllosoma hatching in deeper water are further offshore and therefore likely to have a greater chance of moving quickly off the continental shelf. This is illustrated by the high percentage of the unsuccessful larval releases, 75.6%, dying in Category A1, as ocean currents on the shelf are unable to move them offshore within 15 days.

The outputs from the model also suggest a declining trend of the likelihood of settlement success from north to south in the nine years simulated. This appears to result from the model phyllosoma released in the north tending to experience higher temperature and therefore have shorter overall pelagic larval durations, while those released in the south tend to experience cooler temperature and then longer phyllosoma durations. The area north of Shark Bay also appears as a location which is a source of successfully settling model puerulus. However all of these results are based on equal releases at all latitudes, but in reality the larval releases from this region are much less than from the main fishing areas, particularly the Abrolhos region, which is known to have a high abundance of breeding stock. The overall contribution to settlement from this far northern area is therefore unlikely to be large. The significantly lower numbers of successful settlers from releases directly off Shark Bay (26-27°S) probably reflects the modelled location of the releases being close to the coast in this region.

While the model is currently limited by its functionality in relation to replicating interannual variability in the field, the outputs illustrate that it has the capacity to be a very useful tool for evaluating source-sink relationships in the fishery. The limited assessment of the source-sink relationship between years did highlight that a significant variation between years is likely and that releases from all spawning areas may be important in some years. Further development of the model to better reflect interannual variability in natural puerulus settlement and assess impact on the on the source-sink relationship will be a focus of the next phase of model development.

9.0 References

Bleck, R., and D. B. Boudra, 1981: Initial testing of a numerical ocean circulation model using a hybrid (quasi-isopycnal) vertical coordinate. J. Phys. Oceanogr., 11, 755-770.

Bleck, R., and S. Benjamin, 1993: Regional weather prediction with a model combining terrain-following and isentropic coordinates. Part I: Model description. Mon. Wea. Rev., 121, 1770-1785.

Caputi, N, C. Chubb, and A. Pearce, 2001. Environmental effects on the recruitment of the western rock lobster, *Panulirus cygnus*. Marine and Freshwater Research 52:1167–1174.

Chittleborough, R. G. and L. R.Thomas, 1969. Larval ecology of the Western Australian marine crayfish, with notes upon other panulirid larvae from the eastern Indian Ocean. Australian Journal Marine and Freshwater Research, 20,199—223.

Chubb C. F., E. H. Barker, and C. J. Dibden, 1994. The Big Bank region of the limited entry fishery for the Western Rock Lobster, *Panurilus cygnus*. Fisheries Research Report. Fisheries Department Western Australia 101, 1—20.

Feng M., A. M. Waite, and P. A. Thompson, 2009. Climate variability and ocean productivity in the Leeuwin Current system off the west coast of Western Australia. Journal of the Royal Society of Western Australia, 92: 67—81.

Griffin D. A, J. L. Wilkin, C. F. Chubb, A. F. Pearce, and N. Caputi, 2001. Ocean currents and the larval phase of Australian western rock lobster, *Panulirus cygnus*. Marine and Freshwater Research. 52, 1187—99.

Jenkins, A.,1987. Wind and wave induced currents in a rotating sea with depth-varying eddy viscosity. Journal of Physical Oceanography 17: 938–951.

Jeffs A. G., J. C. Montgomery, and C. T. Tindle, 2005. How do spiny lobster post-larvae find the coast? New Zealand Journal of Marine and Freshwater Research 39: 605—617.

Lemmens, J. W., 1994. The Western rock lobster *P. cygnus* : feeding biology and energetics of the puerulus stage. PhD Thesis University of WA. 206pp.

Liddy G. C., B. F. Phillips, and G. B. Maguire, 2004. Effects of temperature and food density on the survival and growth of early stage phyllosoma of the western rock lobster, Panulirus cygnus. Aquaculture 242, 207—215.

Melville-Smith R, D. Johnston, G. Maguire, and B. Phillips, 2009. Establishing post-pueruli grow-out data for western rock lobster. Final FRDC report- Project No. 2003/213, 112p. [Also data in Johnston *et al*, (2008) paper in Aquaculture vol 279, 77—84].

Melville-Smith R, S. de Lestang, and A. Thomson, 2009. Spatial and temporal changes in egg production in the western rock lobster (Panulirus cygnus) fishery. New Zealand Journal of Marine and Freshwater Research, 43: 151—161.

Monismith, S. G., and D. A. Fong, 2004. A note on the potential transport of scalars and organisms by surface waves, *Limnology and Oceanography*. **49**, 1214-1217.

Oke, P. R., G. B. Brassington, D. A. Griffin, and A. Schiller, 2008. The Bluelink ocean data assimilation system (BODAS) Ocean Modelling Volume: 21, Issue: 1-2, 2008, pp. 46-70

Pearce, A. F., B. F. Phillips, and C. Crossland, 1992. Larval distributions across the Leeuwin Current: Report on the RV Franklin cruise FR8/87 August/ September 1987.

Phillips B. F., 1972. A semi-quantitative collector of the puerulus larvae of the western rock lobster *Panulirus longipes cygnus*. Crustaceana 22, 147—54.

Phillips B. F., 1975. Effect of nocturnal illumination on catches of the puerulus larvae of the Western Rock lobster by collectors composed of artificial seaweed. Australian Journal Marine and Freshwater Research. 26, 411—14. [Short paper].

Phillips B. F., 1975. The effect of water currents and the intensity of moonlight on the catches of puerulus larval stage of the western rock lobster. CSIRO Div of Fisheries and Oceanography. Report No 63, 9pp.

Phillips B. F., P. A. Brown, D. W. Rimmer, and D. D. Reid, 1979. Distribution and dispersal of phyllosoma larvae of the western rock lobster, *P. cygnus*. Australian Journal Marine and Freshwater Research. 30, 773—83.

Phillips B. F. N. G. and Hall, 1978. Catches of puerulus larvae on collectors as a measure of natural settlement of the western rock lobster *Panulirus cygnus* George. CSIRO Div. of Fisheries and Oceanography. Report 98, 18pp.

Phillips, B. F., A. G. Jeffs, R. Melville-Smith, C. F. Chubb, M. M. Nelson, and P. D. Nichols, 2006. Changes in lipid and fatty acid composition of late larval and puerulus stages of the spiny lobster (*Panulirus cygnus*) across the continental shelf of Western Australia. Comp.Biochem.Physiol., B 143, 219-228.

Phillips B. F. and P. S. McWilliams, 2008. Spiny lobster development: where does successful metamorphosis to the puerulus occur?: a review. Review Fish Biol. Fisheries. (On line publication at Springerlink.com). 23pp.

Phillips B. F. L. and Olsen, 1975. Swimming behaviour of puerulus larvae of western rock lobster. Australian Journal Marine and Freshwater Research. 26, 415—417.

Phillips, B. F. and A. F. Pearce, 1997. Spiny lobster recruitment off Western Australia. Bull. Marine Science, 61, 21—41.

Phillips, B. F. and D. W. Rimmer, 1975. A surface plankton sampler for larval stages of the western rock lobster. Australian Journal Marine and Freshwater Research. 26:275—80. (Short paper)

Phillips, B., D. Rimmer, and D. Reid, 1978. Ecological investigations of the Late stage phyllosoma and Puerulus larvae of the Western Rock lobster *P. longipes cygnus*. Marine Biology 45, 347--357

Rimmer, D. W. and B. F. Phillips, 1979. Diurnal migration and vertical distribution of phyllosoma larvae of the western rock lobster *Panulirus cygnus*. *Marine Biology (Berlin)* 54, 109-124.

Ritz, D., 1972. Factors affecting the distribution of rock lobster larvae [P. cygnus] with reference to variability of plankton- net catches. Mar. Biol. 13, 309—317.

Ritz, D., 1972. Behavioural response to light of the newly hatched phyllosoma larvae of *Panulirus longipes cygnus*. J. Exp. mar. Biol. Ecol. 10, 105—114.

Schiller, A., P. R. Oke, G. Brassington, M. Entel, R. Fiedler, D. A. Griffin, and J. V. Mansbridge, 2008. Eddy-resolving ocean circulation in the Asian-Australian region inferred from an ocean reanalysis effort. Progress in Oceanography 76(3), 334-365.

Tolman, H. L., 2002. User manual and system documentation of WAVEWATCH-III version 2.22. NOAA / NWS / NCEP / MMAB Technical Note 222, 133 pp. (0.89Mb pdf file).

10.0 Appendices

Appendix 1 (Intellectual Property)

Background IP: CSIRO include BLULink model output

IP from this project: tools of tracking lobster larval movements adapted to BLUELink model output

Appendix 2 (Staff List)

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Appendix 3 (Raw Data/ Other Relevant Material)

Matlab code of the particle tracking model is available for further sensitivity tests in future research projects. Data generated by this project includes: Statistics of lobster larval movements from the particle tracking model.

The data custodian of the outputs is the CSIRO Marine and Atmospheric Research, Perth, Western Australia.