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Identifying factors affecting the low western rock lobster puerulus settlement in recent years

Final FRDC Report – Project 2009/18

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1.0 Non-Technical Summary

2009/18 Identifying factors affecting the low western rock lobster puerulus settlement in recent years

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Objectives

1. To use a larval advection model and the rock lobster population dynamics model to assess the effect of the spatial distribution of the breeding stock on the puerulus settlement
2. To assess environmental factors (water temperature, current, wind, productivity, eddies) and breeding stock affecting puerulus settlement
3. To examine climate change trends of key environmental parameters and their effect on the western rock lobster fishery

Outcomes achieved to date

The key outcomes of this project include:

- An understanding of the relative importance of breeding stock and environmental factors that may have contributed to the below-average puerulus settlement for six consecutive years (2006/07 to 2011/12).
- Identifying that the Big Bank breeding stock was being affected by a low level of migration caused by a combination of environmental conditions and fishing pressure. This resulted in the management closure of this area in 2009 to protect and rebuild the breeding stock and the establishment of an annual survey in the area.
- Providing information to support adoption of early management interventions following the series of low settlements to increase protection of the overall breeding stock. These management measures were designed to generate a carryover of legal-sized lobsters into years of lower recruitment through effort reductions, introduction of catch quotas, and reducing the maximum size of females.
- As a result of these management actions, the breeding stock has been well above average since 2010 in the six areas monitored since the early 1990s. Hence the spawning stock was not the major factor affecting the extended period of low settlement.
- The oceanographic larval models indicated that the breeding stock at all locations along the West Coast is likely to be important to the settlement.
- The environmental factors, which could have contributed to the low puerulus settlement, may be influenced by climate change. This enables the managers, scientists and industry to take these potential longer-term effects into account in future management planning.
- The Marine Stewardship Council endorsed the certification of the western rock lobster fishery for another five years in 2012. The audit process included an examination of the research undertaken within this FRDC project to assess the cause of the low settlement as well as the management approach adopted to deal with the low settlement.

The settlement of puerulus for western rock lobsters has remained below the long-term average for six consecutive years (2006/07 to 2011/12) with 2008/09 being the lowest in over 40 years. This has occurred despite a strong Leeuwin Current, which is usually associated with above-average settlement, occurring in 2008 and 2011 and relatively high breeding stock levels in most areas of the fishery after the 2010/11 breeding season.

An associated FRDC project 2008/087 examined the source-sink relationship of the fishery using oceanographic larval modelling. Sensitivity analyses have been conducted on the initial model by a systematic adjustment to the parameters of the model and using a post-model statistical analysis of the model output. The post-model assessment correlated the actual and model puerulus settlements to identify the effect of varying some of the model parameters. This sensitivity analysis has identified the following parameters as being important in this assessment: (a) wind effect on the water movement; (b) the level of puerulus swimming allowed in the model; (c) the month of larval release; (d) the abundance and spatial distribution of larval release and (e) larval duration before settlement. The correlation between model and actual puerulus settlement in the main areas of the fishery was significantly improved when the larval release was concentrated in the early months. The reasons why settlement is more sensitive to early releases than later releases is being examined. The different models examined indicated that breeding stock at all locations may be important to the settlement and the low settlements in recent years are to a certain extent due to weakened onshore movement of ocean currents that bring the phyllosoma back to the shelf. The oceanographic model was not able to achieve a reasonable fit to the puerulus settlement in 2011/12 possibly because this was associated with a marine heat wave event that occurred in early 2011 with record high water temperatures. A reassessment of the temperature effects on larval growth/survival at very high temperatures is therefore required.

Oceanographic and meteorological data sets have been examined to understand the effect the environment may have had on rock lobster recruitment. An assessment of the effects of ENSO events and Indian Ocean Dipole on the marine environment off WA and on the rock lobster spawning and recruitment dynamics has been undertaken. A statistical assessment has been undertaken on the relationships between environmental variables at an appropriate spatial and temporal scale with some biological aspects such as migration, timing of spawning, and puerulus settlement. The Leeuwin Current has been shown to affect the pre-spawning northerly migration of rock lobsters in deep water (100-200 m). This has affected the abundance of lobsters in the northern part of the fishery e.g. north of the Abrolhos Is. and Big Bank, as the current strength has generally been above average in January of 2001 to 2008, which will have contributed to a lower level of northern migration. The breeding stock in this northern area was identified as being relatively low. Management measures were introduced in 2009 to stop fishing in Big Bank and there have been significant effort reductions (50-70%) in recent years to increase migration of lobsters into deep water and contribute to the fishery-wide breeding stock. Fishery-independent monitoring of the breeding stock at Big Bank in the last three years has shown a significant improvement since the closure was implemented. The breeding stock has been above average since 2010 in all other six areas monitored since the early 1990s. Hence the spawning stock was not the major factor affecting the extended period of low settlement.

Changes in water temperature during February have historically been associated with significant effects on early puerulus settlement. This relationship has, however, broken down in recent years as the water temperature variation is no longer consistent with the recent pattern of low settlement. The oceanographic model identified the timing of spawning as an important factor explaining some of the variation in puerulus settlement. An examination of the timing for the start of the spawning period based on data from the fishery-independent breeding stock survey has indicated that in recent years there has been an earlier start to the spawning season compared to previous years. This earlier start appears to be due to higher water temperatures near the onset of spawning (October) which have been recorded since the mid-2000s. This may be a key factor why recent years have had consistently below-average settlement. It is possible that the earlier spawning causes a mismatch with other environmental factors such as peaks in ocean productivity and/or storms (westerly winds) that assist the larvae return to the coast.

Rainfall during July to November was identified in the early 1990s as being a significant factor related to puerulus settlement. In this study rainfall during May-October when combined with the breeding time index provided a good fit (R^2=0.72) to the variation in puerulus settlement since the early 1990s. The rainfall represents an index of storm activity affecting the lower west coast of WA. It influences water conditions and is generally associated with westerly winds that may help bring larvae back to the coast. These two variables (breeding time and storms) provide a plausible hypothesis to explain the decline in puerulus settlement in recent years. The 2012/13 settlement provides a test of this relationship and indications are that it will be below average which is what is predicted by the two variables. The later breeding time in 2012 may result in an improved settlement in 2013/14 and preliminary indications are that it will be above average. There may be climate change implications associated with the environmental factors (water temperature and storm activity) affecting the spawning and larval period as both these variables are showing long-term trends.

KEYWORDS: Western rock lobster, oceanographic larval modelling, source-sink, puerulus, water temperature, rainfall, environmental effects, timing of spawning, climate change

2.0 Acknowledgements

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3.0 Background

The low puerulus settlement in 2006/07, 2007/08 and 2008/09 at all the major locations within the western rock lobster fishery (Figures 3.1 and 3.2) was the initial impetus to developing this project. This project is complementary to the FRDC tactical funded research project (2008/087) which involved the redevelopment of a previous oceanographic model to urgently examine the movements and distribution of the larval/puerulus stages and undertake a preliminary assessment of the source-sink relationships for the western rock lobster. This three-year project has examined the relative importance of environmental factors and breeding stock in influencing the recent years of low puerulus settlement. The new oceanographic larval model developed has updated the biological parameters used in the previous models and used the outputs from an integrated spatial stock assessment model of the western rock lobster fishery as indicators of the status of the breeding stock overall and in specific source locations identified by the previous oceanographic model. A scientific workshop was convened in September 2009 to review all the possible factors affecting the puerulus settlement in recent seasons and identify hypotheses for testing with the new model.

An additional impetus for undertaking this project to develop a new oceanographic model was that climate change effects (a long-term warming trend in coastal water temperatures) have been demonstrated to affect many aspects of the life history of the western rock lobster fishery (Caputi *et al*. 2010a). These effects include the impact of increasing temperatures during the phyllosoma larval phase, Leeuwin Current effects on the spatial distributions of puerulus, reduced migration of white lobsters to northern breeding stocks and decreases in the size at maturity and migration. Other climate factors potentially affecting the fishery that were considered, included changes in ocean productivity and variations in the storm activity that affected wind systems off the Western Australian coast (Indian Ocean Climate Initiative 2012).

This project, which assessed the cause(s) of the low settlement, was identified as a high priority by the Rock Lobster Industry Advisory Committee (RLIAC) Research Sub-committee, the Chairpersons of RLIAC and the Western Rock Lobster Council (WRLC), and the rock lobster managers of the Department of Fisheries. Specifically, the future management of the fishery is dependent on understanding whether the recent run of low settlements has been due to short-term environmental effects, long-term climate change effects, or breeding stock effects (overall or in parts of the fishery) or a combination of these factors.

The focus of this report is to use the oceanographic larval modelling and statistical assessment of environmental and biological factors to evaluate the causes of the low settlement.

4.0 Need

At the time that this project was being planned, a number of years of below-average puerulus settlement had occurred including 2007/08 which was the second lowest in 40 years. The early months of the 2008/09 settlement season had also indicated that the settlement levels would be even lower. This below-average level of puerulus settlement continued through to 2011/12 (Figure 3.2).

Previous studies had shown that environment factors such as the strength of the Leeuwin Current and storms in late winter/spring typically affect the abundance and spatial distribution of puerulus settlement (Caputi *et al*. 2001). However during the series of low recruitments since 2007/8, these factors were no longer able to explain the downturn. It was therefore important to identify other environmental influences that may have contributed to the atypically low recruitment and whether any factors identified were exhibiting long-term trends, which could explain the new lower settlement levels. Secondly, the project needed to consider whether the breeding stock in some parts of the fishery is particularly critical to the success of puerulus settlement (as indicated by the previous preliminary source-sink assessment, Caputi *et al*. 2010b, Feng *et al*. 2011b) and model the impact of subsequent changes in breeding stock levels across the fishery.

Advances in quality of satellite data in the 1990s measuring sea surface topography (satellite altimeters) and chlorophyll/productivity (ocean colour sensors) have enabled significant improvements in our understanding of the environmental factors, with the assistance of oceanographic modelling. Previous oceanographic models were of necessity also focused on the open ocean circulation off the continental shelf. Recent advances in modelling have also enabled the development of high-resolution models at 10 km spatial scale, which resolve the dominant processes on the shelf. As a result of these significant changes in ocean monitoring and computer technology generally, there was a need to develop a new larval transport model. This was started with the short-term project and has now been completed with the model now available.

The use of this new modeling system to better understand the causes of recruitment variability and identify any potential long-term trends has important implications in the stock assessment and management of the fishery. That is, the management response would be significantly different if the cause of the series of low recruitments was shown to be mainly due to reduced egg production (overall or particular parts of the fishery) rather than variations in environmental factors outside of management control. However, if there are long-term environmental trends that affect the average recruitment to the western rock lobster stock, then some adjustment to the sustainable harvest rate will also be required.

5.0 Objectives

1. To use a larval advection model and the rock lobster population dynamics model to assess the effect of the spatial distribution of the breeding stock on the puerulus settlement
2. To assess environmental factors (water temperature, current, wind, productivity, eddies) and breeding stock affecting puerulus settlement
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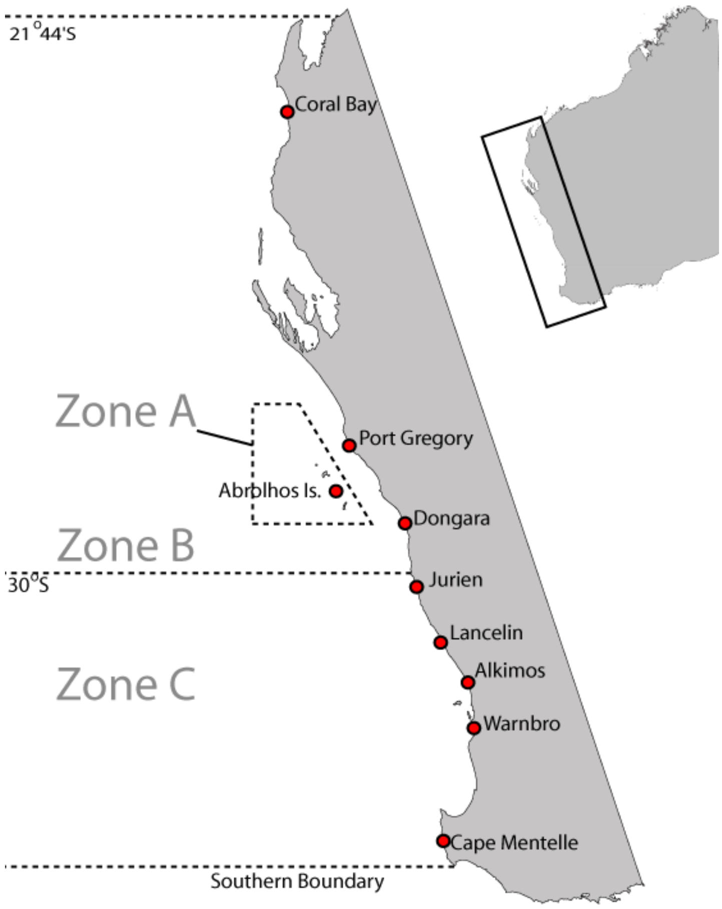


Figure 3.1. Location of current (2012) puerulus settlement sites along the coast.

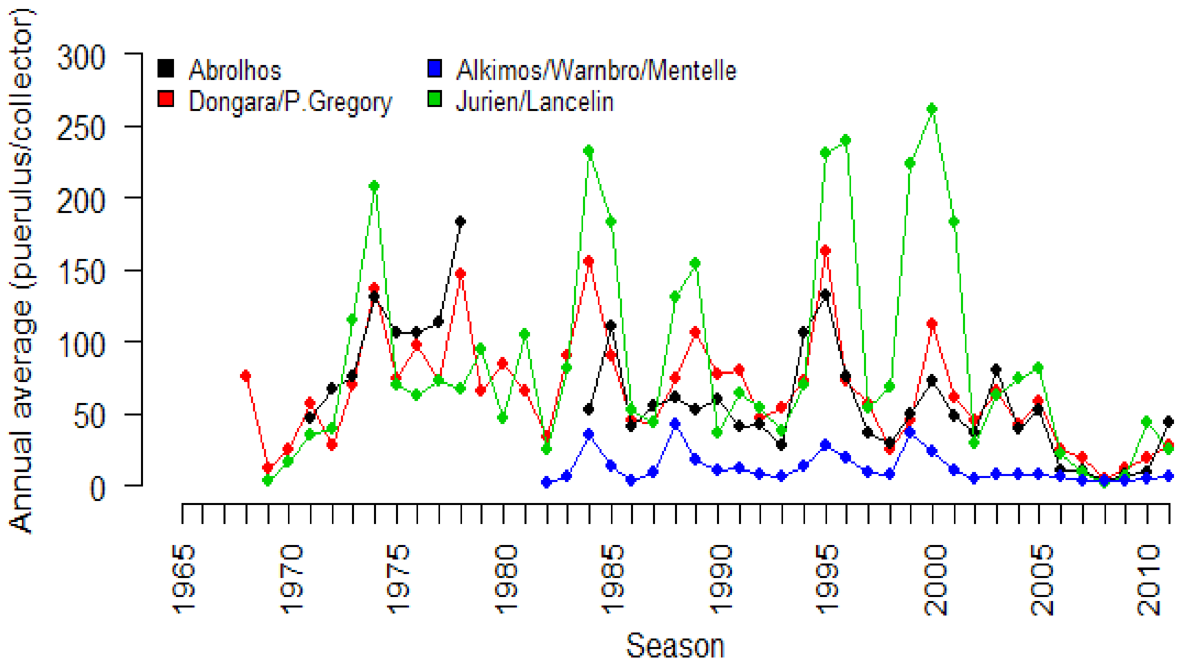


Figure 3.2. Puerulus settlement time series from 1968/69 to 2011/12 with the first year of the season shown.

6.0 Methods

6.1 Oceanographic larval model

6.1.1 Previous model

An oceanographic larval model (2009 model) was developed to simulate western rock lobster (WRL) larval and puerulus settlement processes during nine settlement seasons, 2000/2001 to 2008/2009, for which the data used in wind and wave induced surface current corrections were available (Caputi *et al.* 2010, Feng *et al.* 2011b). The model domain was defined as the waters off the Western Australia (WA) coast between 18-40°S and between 101-129°E. For each settlement season, the model allowed phyllosoma to hatch from mid-October to mid-March, and then tracked the released particles (model phyllosoma) through to successful settlement or their demise which could occur up to the maximum survival period of 420 days (14 months) permitted in the model. A database of the successfully settled particles was maintained and used in post model analysis to investigate factors such as the timing of hatching/release, depth of release, location of hatching etc., and how they influenced puerulus settlement success. These model settlements were assessed against actual puerulus settlement data for the collector sites along the coast over the same years.

The 2009 model 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 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 and more years of data are examined.

The key features of the 2009 physical and larval model are:

Physical model

- In the 2009 model (Caputi *et al*. 2010, Feng *et al*. 2011b), the Bluelink reanalysis (BRAN), developed for the Australian region (Schiller *et al*. 2008), was used to quantify the ocean circulation. BRAN uses the European Centre for Medium-Range Weather Forecasts reanalysis data for wind stress and heat and freshwater flux forcing at the sea surface and assimilates satellite altimeter and other in situ data (Oke *et al*. 2008). BRAN was used to create a 1993 to May 2008 archive of daily values of ocean properties, including ocean currents, salinity, and temperature in three dimensions — resolved at 10 km horizontally and 10 m vertically (in the upper ocean; i.e., to 300 m) for the eastern Indian Ocean study region. For the recent period (i.e., from May 2008) where BRAN was not available, an equivalent forecast product based on BRAN (Brassington *et al*. 2007) has been used.
- QuikScat satellite-derived wind data has been used to generate a correction to the BRAN surface currents. The QuickScat-derived twice-daily global wind speed data at 1/4 degree by 1/4 degree resolution has been averaged into daily values and smoothed in time using a seven-point Hanning filter. The correction term was calculated using 1% and 3% of the wind speed and 20 degrees to the left of wind direction (e.g. Jenkins 1987) and applied to areas

deeper and shallower, respectively, than 200 m. The correction is then interpolated onto the BRAN velocity grid and applied in the 0–20 m layer.

- To further improve the surface water movements, the WAVEWATCH III model (WW3) incorporating significant wave height, wave period, and direction data (Tolman 2002), has been used to derive Stokes drift velocities in the surface layer (0–20 m) off the coast of WA.

Larval model

- Equal numbers of particles were released in the model from 16th October of year (–1) to 15th March of year (0) to cover the full hatching season, at three designated release depths of 40, 60, and 80 m, except in the Big Bank area where 100 m is used instead of 80 m.
- A new "category" system was devised to represent groups of phyllosoma and puerulus stages that could be assigned similar biological characteristics – behaviour in the model. Category A, B, and C particles represent the early (stages I, II, and III), middle (IV, V, VI), and late (VII, VIII, IX) stages of phyllosoma, respectively. Natant (or swimming) puerulus were designated as D1 particles and the settled puerulus as D2.
- Category A: 90 days; B: 60 days; C: > 120 days (C1: 120 days before phyllosoma is capable of metamorphosis); maximum 420 days of total larval duration; vertical migration and vertical profiles were defined for different categories.
- Temperature-dependent larval growth rate
- Shelf mortality: 15 days allowed for category A to remain on shelf and instant mortality for category B and C1 on the shelf.

A summary of the key points from the 2009 model assessment were:

- The model was able to replicate the general larval development process and match the general distribution of puerulus returning to the coast.
- The model was not able to replicate the annual variation in puerulus settlement and the significantly lower recruitment in 2008/09 and 2009/10.
- The model suggested eggs released towards the very northern part of the fishery (e.g. Northern Abrolhos Islands & Big Bank) appear to have a much higher chance, on average, of successfully recruiting as puerulus.
- Settlement success may also be greater for eggs released from deeper water areas (80-100 m) closer to the edge of the continental shelf.
- The water movements generated by the swell (Stokes drift) in winter were identified in the model as a critical factor in the return of phyllosoma and puerulus to the coast.
- The effect of temperature on the growth and survival of larvae was identified as an important component affecting settlement success.
- Higher settlement was associated with early larval release (Nov-Dec) compared with late releases (Feb).

While the 2009 model is currently limited by its functionality in relation to replicating interannual variability in the field, the outputs illustrate that it had 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 was focused on three areas. These were to use sensitivity testing to incorporate environment variability into the model, to improve the biological module to better reflect the behaviour of the phyllosoma/puerulus stages, and fully incorporate the new advances in hydrodynamic modelling and observations.

The individual-based model (IBM) developed, simulated larval and puerulus settlement processes in 9 settlement seasons and generally 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 in the main areas of the fishery was the focus of the stage 2 model of this project to assist in fine-tuning the model. The number of puerulus settlement seasons examined was extended to 18 years (1994/95 to 2011/12).

6.1.2 Model criteria

The performance criteria adopted for the assessment of the 2009 oceanographic larval model were:

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). 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.
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).

The focus of this study was on assessing the model against the additional criteria that:

1. The model settlement should generally match the annual variation in settlement over the main area of the fishery including the series of low settlement since 2006/07.

6.1.3 Sensitivity testing and model changes

The current model (referred to as the 2012 model) has been developed by updating the previous 2009 model (Feng *et al*. 2011b) to include more recent oceanographic inputs and by further improving the biological parameters used to reflect patterns of phyllosoma hatching and behaviour. The model has been updated as the outputs from sensitivity testing have become available. The process to get the model outputs (model puerulus settlements) to better reflect the annual variation and latitudinal distribution of puerulus settlement, has involved two major revisions and many small modifications to the model structure during the three year project period.

2012 Physical model

The updating of the physical model has included:

- Ocean currents and temperatures: The BRAN oceanographic data series, available from 1993 to May 2008, has been extended to cover the period from May 2008 to March 2012 using OceanMAPS outputs, a BRAN forecast product (Brassington *et al*. 2007). Specifically the BRAN outputs plus OceanMAPS have been used in the model to generate ocean currents and temperatures covering the period from 1993 to March 2012. The two products overlap from October 2007 to May 2008 and the correlations for the U and V components of broad-scale ocean currents are 0.93 and 0.89 respectively (Figure 6.1.1) suggesting that the two data sets can be reasonably combined.

- Wind speeds: As a result of the demise of QuickScat satellite, ERA-interim winds have been used to replace satellite winds for the purpose of surface current correction in the model. The correlations between the two wind products are higher than 0.9 on monthly time scale; however, the ERA-interim meridional winds seem to underestimate peak summer winds recorded by QuikScat (Figure 6.1.2). The current model uses the ERA-interim wind data series, and in standard models adopts 1.5% of wind speed as the surface current correction, although an increased correction of up to 3% of wind speed has been used in sensitivity testing. Further, in the later model runs, only winds at night (when the larvae are at the surface) have been used for surface current corrections, to better reflect currents affecting the phyllosoma and puerulus. In the final run, 2012j, the wind correction is set at 3% for category A particles and 1.5% for latter stages, consistent with the 2009 model run.
- Stokes drift: The ERA-interim wave product has been used to replace the original NCEP Wave Watch 3 data (to be consistent with the wind speed correction) in the calculation of Stokes drift (the surface water movements generated by the swell) which proved to be a key component of the 2009 model.

2012 Larval model

A number of improvements have been made to the biological parameters in the 2012 model, to better reflect the phyllosoma/puerulus behaviour described in the historical literature and recent publications. While this updated information has been used to improve the model, the basic oceanographic and biological structures in the model remain similar to the 2009 model (Caputi *et al*. 2010, Feng *et al*. 2011b). Of particular note is that new data on the distribution and seasonality of rock lobster breeding/phyllosoma hatching has been incorporated in the model outputs, through the post model analysis process, i.e. using these data to adjust the survival of the successfully settled puerulus from the model runs. The major variations from the 2009 model are as follows:

1. <u>Phyllosoma release sites:</u> the range of release depths has been changed to include particles now being released at 90, 70 and 50 m uniformly on the main coastline, and inside the Abrolhos Islands (only) particles are also released at 30 m reflecting the unusual breeding distribution in that area.
2. <u>Phyllosoma release dates:</u> To accommodate the new information on variations on the start of the hatching season derived from the independent breeding stock survey (IBSS) database, the model hatching season has been extended forward from October 15 to September 1 for the start of the spawning season and from March 15 to March 31 at the end of the spawning season in all years. This has allowed the post model analysis process to now include the assessment of the impact of annual variations in the general time of hatching, as well as variations in the hatching season at different latitudinal locations across the fishery.
3. <u>Early-stage phyllosoma:</u> To address the issue of on-shelf mortality during category A phyllosoma phase in the 2009 model, which was excessive relative to literature estimates, a number of changes have been incorporated. This need for further refinement in the model was

also supported by newly available information from satellite-tracked drifters with drogues set at category A larval depths (10 m). These drifters released during the rock lobster breeding season at hatching locations along the coast, also indicated that offshore drift of passive larvae can be a slow process. These drifters generally went north and offshore strongly supporting the historical literature (Rimmer 1980), which showed early stage phyllosoma consistently moved off the shelf in the first few weeks. To improve this aspect of the model, boundary reflection was introduced and category A phyllosoma were permitted to survive for extra time on the shelf (i.e. up to 60 days). Further categories B and C1 were also permitted to survive on the shelf for 10 days before termination. These survival periods replace the previous 15 day limit on the shelf for category A and instant mortality for categories B and C1. Note that there is a now a mortality factor that is accumulated through different categories. Temperature-dependent mortality remains the same as in the 2009 model.

4. <u>Total larval duration:</u> To allow more flexibility in the window for settlement, the maximum phyllosoma duration was increased from 420 to 540 days. This allowed the final phyllosoma stage (category C2) to survive for up to 300 days during which time metamorphosis to puerulus could occur, i.e. if the phyllosoma particle crosses the continental shelf boundary (1000 m depth contour). Sensitivity tests were carried out for the total C2 growth period ranging from 240-300 days.

5. <u>Phyllosoma growth rates:</u> the model temperature-growth relationship previously used had the maximum growth at 26°C in line with aquarium information. The maximum growth has been reset to occur at 26°C in line with the correlation between the offshore SST temperatures and actual puerulus settlement, which indicated that maximum settlement occurred when SSTs were at about 26°C. This maximum growth rate – temperature relationship in the model has allowed the model phyllosoma growth to better reflect the temperatures input to the model, which are based on the 0-30 m average temperature of model output. In this context, it was recognised that a sea surface temperature is likely to be one or two degrees higher than that actually experienced by the phyllosoma, which are always at depth during the day and only in the surface layers at night when surface temperatures decrease. In this context, 25°C in the model SST is probably equivalent to 23°C found to be optimal for growth in the rock lobster aquaculture literature.

6. <u>Puerulus metamorphosis and behaviour:</u> The criteria for triggering late stage phyllosoma to metamorphose to puerulus in the 2009 model has been retained as there are no other data available to use for this purpose. However, some changes to the diurnal and swimming behaviour have been tested and incorporated in the current model. The changes from the previous model have included: (i) programming the puerulus to be stationary at depth during the day and only swimming to the surface at night (for 8 hours); for example, in the 2012j model run, the category C2 phyllosoma and puerulus only come to the surface when the wind speed is above 7.5 m/s; and (ii) applying a range of swimming speeds within the known range for the species. To assess the impact of these changes on the model puerulus settlement, three puerulus swimming strategies have all been trialled in separate model runs. These were: (a) puerulus stationary at depth during the day and coming to the surface at night and swimming towards the coast at speeds of 5 cm/sec, (b) as for (a) but with night swimming at 10 cm/sec, and (c) stationary at depth during the day, moving to the surface and remaining in the surface layer at night, but with no directional swimming at night i.e. being moved passively by the surface currents at night. These variations were based on the historical accounts of puerulus swimming behaviour and recent assessments of swimming speeds relative to survival times, based on the nutritional reserves of equivalent puerulus (Wilkin and Jeffs 2011). It appears

that the settlement late in the season may come from an extended C2 and puerulus stage, so that we have relaxed the puerulus duration to 120 days, which can be adjusted in post-model analysis. As the majority of the metamorphosed puerulus settle to the coast within about 20 days, the extended puerulus duration does not significantly affect the results.

6.1.4 Sensitivity testing: post model assessment

The sensitivity of some model parameters (e.g. larval behaviour and puerulus swimming ability) could only be evaluated within the larval model while others (e.g. month and latitude of larval release) could more easily and efficiently be evaluated in a post model assessment. Therefore sensitivity analyses have been conducted using a systematic adjustment to the parameters of the model (section 6.1.3) as well as a statistical approach in a post model assessment (this section) for a range of suitable models.

For this post model analysis, a database of the successfully settled particles from the full array of release dates and locations was maintained for a number of models which provided reasonably appropriate settlement distributions and timing. This post model analysis enabled an investigation of factors such as the timing of hatching, location of hatching, mortality during larval stage, and how they influenced puerulus settlement success.

A sensitivity analysis using a combination of weightings was applied to the successful model settlement from each of the following categories:

- month of hatching – (i) average monthly distribution with peak in December applied to all years as per Feng *et al*. (2011b); (ii) 2 weeks early applied to all years; (iii) 2 weeks late for all years; (iv) individual annual variation applied based on IBSS assessment; (v) northern location 2 weeks early and southern locations average; (vi) northern locations average and southern 2 weeks late; (vii) separate assessment for 15 September-15 October, 16 Oct-30 Nov, Dec-Jan, Feb - 15 Mar;
- latitude of hatching – (i) average distribution assumed for all years; and (ii) separate abundance and spatial distribution applied to individual years using output from stock assessment model;
- mortality during larval phase – (i) related to total larval duration; (ii) related to larval duration in Category A; (iii) daily mortality with additional mortality applied for extreme temperatures.

A statistical analysis correlating the actual puerulus settlement for the collector sites along the coast for the main area of the fishery (see Section 6.4) and the model puerulus settlement (weighted by combinations of the above categories) over the same year has been undertaken to identify the effect of varying some of the model parameters and assessing their effect on the correlation. The main focus of the statistical analysis was the comparison of the annual puerulus settlement and the secondary focus compared the latitudinal and monthly distribution as an average for all the years as well as examining the annual variation in the latitudinal and monthly distribution. These analyses were initially undertaken for the puerulus settlement years before the decline (1994/95 to 2006/07) and then for all years (with and without the most recent year 2011/12 that was associated with a record high water temperatures associated with the marine heat wave (Pearce and Feng 2013)).

A statistical analysis that estimated some of the post model parameters that optimised the correlation between annual actual and model settlement was also undertaken. For example, an estimate of the monthly distribution of hatching was obtained that optimised the correlation between model and actual puerulus settlement.

The spatial distribution of all phyllosoma larvae released each month (September to March) were plotted on a monthly basis with the number of puerulus settling each month recorded. This enabled a visual comparison of spatial distribution for each of the 18 puerulus settlement seasons (1994/95 to 2011/12) examined. The larval distribution could also be combined over the months (with or without weighting for monthly hatching) and taking into account the latitude distribution of hatching.

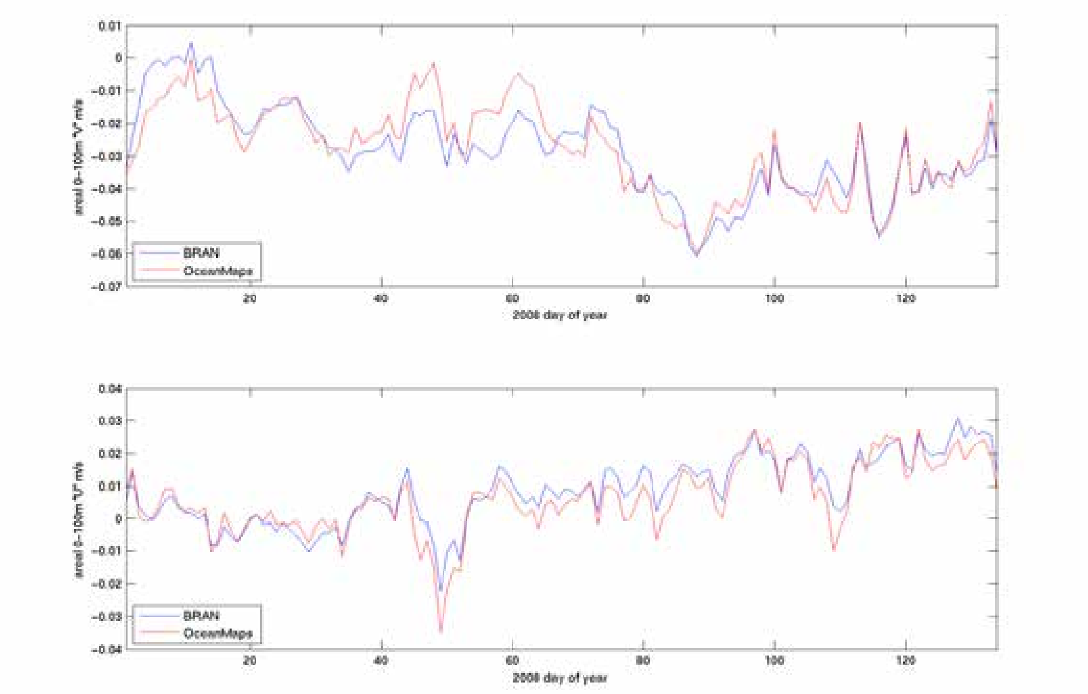
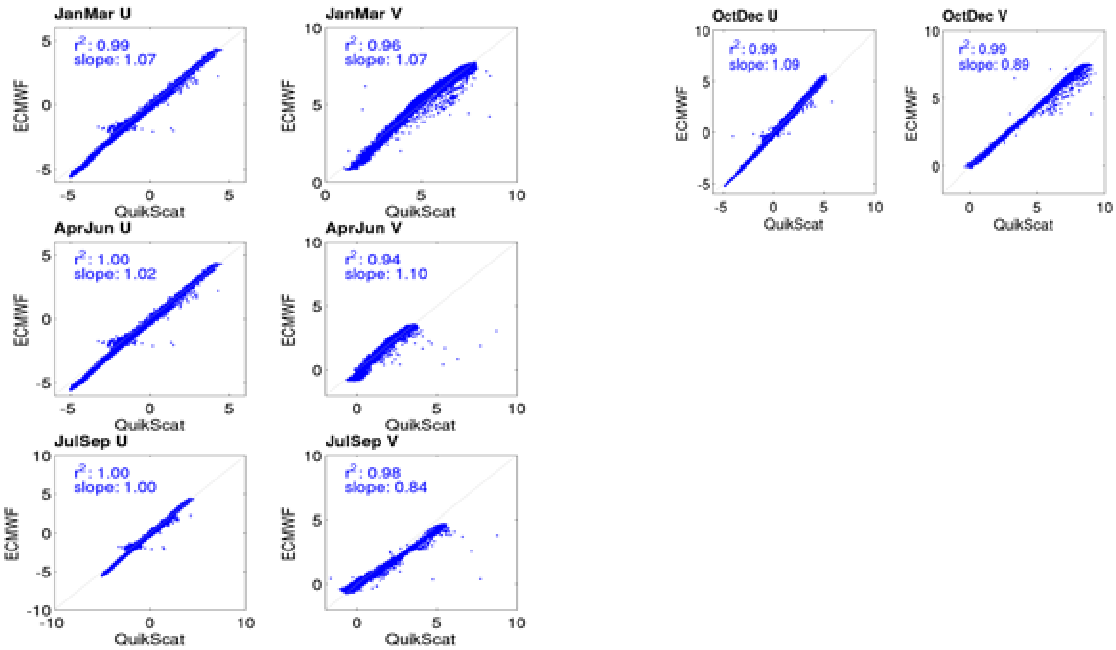


Figure 6.1.1. BRAN currents compared with OceanMAPS. Time-series plots of the 0 to 100 m averaged current velocities for eastward (lower panel) and northward (upper panel) components during the summer and autumn of 2008 over 40-20°S, 105-120°E.

(a)



(b)

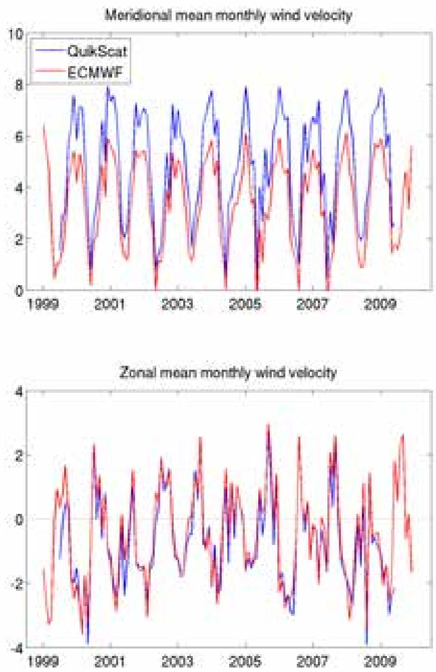


Figure 6.1.2. a) Scatter plots of daily zonal and meridional components of the ERA-Interim (ECMWF) and QuikScat winds averaged over 40-20°S, 100-118°E. All seasons have high correlations with little bias. b) Areal average (over 36-20°S, 105-118°E) comparison of the two components of monthly winds. Note that ECMWF meridional winds seem to underestimate high winds indicated by QuikScat.

6.2 Drifter buoys

A series of current drifters were released along the Western Australian continental shelf in December 2010 to study the currents that would influence the dispersal of early stage rock lobster larvae (Table 6.2.1). The drifters consisted of a surface float unit containing the electronics package and a sea surface temperature (SST) sensor, and a 6.44 m "holey sock" drogue suspended between 2 m and 8 m below the surface float.

Table 6.2.1. Drifter release details.

Drifter Ref	Release Date	Release Location
#0680	22/12/2010	Shelf edge off Cliff Head
#4120	22/12/2010	Mid-shelf off Cliff Head
#5170	22/12/2010	Shelf edge off Leeman
#3670	22/12/2010	Shelf edge off Leeman
#8120	24/12/2010	Shelf edge off Lancelin

6.3 Indian Ocean Dipole/ENSO effect on SST and wind

Global monthly reanalyses from the National Center for Environment Prediction / National Center for Atmospheric Research (NCEP/NCAR) project (Kalnay *et al*. 1996) were used to examine atmospheric fields such as vertical and horizontal circulation, and geopotential heights. An updated version of the Global Sea Ice and SST reanalysis (HadISST1; Rayner *et al*. 2003) with a horizontal resolution of 1° latitude/longitude was used to examine the SST field. ENSO was monitored using the Niño-3.4 index, which is the average SST anomalies over (5°S-5°N, 170°W-120°W). The Indian Ocean Dipole (IOD) was monitored with the Dipole Mode Index (DMI; Saji *et al.* 1999), which is the difference of the area mean SST anomalies between a western IO region (10°S-10°N, 50°E-70°E) and an eastern IO region (10°S-Eq, 90°E-110°E). The Southern Annular Mode (SAM) index was obtained from the British Antarctic Survey (Marshall 2003), calculated from station-based mean sea level pressure (MSLP) observations. The analysis was conducted over the period 1970-2010. Further details of data used in this assessment can be obtained in Weller *et al*. (2012).

6.4 Environmental effects on puerulus settlement

Environmental factors have been identified as having a significant effect on the abundance and distribution of puerulus settlement. In particular the effect of the Leeuwin Current has been identified as a major factor affecting puerulus settlement over a number of studies (Pearce and Phillips 1988, Caputi *et al.* 2001) with good settlement being associated with strong Leeuwin Current that are usually associated with La Niňa conditions. A strong Leeuwin Current can influence the level of puerulus settlement in a number of ways such as due to the strong eddy formation and warmer water temperatures (Caputi *et al.* 2001) as well as resulting in the mean latitude of settlement occurring further south (Caputi 2008).

Caputi and Brown (1993) also identified the effect of strong westerly winds associated with late winter and spring storms as being a positive influence on the puerulus settlement. However these environmental factors that have generally explained the variations in puerulus settlement for over 35 years do not explain the decline in puerulus settlement which has remained below average for six consecutive years (2006/07 to 2011/12) with 2008/09 being the lowest in over

40 years. These low settlements have occurred despite a strong Leeuwin Current in 2008 and 2011. This has focused attention on other environmental and biological factors that may have contributed to this recent decline.

This section examines the relationships between environmental variables at an appropriate spatial (usually 1 degree block) and temporal (usually monthly) scale and the puerulus settlement at a number of locations (or combined over the locations) to understand the effects of the environment on the puerulus settlement.

The correlation assessments between the level of puerulus settlement and the environmental variables have been undertaken using two time periods: with and without the recent years (since 2006/07) of low puerulus settlement to assess whether there has been a change in the environmental factors that affect the settlement between the two periods. Combinations of environmental factors that may affect the settlement as well as effect of the spawning stock are examined using multiple regression in section 7.8.

Puerulus settlement

The puerulus settlement data is currently sampled monthly from nine locations throughout the rock lobster fishery (de Lestang *et al*. 2012) with Dongara being the first location sampled in 1968.

A standardised annual mean of fishery-wide puerulus settlement was determined from nine locations; Port Gregory, Horrocks, Rat Island (Abrolhos Is.), Seven Mile Beach (Dongara), Jurien Bay, Lancelin, Alkimos, Warnbro Sound and Cape Mentelle (Figure 3.1). The index is obtained from a GLM analysis and the annual index is standardised for location and month of sampling using a GLM and the "lsmeans" package in R (R Development Core Team 2012).

The monthly distribution of puerulus settlement was examined for the period before and after the recent period of low settlement in 2006/07 to assess whether the decline in settlement was uniform across all months. The relationship between the timing of peak settlement and the level of settlement was then examined to assess whether the decline in abundance followed the pattern observed in previous declines with the peak settlement occurring in later months when settlement was low. The timing of peak settlement was determined by fitting a normal distribution to the total number of puerulus sampled during each sampling occasion each settlement season using the following equation:

$$N_L = \frac{\lambda}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{O-\mu}{\sigma}\right)^2}$$

where N_L is the annual number of puerulus settling during each sampling occasion (O), μ is the mean day of settlement and λ is a scaling factor. The model was fitted using the "fitdistr" function from the R package "MASS". A Maximum Likelihood approach was used to fit the normal distribution function using the R routine "optim" (R Development Core Team, 2012) which employs a Gauss-Newton algorithm.

Leeuwin Current and sea surface temperature (SST)

The SST of the lower west coast of WA is influenced by the strength of the Leeuwin Current and therefore can be regarded as an indicator of the current strength. The Fremantle sea level (FSL) has also been used as an indicator of the strength of the Leeuwin Current and an indicator of strength of the eddy structure associated with the current (Feng *et al*. 2009). The Leeuwin

Current is influenced by ENSO events and the Southern Oscillation Index (SOI) is an indicator of strength of the events. All these variables have been used to understand the variation of puerulus settlement in various studies (Pearce and Phillips 1988, Caputi *et al*. 2001) but the SST data has historically provided the best relationship with puerulus settlement and has been the main focus of this study.

The SST data has been obtained using interpolated satellite imagery (Reynolds and Smith 1994) at 1° by 1° resolution for blocks ranging from 10 to 50°S and 90 to 130°E by month since 1982 (de Lestang *et al*. 2012).

The correlation between monthly SST in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement up to 2006/07 at four locations was undertaken to identify the key months that SST may be affecting the settlement. This assessment was then used to identify the SST in a combination of months and blocks that explained the variation in puerulus settlement and the influence of the recent low years of settlement on the SST – puerulus relationship.

To assess whether the monthly SST – puerulus relationship was applicable to the puerulus settlement throughout all months of the peak settlement period, the puerulus settlement at Jurien (which is near the centre of the fishery) was broken down into three periods: August/September, October/November and December/January. The correlation between monthly SST in blocks off WA and the Jurien puerulus settlement in each of these three periods was examined.

Wind strength and direction

Monthly mean northward and eastward wind and wind stress components in approx 1.9° latitude/longitude blocks (approximately 200 km) off Western Australia are available from the National Center for Environmental Prediction (NCEP). Monthly 10 m wind components were derived from the 6-hourly global NCEP/NCAR reanalysis surface dataset, which uses a continually updated global analysis of the current atmospheric state through data assimilation. The wind stress components were derived from the 6-hourly winds and the monthly mean wind stress components were then calculated from the NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/ (Kalnay *et al*. 1996). The effect of the wind strength and direction during the period of early larval movement offshore and the period of late stage larvae/puerulus movement onshore was examined. The correlation between the monthly wind stress components and the subsequent annual puerulus settlement up to 2006/07 at four locations was investigated by considering the effect of the meridional and zonal components individually. The multiple correlation was also investigated using a linear combination of the meridional and zonal components.

Wave height

Monthly modelled wave heights in 1 degree latitude by 1.25 degree longitude blocks (approx. 100 km * 125 km, at the equator) off Western Australia were obtained by CSIRO for the block 10° to 40°S, 100° to 120°E. The WaveWatch 3 model is driven by 3-hourly winds derived from the operational Global Data Assimilation Scheme (GDAS) and the Medium Range Forecast model; 3-hourly outputs from the model are downloaded from the site ftp://polar.ncep.noaa.gov/pub/history/waves/ by CSIRO, and have been converted to monthly means for our purposes. The effect of the wave height during the period of early larval movement offshore and the period of late stage larvae/puerulus movement onshore was examined.

Water movement

The zonal and meridional components of the BRAN ocean surface current (Section 6.1.3) were used to examine the effect of the current during the period of early larval movement offshore and the period of late stage larvae/puerulus movement onshore.

A water movement vector combining the BRAN ocean current, the surface current correction (using 1.5% wind speed), and wave-induced Stokes drift was developed in order to replicate the resultant movement experienced by particles in the oceanographic model (see Section 6.1.3). The effect of the combined water movement during the period of early larval movement offshore and the period of late stage larvae/puerulus movement onshore was examined via a linear regression model involving the northward and eastward water movement components.

Rainfall

Monthly rainfall data are collated from Bunbury, Mandurah, Rockingham, Fremantle, Rottnest, Lancelin, Jurien, Dongara, Geraldton and Kalbarri (e.g. Bureau of Meteorology 2007). Rainfall is used as a proxy for the effects of the winter storms on the ocean environment (e.g. swell and waves action) and the westerly winds associated with storms crossing the coast in winter and spring. The rainfall data for the period July-September and October-November were examined for locations north and south of Jurien to update the assessment of Caputi *et al.* (2001).

Indian Ocean Dipole

The Indian Ocean Dipole (IOD) was monitored using the Dipole Mode Index (DMI; Saji *et al*. 1999) which is the difference of the area mean SST between the western and eastern Indian Ocean near the tropics (see section 6.3). The effect of the monthly IOD on the puerulus settlement was examined.

Self-organising weather maps (A. Denham, P. Hope, K. Keay, N. Caputi)

Self-organising maps (SOM) were used to examine the type of afternoon weather systems off the west coast of WA during January to June and July to December (Indian Ocean Climate Initiative 2012) to assess their effect on puerulus settlement. Reanalyses data for mean sea-level pressure (1948-2010) at 2pm each day was used to define a continuum of 35 map types (e.g. Figure 6.4.3). This SOM data was obtained from Dr Pandora Hope and Kevin Keay, Bureau of Meteorology, Melbourne.

The SOM show that a full range of synoptic types occur over July-December (Figure 6.4.3). These range from deep low-pressure systems (most evident in the top 2 rows of the SOM) to bands of very high pressure (bottom rows). Maps illustrating the composite of winds associated with each weather type were also produced (e.g. Figure 6.4.4). The vectors in the region of the southern west coast are predominantly onshore, except for the weather types in the bottom right corner of the SOM (Figure 6.4.3). The latter are types with offshore flow (e.g. types D7 and E7). These types with offshore wind flows were the most numerous, relative to other types, in 2008, and again in 2010. The wind anomaly for type E7 clearly shows the off-shore flow that is evident along the west coast (Figure 6.4.4). This type occurred predominantly in August in 2008.

The daily frequency of each of the 35 self-organising map (SOM) types from the January-June and July-December periods were considered as explanatory variables in a multiple linear regression model with the natural logarithm of the annual puerulus index (obtained from a GLM using the puerulus index from the 8 collector locations) as the response variable. The puerulus index from season 1970 to 2010 was used where season 1970 refers to the puerulus settlement from May 1970 to April 1971. The SOM counts used were from the corresponding year i.e. the relationship between the SOM counts in year t and the puerulus settlement in season t (May of year t to April of year t+1). As counts of the SOM types were available for 2 periods in the year there was a total of 70 possible explanatory variables.

Altimeter – onshore larval flow

Altimeter data measuring sea surface height (SSH) for the waters off the West Australian coast from a number of satellite passes (Figure 6.4.1a) was examined for the period between September 1992 and December 2011. Data was selected from one ‘transect’ that ran parallel to and just to the west of the continental shelf break (Figure 6.4.1b). It covered a Latitudinal range from 24°S to ~33.5°S.

A mean sea surface height (MSSH) was calculated from the full time series for points along the transect (0.05° intervals of both latitude and longitude), resulting in 356 points along the transect. The sea surface height anomaly (SSHA) (Figure 6.4.2) was then derived for time (t) at longitude (x) and latitude (y) by:

$$SSHA_{t,x,y} = SSH_{t,x,y} - MSSH_{x,y}$$

Variation in the SSHA magnitude was considered to result from changes in water masses, with positive and negative SSHA being associated with warm and cold water systems, respectively. A rapid change in SSHA in a southwards direction down the transect from high to low (a negative trend) would therefore represent an area with a warm water system directly north of a cold water system, a situation which generally results in an onshore flow of oceanographic water (Figure 6.4.2). Thus the rate of change between sequential SSHA measurements along the transect could be used to determine the location and timing of onshore jets of oceanographic water.

The rate of change of SSHA was calculated using multiple linear models each spanning about 1° of Latitude or 20 adjacent observations. Excluding the first and last ten points along the satellite transect, ten points either side of each transect point was described with a linear model, with the slope of this model describing the rate of change in SSHA at that central point. This was conducted for each satellite pass (~ every 10 days), with the latitude and magnitude of the greatest negative slope being recorded.

Sea surface temperatures (SST) were also available for the West Australian coast (Bureau of Meteorology “http://opendap.bom.gov.au:8080/thredds/dodsC/.”) from June 2006 to December 2011. Data was trimmed to enable the sea surface temperature along the same transect as the altimeter data to be extracted and compared with SSHA. SST was captured at the same resolution as MSSH (0.05° intervals of both latitude and longitude), and SST anomalies (SSTA) calculated as for SSHA (above). Again a rapid change from warm to cool water was considered to represent a warm water system directly north of a cold water system and the location of a potential onshore jet of oceanographic water (Figure 6.4.2). The magnitude and latitude of SSTA was determined in the same manner as for the SSHA.

Comparisons between altimeter and SST and the timing and magnitude of puerulus settlement were conducted during the period when MSSH and SST recordings were available. Details of puerulus collector locations and methodology are outlined in de Lestang *et al* (2012). Settlement numbers were based on the combined annual average of collectors at Dongara and Jurien. The mean annual latitude of settlement was based on a normal distribution fitted to the latitude of collectors and the annual puerulus settlement (Port Gregory/Horrocks, Abrolhos Islands, Dongara, Jurien, Alkimos, Warnbro and Cape Mentelle). See section 6.4 for more details.

Water productivity ChlA

Monthly satellite-derived near-surface chlorophyll concentrations (from the ocean colour sensor on the SeaWiFS satellite) were available in 1 degree lat/long blocks (approx. 100 km square) from 10° to 50°S, 90° to 130°E. The data set extended from September 1997 to December 2008 with data gaps in January-March and July 2008.

The dataset provides larger-scale near-surface chlorophyll concentrations off Western Australia, however it should be noted that: (1) the data are near-surface (within the upper 20 to 40 m of the water column, depending on the turbidity) so will not show the Deep Chlorophyll Maximum; and (2) in water shallower than about 30 m there may be some "contamination" of the signal by reflection from the seabed, so the inshore data should be viewed with caution.

Environmental effect on latitudinal distribution

The strength of the Leeuwin Current has been shown to not only influence the abundance of settlement (discussed above) but also its spatial distribution. The relationship between the strength of the Leeuwin Current, measured using the Fremantle sea level during June to December, and mean latitude of puerulus settlement was updated from the assessment by Caputi (2008). The mean latitude was determined from the puerulus settlement at the following locations: Port Gregory, Abrolhos, Dongara, Jurien, Alkimos, Warnbro and Cape Mentelle.

The annual mean latitude of puerulus settlement was determined by describing the spatial variation in puerulus settlement by a normal curve with a peak in puerulus settlement near the centre of the fishery between Dongara and Lancelin and lower levels of settlement in the north and south. The observed annual distribution of settlement at each of the eight collector sites was described using a normal distribution (see Puerulus settlement section above).

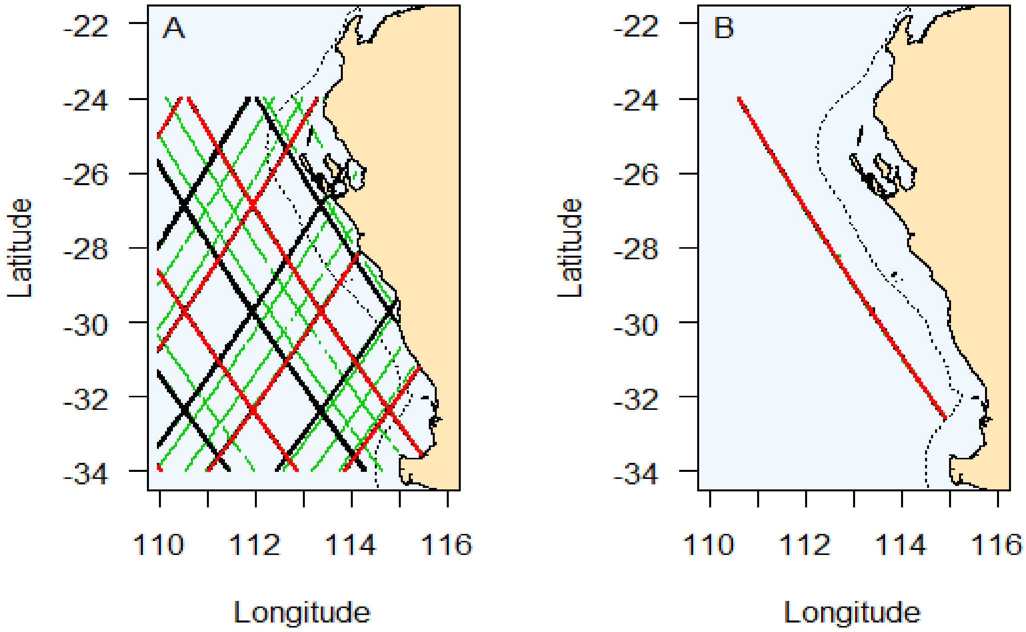


Figure 6.4.1. A) Satellite tracks (three satellites represented by black, green and red lines) off the West Australian coast that provided altimeter data; B) the satellite track used in analysis of altimeter data. Dotted line represents the location of the shelf break (200 m isobath). Note all three satellites recorded data along the track used for the analysis shown in plot B.

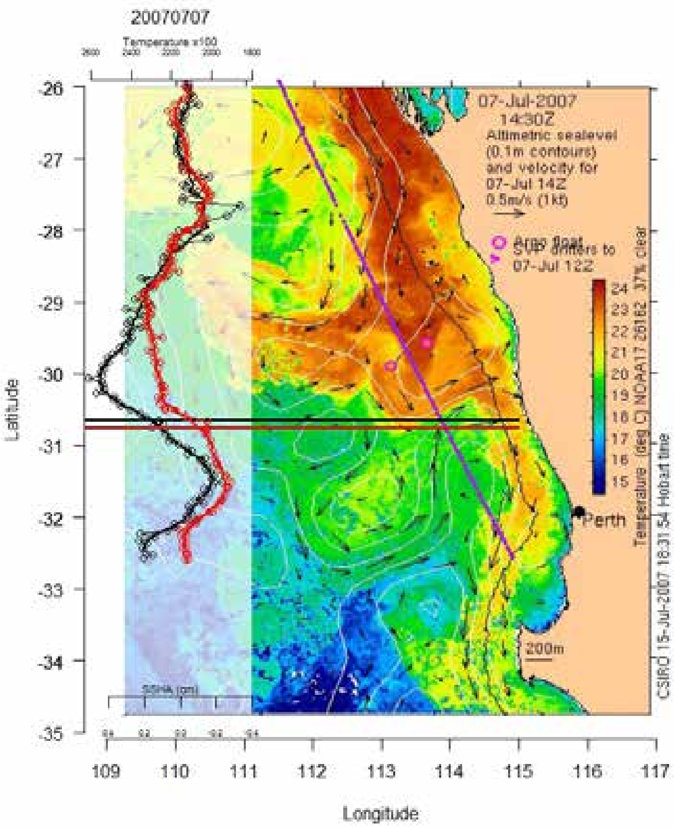


Figure 6.4.2. Sea surface height anomaly (SSHA; black dots) and sea surface temperature changes (SST: red dots) with a 7 point fitted smoothed moving average (line) for a satellite pass on the 7 July 2007 superimposed on a sea surface temperature image of the lower west coast of Western Australia. The purple line indicates the location of the transect with the horizontal lines indicating the location of the greatest negative slope for SSHA (black) and SST (red).

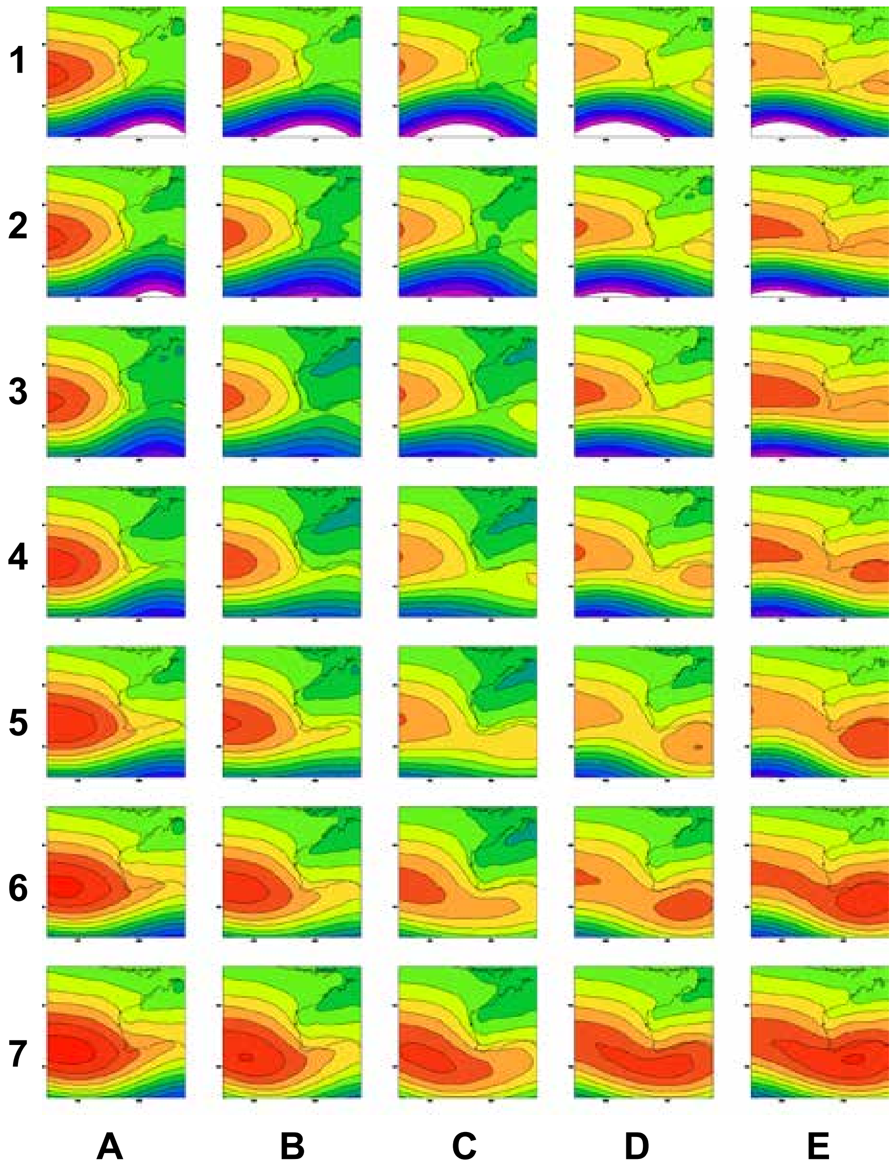


Figure 6.4.3. Self-organising map of 2 pm mean sea level pressure for the synoptic (weather) types during the July-December half year over the 1948-2010 period. Blue through fuschia to white areas represent low pressure, orange to red areas high pressure

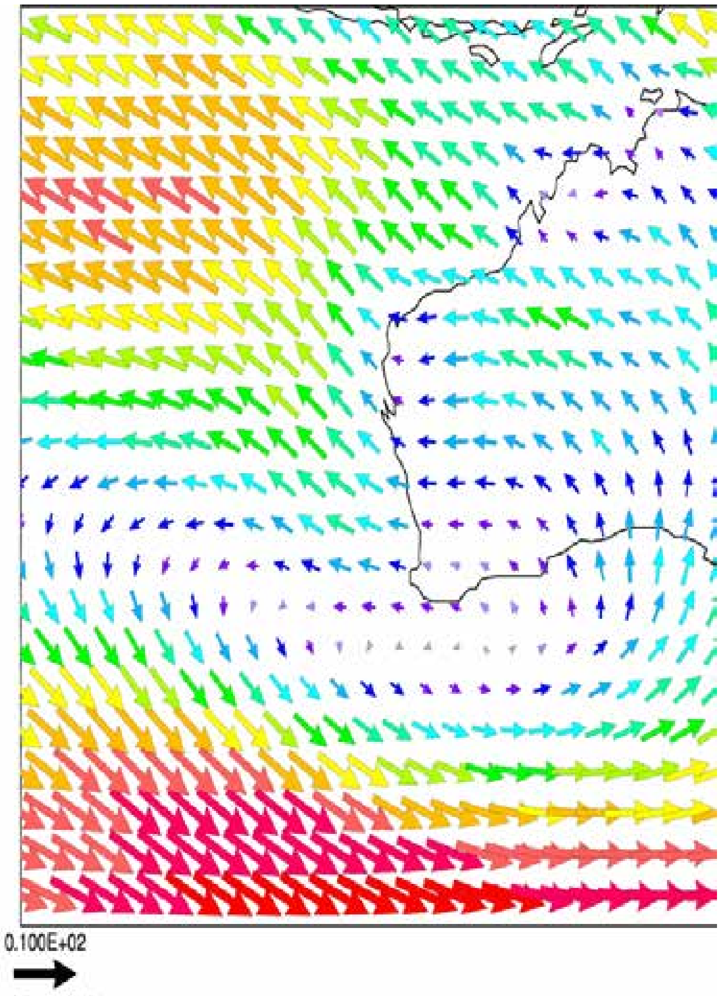


Figure 6.4.4. Arrows indicate wind direction and strength (larger red arrows = stronger winds). This figure shows the composite winds for synoptic type E7 from the bottom right of the SOM (Figure 6.4.3).

6.5 Environmental effect on migrating lobsters

The breeding stock has been within historic ranges for all the main areas of the fishery (de Lestang *et al*. 2012) since the start of the low puerulus settlements in 2006, however there have been concerns about the status of the stock in northern part of fishery due to the downturn in catches in Big Bank which is just north of the Abrolhos zone. Since most of the catches landed in Big Bank are comprised of migrating white lobsters caught predominantly in January and February (Chubb *et al*. 1994), it is likely that the abundance of lobsters in this area is also affected by how far north lobsters migrate each season. These migrating lobsters are expected to mature and join the breeding stock in the spring of that year. This section examines the annual variation in the northern migration and the factors that may influence this migration such the level and distribution of puerulus settlement at an appropriate lag and environmental conditions that have been shown to affect lobster migration, e.g. water temperature, swell and currents.

Latitude of migration

The mean latitude of migration was determined using data derived from the Department of Fisheries Western Rock Lobster Volunteer Research Log Book which has historically been completed by

≈30% of the commercial Rock Lobster Fleet (de Lestang *et al*. 2012). The log book contains information to determine the catch rate of undersize lobsters in 18 m (10 fathom) depth intervals and 10 minute latitudinal transects. The estimate of mean latitude of northwards migration is based on the assumption that the majority of undersize lobsters present in deep water areas (depth > 73 m) arrived into those locations after migrating from shallow water nursery areas (Chittleborough and Phillips 1975, Phillips 1983, Gray 1992). Therefore within the deep-water areas of the fishery the latitude where the majority of undersize lobsters are caught after the migration period can be considered to be an indicator of the northern extent of the migration for that year. The weighted mean (± se) latitude of migration was determined using an ANOVA with fishing season as a factor, weighted by catch rate of undersize lobsters caught between February and June in water depths ≥ 73 m (40 fathoms). Observations for a particular season and 10' latitudinal transect combinations were not included if the data were derived from less than three independent observations (three separate fishing trips which equates to ≈450 pot-lifts).

Puerulus settlement

A standardised annual coast-wide puerulus settlement index was obtained from a GLM analysis with factors, location, month and season (see section 6.4 'Puerulus settlement'). The annual mean latitude of puerulus settlement was determined as described above under section 6.4 "*Environmental effect on latitudinal distribution*".

Environmental data

Ocean bottom current and temperature data sets were derived from the Australian Bureau of Meteorology's BLUElink ocean data products (http://opendap.bom.gov.au/index.shtml; accessed 22/05/2012). The ocean current data represents the monthly mean meridional (north-south) component of water movement for the bottom 10 m layer of the modelled region in cms^{-1}, and the temperature data represents the monthly mean value of this same bottom 10 m layer in °C. Both data sets have a spatial resolution of 0.1° latitude x 0.1° longitude. Ocean swell height data represents a monthly mean value on a spatial resolution of 1.25° latitude x 1.25° longitude.

Commercial catch data

Commercial catches from the Big Bank region were derived from commercial fisher's compulsory monthly catches and effort statistics (CAES) who had nominated to fish in this area for that season (see de Lestang *et al*. 2012 for more details).

Statistical analysis

Log-linear models were used to examine the relationships between the annual mean latitude of migration and the environmental conditions (temperature, current and swell height) and indices of puerulus settlement three or four (or their average) years previously. The equation used was;

$$L_y = \alpha E_{y,s} + \beta log\left(P_{y-t}\right) + \varphi M_{y-t} + \delta ,$$

where the L_y is the mean latitude of undersize lobsters caught in deep water of year (y), $E_{y,s}$ is the environmental variable during the migration period of that year in a spatial position (s), P_{y-t} is the magnitude of puerulus settlement either three or four, or their average, years (t) previously, M_{y-t} is the mean latitude of puerulus settlement and δ is the model intercept. The environmental spatial positions tested in the above model were restricted to those in the vicinity of the areas where *P. cygnus* is found, i.e. on or near the continental shelf break in water depths < 200 m.

Any environmental factors that displayed significant relationships with the mean latitude of migration were further examined to identify whether the relationship were occurring in locations along the migratory route of *P. cygnus*. This was conducted by spatially plotting all model correlations resulting from comparisons with the chosen environmental factors on a bathymetric map of the fishery and identifying the locations of all significant correlations. The above log-linear model was then re-fitted using the environmental factor averaged over all key locations that were deemed to make biological sense, i.e. the locations were in areas where migrating lobsters occur.

The mean latitude of migration, and any environmental variable detected as influencing the migration (converted to an annual average of max locations), were used in a catch prediction model to determine whether any or both of the factors was significantly correlated with Big Bank lobster catches. The catch prediction equation used was;

$$\log\left(C_y\right) = \alpha F_y + \beta log\left(P_{y-t}\right) + \varphi M_{y-t} + \delta \, ,$$

where the C_y is the Big Bank catch in year (y), F_y is the factor (either mean latitude of migration or environmental measure) in that year.

6.6 Environmental effect on timing of spawning

The oceanographic larval model identified the timing of spawning as an important factor affecting puerulus settlement, with early releases providing the best fit between the model settlement and actual settlement. Therefore the effect of the variation in timing of spawning on the puerulus settlement was examined.

The timing of the start and end of spawning for *Panulirus cygnus* varies between years, most likely in relation to inter-annual variation in winter and spring water temperatures. The usual pattern of reproduction is for mating to start in about June, fertilisation to begin in September, reaching its maximum of almost all mature females being ovigerous in November and December. Because the larger females can spawn twice there are two peaks in egg release during the season. The number of ovigerous, mature females declines after December to only a few still being found in March.

The timing of spawning of *P. cygnus* has been examined using the prevalence of ovigerous (egg bearing) females caught during the Independent Breeding Stock Survey (IBSS) (October/November) and in commercial catch monitoring by Department of Fisheries staff (February) to represent the onset and completion of spawning each year, respectively.

The timing of the onset of spawning each year was determined based on the mean stage of spawning of mature females sampled during the IBSS in October or November each year since 1992. The IBSS is conducted at three locations every year (Lancelin, Dongara and the Abrolhos Islands) and intermittently at four other locations (Fremantle, Jurien, Kalbarri and Big Bank). Data from the Kalbarri and Big Bank regions were not used in constructing the index of onset of spawning. The annual estimate of the onset of spawning is a least-squares mean standardised for location of capture, the survey's exact timing within October/November and carapace length using a generalized linear model. The stage of spawning was assigned according to the presence and developmental stage of eggs on mature females (females are designated as being mature if they have mated (possess an external spermatophore) or have developing gonads. Spawning stages used are: 0 = mature female with no eggs; 1= recently fertilised eggs; 2 = half-way through egg development; 3 = eggs fully developed; 4 = residual egg remnants from larval release; 5 = used spermatophoric mass but no egg remnants.

The completion of spawning was determined based on the presence or absence of external eggs on mated females in research monitoring of commercial catches at the end of the spawning season. The annual index was a least-squares mean, standardised for location of capture, the exact timing of sampling between January and March and carapace length using a generalized linear model. Commercial monitoring is conducted at five coastal locations (Fremantle, Lancelin, Jurien, Dongara and Kalbarri) every month of the fishing season (15 November – 30 June). Data was restricted to sampling in the breeding grounds, i.e. water depths > 40 m.

Variation in the onset and completion of spawning between years would presumably be due to variation in one or more of the environmental cues used by this species to initiate reproduction. The most likely cue for the onset of spawning is water temperature. A time series of bottom water temperatures on the spawning areas was not available therefore bottom water temperature from the oceanographic model in the spawning depth zone (Section 6.1) was examined for the period prior to and during the spawning period.

6.7 Stock-recruitment-environment relationship

This section examines whether the spawning stock has been a significant factor in the recent decline in puerulus settlement. It also brings together the key environmental factors identified in the previous chapters that may be influencing the puerulus settlement to determine a stock-recruitment–environment relationship to assess the combined effect of spawning stock and environmental conditions on the puerulus settlement.

The previous assessment of the stock-recruitment-environment relationship (SRR-E) for western rock lobster showed that environmental conditions explained most of the variation in puerulus settlement at the coastal sites with spawning stock not being significant (Caputi *et al*. 1995). However a decline in puerulus settlement at the Abrolhos Is. in the late 1980s and early 1990s had occurred at a time of declining spawning stock and this contributed to a significant reduction in fishing effort and greater protection of mature females in 1993/94.

During the recent period of low settlement the spawning stock was within historic levels at all sites that had been surveyed since the early 1990s which covered the main part of the fishery. However there were concerns about the status of the stock in the northern part of the fishery (e.g. northern Abrolhos Islands and Big Bank) which did not represent a major area of the fishery and therefore had not been regularly surveyed. The long-standing levels of fishing when combined with a run of environmental conditions unfavourable for the northward migration of the whites (section 7.5), led to a reduction in lobsters and therefore egg production in this northern area.

In 2009 the Big Bank area was closed to fishing to enable the stock in this area to recover and a breeding stock monitoring site was established to assess the recovery. There were also significant effort reductions introduced in 2008/09 in response to the poor puerulus settlement in order to protect the spawning stock into the future.

The spawning stock is examined in a number of ways including the egg production from the Independent Breeding Stock Survey (IBSS) and that from the stock assessment model which includes data from the IBSS.

Egg production: fishery-independent breeding stock survey

The IBSS survey has been conducted annually (October/November) at 3 to 6 locations throughout the fishery since the early 1990s (de Lestang *et al*. 2012). In 2009 an additional site was added at Big Bank, north of the Abrolhos, because of concerns about the status of the stock in that area which resulted in the closure of that area in 2009. The egg production index is determined by taking into account the fecundity of females at different sizes in the catch rate of mature females caught in the survey (de Lestang *et al*. 2012).

Egg production: stock assessment model

The stock assessment model incorporates all the biological information available on the fishery from puerulus through to the breeding stock and takes into account the fishery-dependent catch rates from the fishery as well as the information from the fishery-independent breeding stock surveys (de Lestang *et al.* 2012). The model uses the fecundity-size relationship to estimate the egg production each year for four key breeding stock management areas (BSMA) of the fishery (Figure 6.7.1) which are proposed as indicators for the harvest strategy used to assess the sustainability status of the fishery:

- BSMA 1 – Deep water areas (>20 fm) of the fishery north of 28°S. This encompasses the northern Abrolhos and Big Bank regions.
- BSMA 2 – Deep water areas (>20 fm) of the fishery between 28° and 30°S. This encompasses southern Abrolhos and offshore Geraldton and Dongara areas.
- BSMA 3 – Shallow water Abrolhos Islands (<20 fm around the Abrolhos Is.)
- BSMA 4 – Deep water areas (>20 fm) of the fishery south of 30°S which encompasses all of Zone C deep water.

The number of eggs produced in each offshore area of the model (>= 40 m) and the shallow water Abrolhos Islands region were summed to produce a fishery-wide index. The projected egg production after 2010 assumes that future catches will be similar to 2010/11.

Puerulus settlement index.

A standardised annual mean of fishery-wide puerulus settlement was obtained from a GLM analysis with the annual index standardised for location and month of sampling (see Section 6.4 Puerulus settlement).

Sea surface temperatures.

Levels of puerulus settlement have historically shown a strong relationship with offshore water temperatures in an area northwest of the fishery (26 – 29°S, 108 – 111°E) (Figure 7.4.3) during the early larval stages, February-April. The temperature data used are the NOAA_OI_SST_V2 dataset provided the NOAA web site at http://www.esrl.noaa.gov/psd/ (Reynolds *et al.* 2002).

Timing of onset of spawning.

The onset of spawning has been shown to vary between years with an early start possibly being related to a poor subsequent puerulus settlement (section 7.6). This index, which is derived from sampling during the Independent Breeding Stock Survey at the start of the spawning season, ranges from ~0.2 which represents an historical average timing of onset of spawning to 1.04 which represents an early start to spawning (a greater proportion of spawning lobsters in the catches).

Rainfall

Rainfall has been previously used as an index of storms that affect the lower west coast of Western Australia (Caputi and Brown 1993, Caputi *et al*. 2001). The storms are generally associated with westerly winds and increased swell/Stokes drift which was found to be an important factor in phyllosoma/puerulus transport in the larval model (see section 6.4 for further details).

Statistical model

The stock-recruitment-environment relationship based on puerulus settlement in year t+1, the spawning stock in year t and other environment and biological variable(s) such as water temperature, egg stage development and rainfall are examined as follows:

$$\log\left(P_{t+1}\right) = \alpha \log\left(S_t\right) + \beta E_t^1 + \delta E_t^2 \ ,$$

where P_{t+1} is the puerulus settlement in year $(t+1)$, S_{t+1} is the measure of egg production and E_t^n is the environmental index or indices if included. This linear model utilised a log transformation for the puerulus and egg production indices to take into account the skewed nature of their abundance distributions.

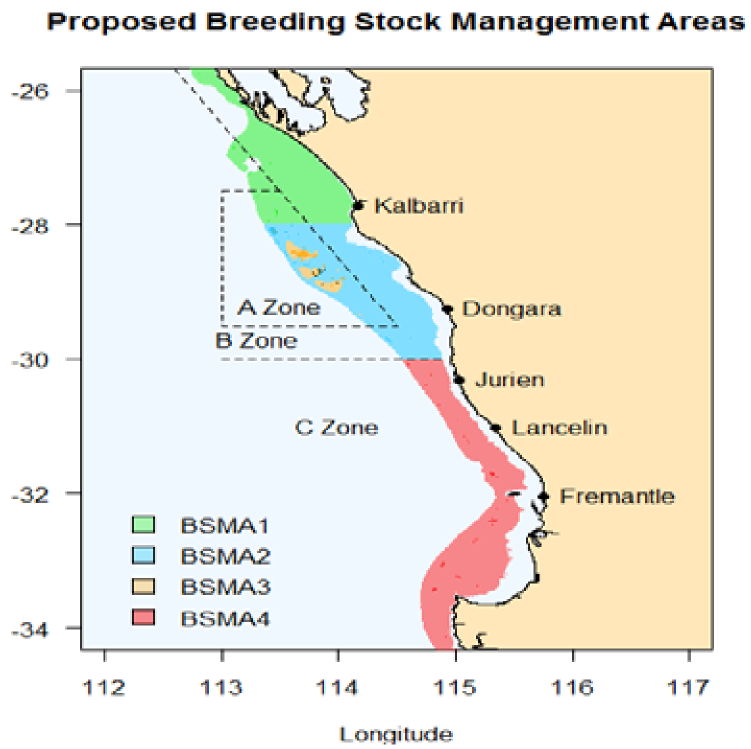


Figure 6.7.1. Four Breeding Stock Management Areas covering areas of significant egg production throughout the fishery. Note two areas, BMSA1 and BMSA2 cross the border between Zones A and B.

6.8 Climate change effects

The climate change component of the current study examines the environmental factors that have been identified as possibly affecting the recent series of low puerulus settlement. The historic variations in these environmental variables, such as Fremantle sea level as an index of the Leeuwin Current, sea surface temperatures and various wind products, have been examined to assess the long-term trends in the Leeuwin Current and ocean temperatures in the past.

The representation of the Indonesian Throughflow and the Leeuwin Current in the IPCC climate model simulation was evaluated. The projected future climate change trends of the Leeuwin Current strength are also assessed.

7.0 Results/Discussion

7.1 Oceanographic larval model

7.1.1 2012 oceanographic larval model outputs

A number of suitable model runs were saved from the systematic variation of model parameters. Common parameters for these model runs include:

- Model domain: 16.5-39.5°S, 101.5-128.5°E
- Boundary reflection
- A diffusivity 1 ms^{-1} is used to simulate the random walk effect
- 2 releases per location at daily rate
- Shelf mortality: Category A-60 days, Category B-10 days, Category C-10 days
- Metamorphosis into puerulus occurs once phyllosoma crosses the 1000 m depth contour

A complete list of the model parameters associated with these 24 model runs (2011g-2011t, 2012a-2012j) are outlined in Table 7.1.1.

Here we use the 2012j model as an example for the larval model output results. Two particles are released each day during the period of 1 September to the end of March (212 days) along the coast, and a total of 156,880 particles were released to the model domain. On average 430 particles per year settle onto the coast, or about 0.3%, which is consistent with the 2009 model. Of the unsettled particles, about 50% suffered from shelf or temperature mortality, 32% were drifted out of the model domain; and less than 3% exceeded the 540 day larval duration. The rest of the particles were still within the model domain, but away from the coast, at the end of the model run.

An increased focus of the 2012 model was on the larval release and settlement in the main part of the fishery, to take advantage of the availability of the extended time series of spawning stock and puerulus settlement available for this area of the coast. The temporal variations of monthly counts (unadjusted for timing and distribution of hatching) of different larval categories (Figure 7.1.1) are consistent with the 2009 model, although the spawning period is extended by 2 months. The peak values of categories A, B, and C1 are similar to the 2009 model, while the category C2 peak is delayed by about one month. Category D1 (puerulus) numbers are higher than the 2009 model, which is likely due to better survival rate of late stage phyllosoma. Note that only a small percentage of the D1 are actually settling on the coast, due to the lower but more realistic swimming speed of puerulus at 5 cm/s. In a sensitivity model run, an increase in puerulus swimming speed to 10 cm/s also increases the average settlement number by 35%. The increase in puerulus swimming speed also reduces the decadal contrast between the good settlement period and the recent low settlement period, especially for the 2008/09 settlement season when there is a 70% increase in settlement when increasing the swimming speed from 5 cm/s to 10 cm/s. By reducing the swimming speed, the puerulus are more susceptible to ocean current advection. This could be indirect evidence that the recent low puerulus settlement is partly due to unfavourable oceanographic conditions during the puerulus stage.

Another difference between the 2012j model and the 2009 model is the way that the wind correction to the ocean surface current is applied. In the 2009 model, the 3% wind speed correction was applied when the particles are on the shelf (less than 200 m), and 1% wind speed correction was applied when the particles are offshore (Feng *et al.* 2012b). In the 2012j model, 3% wind speed correction is applied for category A particles (90 days), and 1.5% wind speed correction is applied to the rest of the larval stages. The 3% wind speed correction for category A would push early stage particles further offshore in the 2012j run, compared to the 2009 model. A few adjustments are being made to the 2012 model in order to improve the settlement behaviours.

The successful settlement of larvae released over 28-34°S where the major part of the stock resides was similar based on 17-year average of raw (unweighted) model results (Figure 7.1.2a). Unlike the 2009 model which showed that particles released in the areas north of the main stock had a better chance to settle, the 2012j model has less successful settlement coming from particles released north of Shark Bay. This is likely due to the difference in wind speed correction and the slower puerulus swimming speed in the 2012j model so that they are less likely to overcome the shelf current and cross the wide shelf in the Shark Bay area. As a result, there is no settlement north of Shark Bay, as compared with the 2009 model where there was a large proportion of particles settled north of Shark Bay. Nearly half of the settlements in the 2012j model occur around Abrolhos, with a secondary peak near Lancelin (Figure 7.1.2b). These unweighted settlement patterns (from the 2012 models generally), and the corresponding release locations now show a much closer relationship to the actual fishery with the exception of the lack of model settlement from Shark Bay northwards. The lack of model settlement in the northern region does not fit with observed good settlement in that area and is an area of the model that needs to be examined in future assessments. The focus of the 2012 model was on the larval release and settlement in the main part of the fishery where there was an extended time series of spawning stock and puerulus settlement available.

Compared with the 2009 model where particles were only released from 15 October onwards, the 2012j model has more settlement coming from October releases, as well as about 20% from September (Figure 7.1.3a). Otherwise, the raw model results are consistent, indicating that early larval release have a strong influence on the total settlement. The raw model settlement distribution with months is also consistent with the 2009 model, though the September settlement peak is more prominent (Figure 7.1.3b).

The raw model settlements in 2012j model show a gradual decline from 1995 to 2010 (Figure 7.1.4), despite equal larval release in terms of both time and locations among the model years. All the raw (unweighted) settlement numbers are below long-term average since 2003, except in 2011 when the marine heat wave (Pearce and Feng 2013) has probably induced too rapid growth of phyllosoma in the model. The average settlement between 2006 and 2010 is about 50% of the long-term averages, despite a strong Leeuwin Current occurring in 2008. The record-high water temperature during 2011 and its resultant effect of high level of model settlement needs to be re-examined as the model settlement did not agree with the observed below-average settlement. This will require an assessment of the model larval growth and survival under different water temperatures. The model settlement in 2011 has not been used in any of the post-model assessments in Section 7.1.2.

We assessed the decadal physical environment changes during this period, in an attempt to identify factors affecting the model settlement.

The Fremantle sea level, an index for the strength of the Leeuwin Current, has a rising trend over the past two decades (Feng *et al*. 2011a), thus, the monthly averaged sea levels during 2006-2011 are generally higher than those during 1993-2005 (Figure 7.1.5a). The difference between the two periods shows a prominent increase during austral summer in November-

March, by about 80 mm, which indicates that the Leeuwin Current tends to be stronger during austral summer since 2006 (Figure 7.1.5b). The increase in the Leeuwin Current appears to be weaker during 2006-2011 during the winter months of May-July when the current is strongest in an annual cycle. The overall strengthening trend of the Leeuwin Current over the past two decades has been confirmed by independent datasets (Feng *et al*. 2010; 2011a), however, the seasonal variations of the decadal changes have not been examined before. The drivers of the changes are likely to be forced by both remote wind forcing in the Pacific and local winds off the WA coast.

The monthly variations of the decadal trend in the Leeuwin Current appear to result in seasonal variations in bottom water temperature trends off the WA coast. South of Abrolhos, there is a shift forward in seasonal cycle in ocean temperatures by one month in the summer peak, from April during 1993-2005 to March during 2006-2011 (Figure 7.1.5c). The minimum temperature in the season has become warmer, and the coolest temperature also shifts forward from October in 1993-2005 to a less prominent trough peak in August in the 2006-2011 average. There appears to be an average increase in water temperature of about 1°C during October-December which could have a significant effect on the spawning cycle (section 7.6). Note that significant interannual fluctuations exist.

The low model settlements during 2003-2010 are to a certain extent due to either higher shelf mortality or more particles drifting out of the model domain during those years, as shown in the June statistics at the start of the settlement season (Figure 7.1.6a). From the distribution of category C phyllosoma in June, there also tends to be lower percentages occurring within the 33-26°S, 110°E-coast box, where most of the settled particles congregate in that region during that period, after 2003, except 2008 and 2011 (Figure 7.1.6b). A stronger Leeuwin Current before March may have affected the spatial distribution of phyllosoma before the settlement season.

The metamorphosis puerulus numbers tend to be lower for the whole coast during 2006-2010 due to the high mortality and adverse environment conditions (Figure 7.1.7a). Between 33-26°S, the puerulus numbers also tend to be lower during 2006-2010, except 2008, with 2011 puerulus numbers being exceptionally high (Figure 7.1.7b). Generally speaking, the settlement ratios between 33-26°S (~42%) tend to be much higher than the whole coast (~12%), likely due to narrow shelf and favourable wind/wave and ocean current conditions. Among the years, 1994, 2006, 2008, and 2010 have relatively low settlement ratios between 33-26°S, likely due to wind and current anomalies during those years (Figure 7.1.7c).

Table 7.1.1. Summary of different versions of the 2012 IBM model (2011g to 2012j) developed to correct some aspects of the oceanographic model, including an increase the number of years used in the assessment and undertake some sensitivity assessment of some parameters. The 2011 runs involved seasons 1994-2010 whilst the 2012 runs involved the additional 2011 season. The model hatching for the 2011 runs ran from October 15th to March 15th whilst for the 2012 runs this was extended to involve the period September 1st to March 31st. Wind (1=standard wind of 1.5% of wind speed, 2= double wind, 3=double wind current only applied after April, 4=double wind current only for category A, 5=double wind current for category A and no wind after Category A, 6=double wind current with zero wind current for stage C2 and D1 where wind<7.5 m/s, 7=single wind current with zero wind and wave current for stage C2 and D1 where wind<7.5 m/s, 8=double wind current for Category A, single wind elsewhere with zero wind and wave current for stage C2 and D1 where wind<7.5 m/s). Night time winds apply after run 2011k. Wave (1=standard Stokes drift correction, 2= double, 3=half). Swim (0=no swimming, 1=swimming at 15 cm/s or 13 km per day, 2=swimming at 7.5 cm/s, 3= swimming at 5 cm/s). Growth (1=270 days, 2=240 days, 3=300 days). Maximum puerulus duration (1=60 days, 2=12 days, 3=120 days).

Model	Wind	Wave	Swim	Growth	Maximum Puerulus Duration
2011g	1	1	1	1	1
2011h	1	1	0	1	1
2011i	2	1	0	1	1
2011j	2	1	1	1	1
2011k	1	1	1	1	1
2011l	1	1	0	1	1
2011m	1	1	2	1	1
2011n	2	1	2	1	1
2011o	1	2	2	1	1
2011p	2	3	2	1	1
2011q	3	1	2	1	1
2011r	2	1	0	1	1
2011s	4	1	2	1	1
2011t	5	1	2	1	1
2012a	3	1	2	2	2
2012b	3	1	1	2	2
2012c	2	1	2	2	2
2012d	4	1	2	2	2
2012e	2	1	2	1	2
2012f	2	1	2	3	2
2012g	6	1	2	3	2
2012h	2	1	2	1	3
2012i	7	1	3	1	3
2012j	8	1	3	1	3

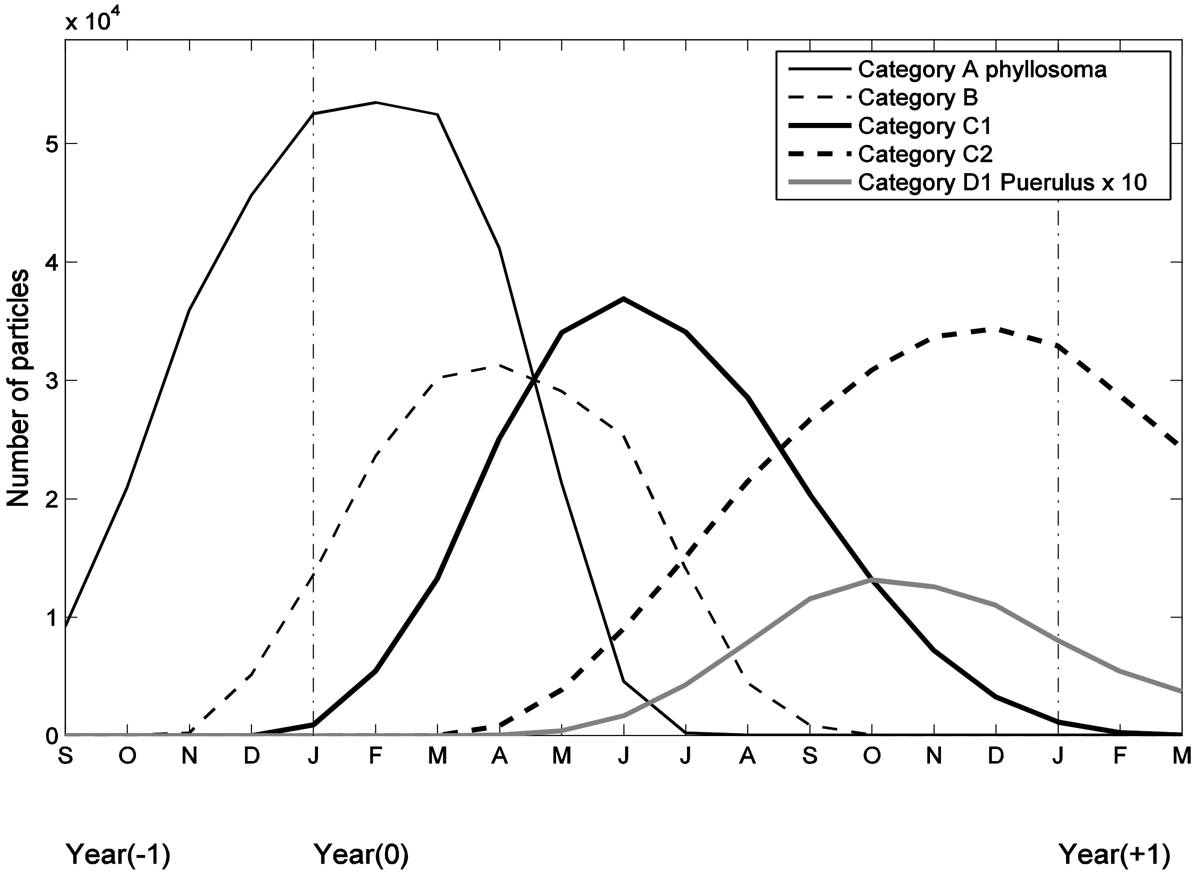


Figure 7.1.1. 17-year average monthly counts (unweighted and no mortality applied) of different categories of particles from September near the start of the hatching season to March near the end of settlement season in the 2012j run. (Note the D1 particle (puerulus equivalent) counts have been multiplied by 10 to enable the monthly pattern to be visible.) 2011/12 season is excluded from the calculation due to unusual growth in extreme warm temperature.

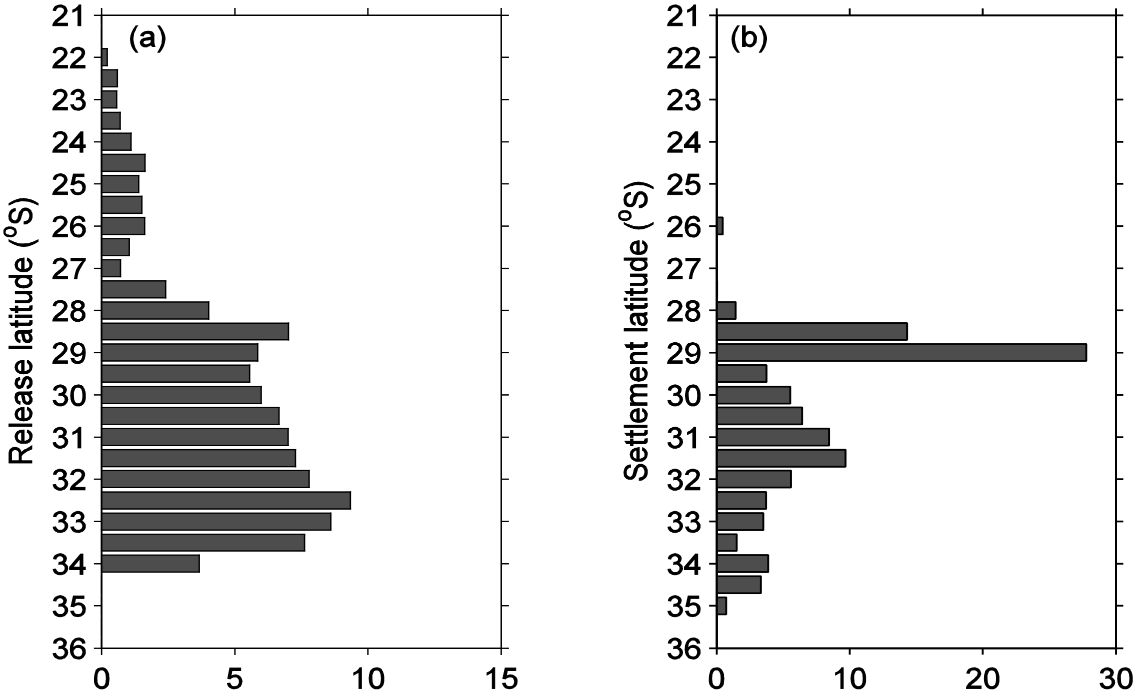


Figure 7.1.2. Percentage of (a) release and (b) settlement latitudes of (unweighted) successfully settled particles along the west coast of WA, averaged over 17 years of the 2012j model run.

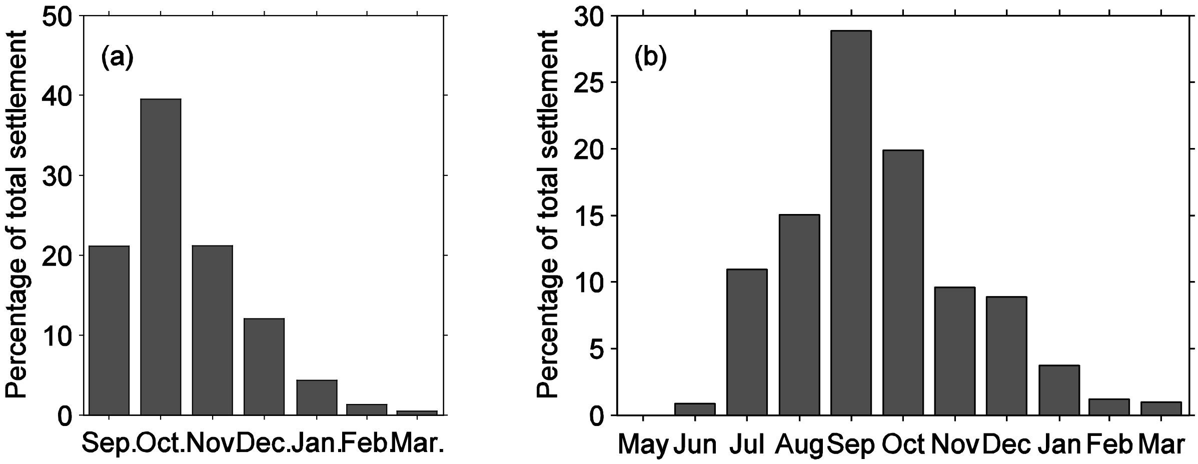


Figure 7.1.3. Percentage of (a) release and (b) settlement months of (unweighted) successfully settled particles along the west coast of WA, averaged over 17 years of the 2012j model run.

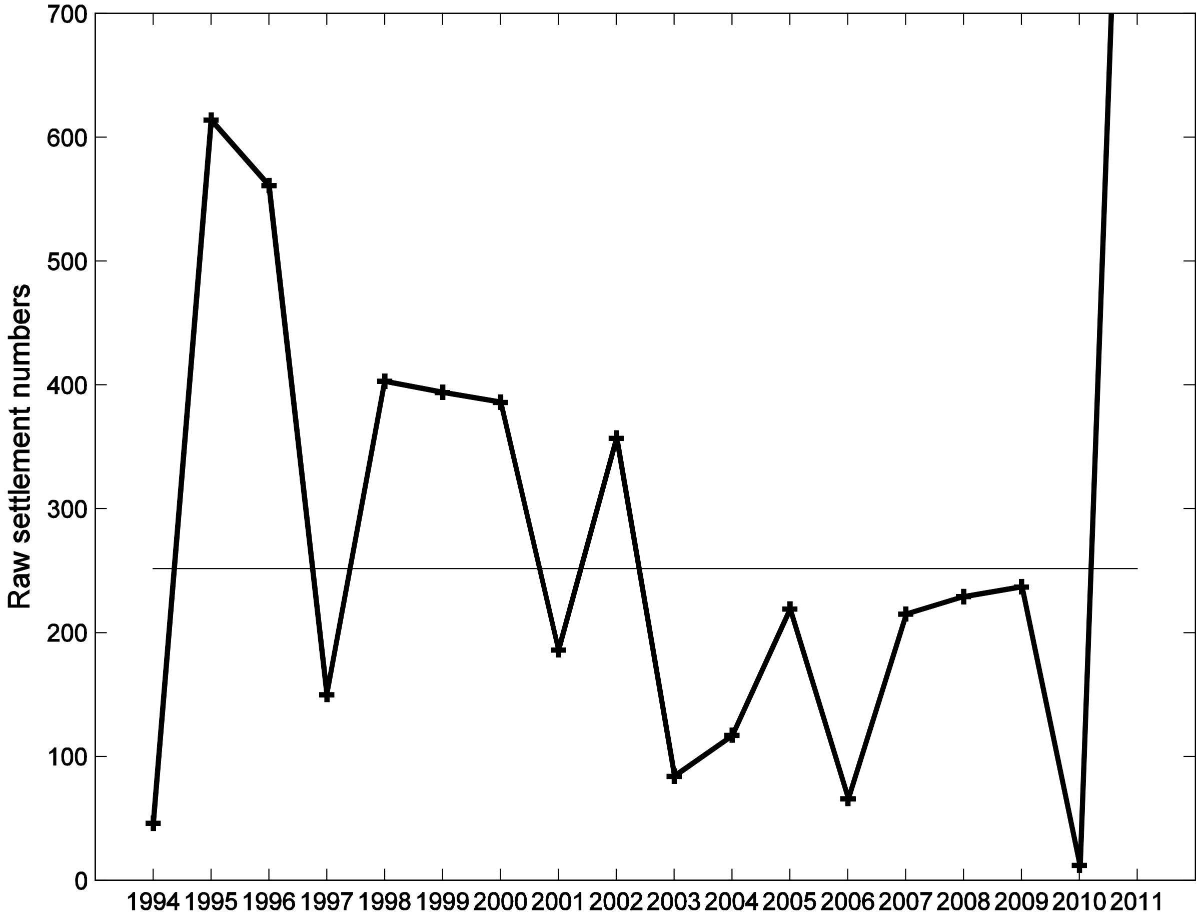


Figure 7.1.4. Raw (unweighted) settlement counts of the 2012j model. The horizontal bar denotes the 17-year average, excluding the 2011/12 settlement season. Year shown is start year of settlement season

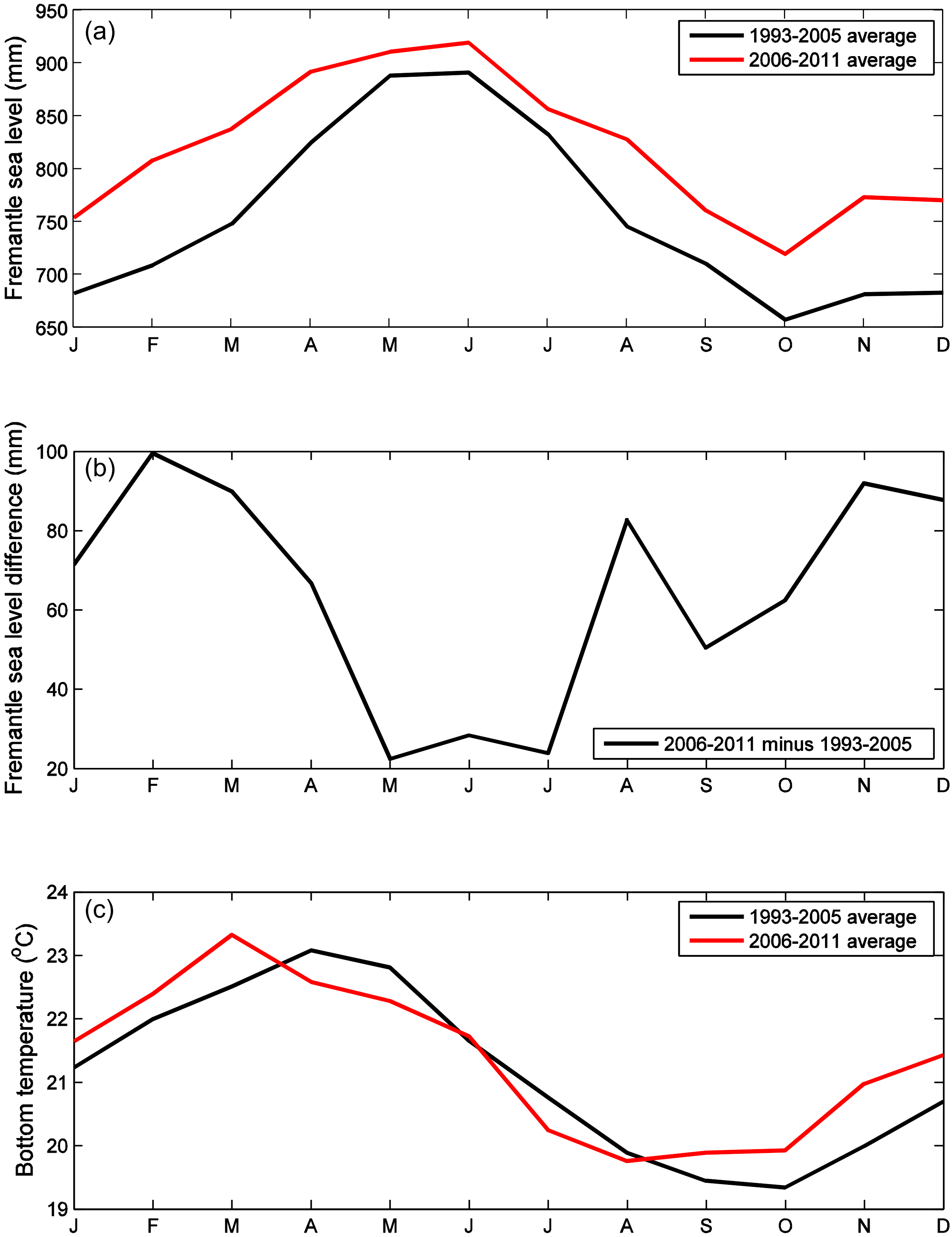


Figure 7.1.5. Fremantle sea level (a) averaged during 1993-2005 and 2006-2011, (b) their difference, and (c) bottom ocean temperature on the shelf south of Abrolhos (31-29°S), within the 200 m depth contour. The temperature bias between BRAN and OceanMAPS are corrected using their overlapping period.

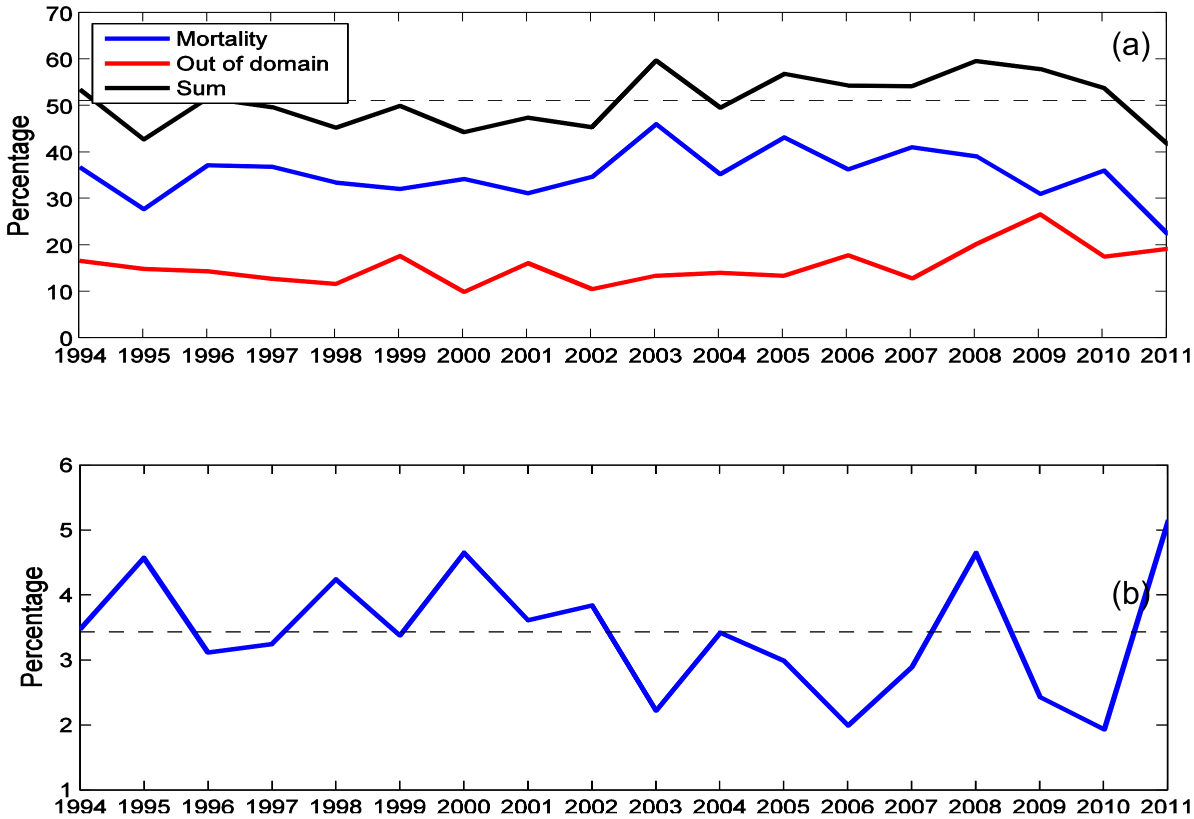


Figure 7.1.6. (a) Phyllosoma loss (unweighted) on 15 June each year of the 2012j model, from the combination of shelf and temperature mortality, those that move out of model domain, and their sum. (b) Percentage of category C phyllosoma that are distributed within 33°S-26°S, 110°E-coast box on 15 June each year of the 2012j model. The dashed lines denote the temporal averages.

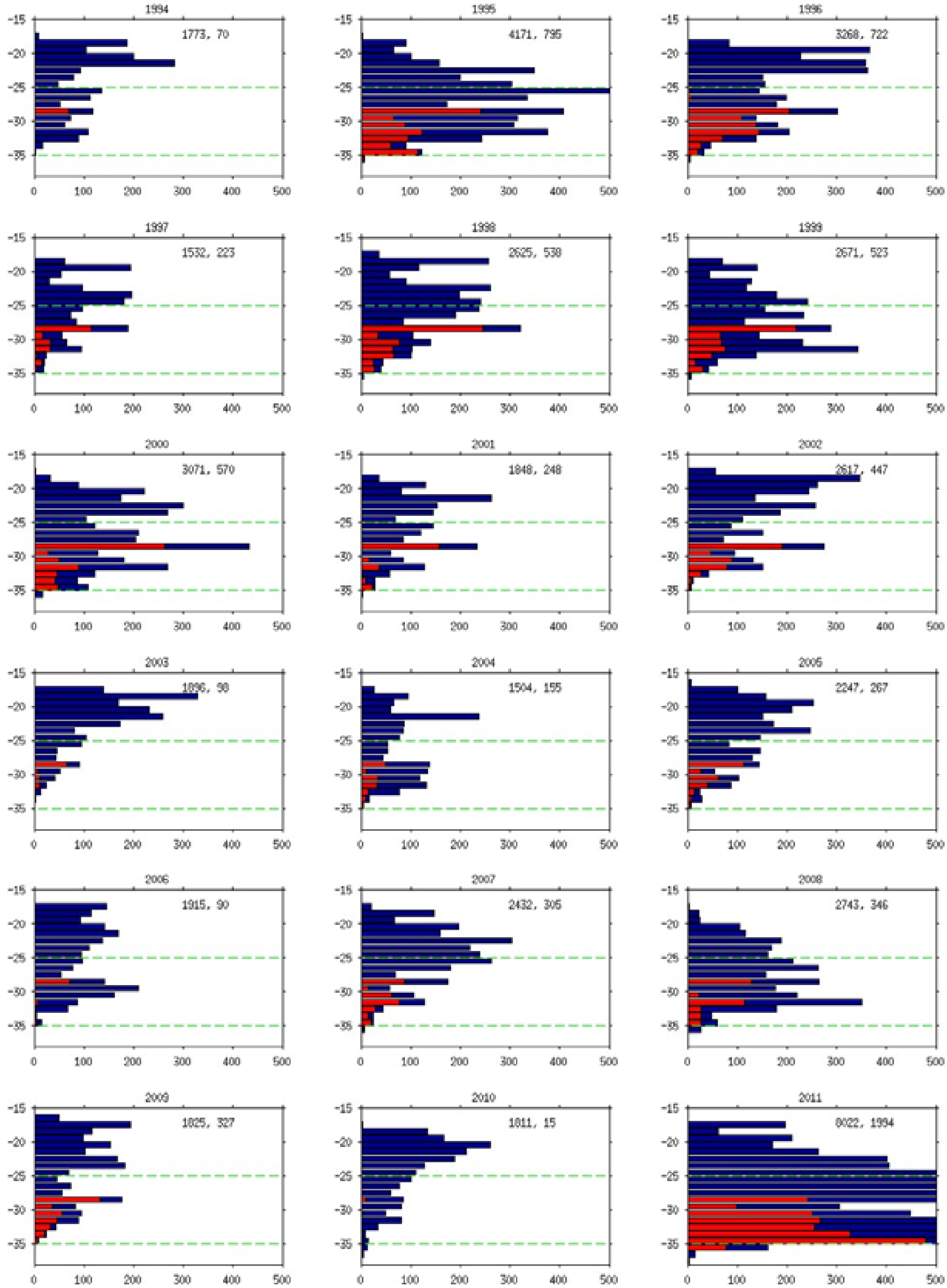


Figure 7.1.7. Latitudinal distribution of total metamorphosed puerulus (blue bars, first numbers), and settled puerulus (red bars, second number) among different model years in the 2012j run. The latitudes are based the location where the puerulus perished, settled, or at the end of the settlement season on 15 March.

7.1.2 Sensitivity testing: post model assessment

Sensitivity analysis using a post-model assessment was conducted for 24 runs of the IBM model (2011g-2011t, 2012a-2012j), with the parameters of the various model runs outlined previously in Table 7.1.1. Model outputs were assessed primarily on their ability to reproduce the interannual variation of the observed puerulus settlement, and secondly on their capacity to capture the monthly and latitudinal distribution of puerulus settlement.

Raw Model Outputs

A snapshot of the spatial distribution of all phyllosoma larvae alive on the 15th day of the month for the 2012 model runs were plotted on a monthly basis by their month of release (September to March) along with the number of puerulus settling each month for each of the 18 puerulus settlement seasons (1994/95 to 2011/12) examined. As an example, the spatial distribution for the 2000/01 season from model run 2012j is shown in Figure 7.1.8. There was an obvious lack of larvae in close proximity to the coast and therefore available to settle above 28°S during the settlement period. The figure also highlights the differences in phyllosoma numbers from the releases in different months near the time of settlement that affects the level of settlement. In the example shown, releases in October-December contribute most to the settlement.

Annual Settlements

Raw (unadjusted) model settlement numbers aggregated for each settlement season (May to following April) were correlated with the annual puerulus data from 8 locations across the fishery for each model run. Only successful model settlements in the main part of the fishery where there had been long-term settlement observations, between 27°S and 34°S, were considered for this analysis in order to compare with the spatial range of the puerulus collector locations. The raw settlement numbers were of a different scale than the observed puerulus data so only the relative annual trends can be compared (Table 7.1.2).

Linear correlations were calculated for each model based on raw model numbers, first using seasons 1994/95-2006/07 (i.e. prior to the recent decline in settlement) and secondly using all seasons 1994/95-2010/11, except for the anomalous 2011/12 season that was affected by the marine heat wave (Table 7.1.3, Figure 7.1.9a). This was to investigate any change in behaviour in the more recent years as these were seasons that had deviated from the historical trend. All model runs showed moderate positive linear correlation with the puerulus data of seasons 1994/95-2006/07, with the highest levels of correlation seen for the “2012” model runs, suggesting the importance of the contribution from the extended larval release period used in the 2012 runs.

With the inclusion of the four recent seasons (2007/08-2010/11) the correlation of observed and modelled annual settlement numbers generally decreased for all model runs. For the models that showed a decrease in correlation, the decrease varied from 2% (2011h) to 46% (2011o). Further inspection revealed that for all 2011 runs by omitting the 2008/09 season, the correlation of the other 16 seasons 1994/95-2010/11 actually increased by 3.0% (2011r) to 32% (2011g). This occurred primarily as the number of successful model settlements for the 2008/09 season of the 2011 runs was one of the highest across all seasons, whilst the actual puerulus numbers for this season was one of the lowest on record (Figure 7.1.10). The same was not evident for the 2012 runs where correlations still decreased by 0.6% (2012h) to 15% (2012d) with the omission of season 2008/09, as season 2008/09 no longer appeared as a significant outlier.

The highest correlation (0.816) of raw modelled settlement numbers with annual puerulus numbers is seen for the 2012c run which involved double winds, swimming at 7.5 cm/s and growth at 240 days. The 2012c run also showed the highest correlation (0.677) for the 1994/95-2010/11 period. All other 2012 runs, with the exception of 2012i and 2012j, also showed correlations above 0.7 for the 1994/95-2006/07 period. Four of these 2012 runs (b,d,e,h) also showed correlations above 0.6 for the 1994/95-2010/11 period.

Plots of the comparison of annual modelled versus observed settlement for model runs 2011j, 2011p, 2012c and 2012j indicate that changes to the model structure for the 2012 models has helped explain the lower settlement that occurred in 2008/09 (Figure 7.1.10). They also highlight that 2011/12 is a significant outlier.

Monthly Distribution

Raw (unadjusted) model settlement monthly settlement numbers were converted to proportions and averaged over the seasons 1994/95-2006/07, which were then correlated with the monthly puerulus proportions from 8 locations across the fishery averaged over for the same period. A concordance correlation was used to measure the agreement between two variables by assessing the degree to which pairs of observations fall on the 45° line through the origin (Zar 2010). This analysis was repeated using the period 1994/95-2010/11 to investigate any change in behaviour in the more recent years from the historical trend. As for the annual data, only successful settlements between 27°S and 34°S were considered for this analysis (Table 7.1.3, Figure 7.1.9b). All model runs showed positive concordance correlation with the puerulus data, varying from 0.25 to 0.90. The lowest levels of correlation were seen for the first five “2012” model runs (a-e), where high proportions of settlement were recorded in July and the peak in settlement occurred around August and then rapidly decreased (2012c in Figure 7.1.11). This was in contrast to the observed data peaking in September-December before declining more rapidly across the remainder of the season. The monthly concordance correlation was higher for the later 2012 model runs with the 2012i and 2012j runs showing monthly correlations around 0.8 which was similar to the high levels observed in some of the 2011 runs (Figure 7.1.9 and 7.1.11).

Including the four recent seasons of low settlement (2007/08-2010/11) in the analyses did not significantly change the monthly concordance correlation for most model runs (Table 7.1.3, Figure 7.1.9b).

Plots of the comparison of monthly proportions of modelled versus observed settlement for model runs 2011j, 2011p, 2012c and 2012j highlight the improved monthly fit associated with 2012j compared with some of the earlier models that featured a strong peak in settlement in August-September followed by a sharp decline (Figure 7.1.11).

Latitudinal Distribution

Raw (unadjusted) model settlement proportions (by 0.2° latitude) averaged over the seasons 1994/95-2006/07 were used to compute a mean latitude of settlement, which was compared with the mean latitude of settlement obtained from puerulus data for the same period from 8 locations across the fishery. A difference in mean latitude of settlement (modelled minus observed) was computed. This analysis was repeated using the period 1994/95-2010/11 to investigate any change in behaviour in the more recent years from the historical trend. As for the annual and monthly comparisons, only successful settlements between 27°S and 34°S were considered for this analysis. The difference in modelled mean latitude to observed mean latitude varied from -0.15° to 0.48° (Table 7.1.3, Figure 7.1.9c) where a positive value indicates that the mean model settlement is south of the observed mean settlement. The 2012 runs a-d, using the faster growth, displayed the highest difference in magnitude of mean latitude of settlement, with the modelled settlement being consistently higher that the observed settlement due to a second peak of settlement values at 31°S.

Plots of the comparison of monthly proportions of modelled versus observed settlement for model runs 2011j, 2011p, 2012c and 2012j are shown in Figure 7.1.12. A peak in the settlement distribution is observed around 31°S (Jurien) but the peak of greatest magnitude is observed around 29°S. As this is the latitude corresponding to the Abrolhos Islands, a subsequent analysis was perfomed to assess the influence of the settlements at these off-shore locations. Using only settlements occurring on the mainland, the latitudinal distribution was compared again with the observed settlements (Figure 7.1.13). This results in an improved fit as the model settlements appear to have a high level of settlement at the Abrollhos as they are more likely to reach the Abrolhos than any coastal location. Comparison of the mainland settlements with the observed data showed no increase in correlation for the monthly and annual distribution if the Abrolhos model settlement was removed.

Weighting Model Settlements

The analyses of raw (unweighted) number of successful settlements produced by each model run assumed a constant release of larvae by time and location. Weighting of model settlements was undertaken to produce a more realistic distribution of larval release, offshore larval distribution and settlement of puerulus along the coast by location and time by weighting the distribution of locations and times of larval release based on expected spatial and temporal distribution of larval release. Additional effects of mortality other than those experienced in the model were also introduced by weighting factors based on the duration in one or more larval stages i.e. applying a higher level of mortality associated with longer larval duration required to reach settlement.

Weighting model settlements by time of larval release

The weighting of successful settlements was investigated for a number of scenarios involving the timing of larval release. An initial monthly distribution of hatching from the October to March period preceding the settlement season was inferred from Chubb (1991). This distribution was shifted by 2 weeks, forward and backwards as part of the sensitivity assessment, to assess the effect of an “early” and “late” distribution (Figure 7.1.14, left). Individual weightings for each season were considered by classifying each season as early, average or late hatching from a breeding stage index (see Figure 7.6.1). An alternative daily hatching weighting was produced by modelling the release of larvae as the sum of two normal distributions separated by 50 days across the breeding period to reflect the double spawning that larger lobsters undertake. The daily hatching scenario was also modelled as early, average or late, as well as by individual years classified as early, average or late hatching (Figure 7.1.14, right) using the breeding stage index.

Another scenario considered was weighting the northern and southern releases separately where northern settlements were defined as release latitude above 30°S and southern below. Pairs considered were North-early/South-average, North-average/South-late and North-early/South-late to reflect that spawning generally occurs earlier in the northern region compared to the southern region.

The September to March hatching period in the model was also considered in four subsets: (Very early: 1 Sep-15 Oct, Early: 16 Oct-30 Nov, Mid: Dec-Jan, Late: Feb-Mar) and the resulting model settlement numbers compared with the actual puerulus numbers.

The best fit of annual weighted model settlements to observed puerulus for all 2011 model runs was for weighting by early period (Oct-Nov), for seasons up to 2006/07 or the extended period 2010/11, with slightly lower correlations when considering seasons up to 2010/11 (Table 7.1.4). The correlations of the weighted settlements were not a substantial improvement higher than that seen for the unweighted settlements. Even when the recent four anomalous years were included, the correlation was similar to that from the raw settlement numbers. Conversely the settlements from the larval releases in Dec-Jan and Feb-Mar showed little, if any, correlation with the puerulus data, with or without the final four seasons. For the 2012 runs, 2012a and 2012b showed a slight improvement when considering the Oct-Nov settlements up to 2006/07 whilst 2012f and 2012g showed a slight improvement when considering the Sep-Nov settlements up to 2010/11. The remaining 2012 model runs did not show an increase in correlation over the raw settlements for any weighting by timing of larval release.

If weighting by period was excluded, the early distribution of hatching produced a better correlation with settlement than the late distribution. The trial which considered weighting individual years by average, early or late settlement did not result in an increase in correlation being observed.

In all cases, the correlation observed for years up to and including the 2006/07 season was greater than that including all seasons to 2010/11. This was largely attributed to the 2008/09 season which the model predicted much higher numbers of settlement for than was evident in the puerulus numbers.

In contrast to the analysis of annual correlation, the concordance correlation of monthly proportions of observed and modelled settlements were highest for weightings by later releases (Table 7.1.5). For all model runs, weighting by later releases resulted in an increase in correlation with the observed monthly distribution for the period up to and including the 2006/07 season, along with that including all seasons to 2010/11. The increase in correlation was particularly noticeable for the early 2012 runs where correlation values around 0.3 were increased to around 0.6. This highlights an important compromise that is required in the larval model between fitting the annual settlement and the monthly distribution of the settlement.

Weighting model settlements by latitudinal hatching

Weighting by latitudinal hatching was based on 1-degree bands of latitude, with the weighting values determined from stock assessment model (de Lestang *et al*. 2012). An average latitudinal distribution of hatching was derived for all years, and also individually for each season (Figure 7.1.15). For all 2012 model runs, weighting by the individual latitudinal hatching for each season resulted in a greater increase in correlation with the annual puerulus data than the average weighting when considering seasons up to 2006/07 or up to 2010/11 (Table 7.1.6). For the 2011 runs, when considering only seasons up to 2006/07, the highest correlation was sometimes observed for weighting by individual years and sometimes for average weightings, depending on the model run. However, when considering all seasons up to 2010/11, the weighting by individual years consistently produced a higher correlation than that obtained by average weighting.

The concordance correlation of monthly proportions actually decreased slightly for weighting by average or individual latitudinal hatching, with individual weights marginally better for the 2012 runs (Table 7.1.7). Hence the monthly distribution of settlement in the larval model was not sensitive to the latitudinal distribution of larval releases.

Weighting model settlements by mortality

In addition to the mortality experienced in the model from boundary effects and temperature effects on growth, several additional "natural" mortalities have been incorporated to emulate the "predation" component of natural mortality. These mortalities have been incorporated in the modelling process through the use of post model analysis. This process has been used to apply additional mortality to the settled puerulus in the model runs, during two periods of the growth cycle i.e. to any phyllosoma which was spending an extended period in category A and then again if the settling puerulus had to spend an extended period from category A to category C2.

The additional mortality applied during Category A started when the phyllosoma reached an age of 60 days and acted to reduce the numbers surviving each day such that none survived beyond 150 days in category A. An alternative mortality based on the total pelagic larval duration (PLD) started when the phyllosoma reached 180 days and acted to reduce the numbers surviving each day such that none survived beyond 420 days. In a further sensitivity test, an additional small continuous mortality (1% per day) was applied to all of the model phyllosoma as they progress through each phyllosoma category in the model with an additional 1% applied for days when the phyllosoma experienced temperatures above 24°C. This separate sensitivity testing process was designed to assess the potential impact of the general mortality from predation, which can be expected to occur throughout the full period to settlement, along with the additional impact of high temperatures. These three alternative weightings were applied independently of one another.

Weighting by PLD (mortality associated with phyllosoma larval duration) resulted in an increase in correlation of annual values to that observed with the raw settlement values for all model runs when considering years up to and including 2006/07 (Table 7.1.8). Weighting by mortality based on duration in larval Category A for the same period did not always result in an increase in correlation and when considering seasons up to 2010/11 typically led to a decrease. When all seasons (1994/95-2010/11) were considered, the increase in correlation was generally observed for weighting by daily predation including temperature.

The concordance correlation of monthly proportions weighted by mortality with observed monthly proportions was higher for larval Category A for both periods (Table 7.1.9). Application of PLD weighting performed poorly for all models as this probably reduced the numbers of settlers in the latter month.

Combined Weightings

Weighting by month of hatching, latitude of hatching and mortality, using the individual weightings mentioned previously, were considered in combination in an endeavour to produce a realistic distribution of successful settlements. Considering seasons up to and including 2006/07, the highest correlations with annual puerulus settlements were achieved using different combinations of weightings for each model run (Table 7.1.10). A common element producing the highest correlation for most model runs involved weighting by early releases. However, to achieve higher concordance correlations of observed and modelled monthly proportions, later releases were more important along with a mortality weighting based on duration in Category A (Table 7.1.11).

When considering seasons up to and including 2010/11, weighting by early releases, latitudinal hatching for individual years along with a daily mortality weighting including the added temperature component provided the maximum correlation of modelled and observed annual settlements (Table 7.1.12). However, the monthly distribution of settlement was more accurately achieved using weightings by late release and mortality based on time spent in category A (Table 7.1.13). This conflict between the weightings required for the annual and monthly settlement fit identifies an area of further research to understand the cause of this conflict. It is most likely that the conflict is due to the lack of late settlers in most models, which somehow comprise the weighting process, and in the 2012j model run the conflict is greatly reduced.

Table 7.1.12 also shows the monthly concordance correlation achieved for the combination of weights indicated that maximised the annual puerulus settlement correlation for each model as well as the mean difference in the latitude of settlement. This enables us to select some models that provide a reasonable fit between the annual and monthly pattern of settlement as well fitting the mean latitude. Model runs 2011k, 2012i and j show reasonable annual correlations (0.56-0.59) along with reasonable monthly concordance correlations (0.63-0.73) as well as fitting close to the mean latitude of settlement (0.02-0.14°). The outputs from these models will be examined further in source-sink relationships.

Optimising Weightings

The assessment that examined the optimising of weightings of larval release and mortality assumed that the weightings for latitudinal hatchings, based on the stock assessment model were appropriate. As the individual weightings performed consistently better than the average annual latitudinal weightings (Table 7.1.6), the individual weightings were used. An optimisation process was then undertaken to maximise the correlation of the annual observed and weighted modelled settlements by estimating the daily mortality and the daily weightings of timing of release modelled as a combination of two normal distributions (see Figure 7.1.4 right). The hatching parameters included mean time of early release, standard deviation and time between peaks of hatching that reflected the double spawning of larger lobsters. Restrictions were placed on these parameters to maintain the larval release within the appropriate period.

The optimisation of annual settlement correlation for both periods resulted in improved correlations (Table 7.1.14 and 7.1.15) compared to the sensitivity analysis approach of different weighting levels (e.g. Table 7.1.2 and 7.1.4 for the extended period). This analysis also confirmed that optimum parameters indicated an early larval hatching date (day -5) for nearly all model runs when assessing the annual puerulus settlement but a late larval hatching date (day 70) when optimising the monthly distribution. This again highlighted the conflict with fitting the monthly pattern distribution where the optimum parameters suggested a later larval hatching period. These preliminary optimisation results have identified a valuable statistical approach that should be explored further to simultaneously fit the annual and monthly distribution.

Source-Sink Relationship

The source-sink relationship for three models that show a reasonable fit to the settlement criteria, models 2011k, 2012i and 2012j, are shown in Figure 7.1.17 where the successful settlements have been weighted by the 3 categories indicated in Table 7.1.12 for maximum correlation with annual observed settlement data. The relative success of larvae released along the coast (unweighted) for the three models is also shown for comparison (Figure 7.1.18). These figures show that larval releases along all of the main part of the fishery (27-33°S) contribute to the settlement with some variability apparent between models. The source-sink assessment again highlights that the model does not accurately reflect the good settlement that is observed in the areas north of the main part of the fishery (i.e. Shark Bay north). This reflects the focus of this study on achieving a reasonable fit to the annual puerulus settlement in the main area of the fishery, including the recent years of low settlement, by reducing the active swimming speed of puerulus from 15 cm/s to 5 cm/s in the more recent runs. Various puerulus swimming speeds were used in the three model runs shown in Figure 7.1.17: 2011k (15 cm/s); 2012i and 2012j (5 cm/s). Active swimming appears to be rather important for puerulus to settle in the wide-shelf coast region off Shark Bay, in order to overcome the prevailing shelf current.

Summary

The larval model analyses undertaken in this study have resulted in a significant improvement in the model fit to the annual puerulus settlement compared to previous assessments (Griffin *et al*. 2001, Feng *et al*. 2011b). The study has also provided a reasonable model fit to most of the recent years of anomalous low settlement (2007/08 to 2010/11) with the 2011/12 settlement affected by the marine heat wave remaining an outlier. The model also provided a reasonable fit to the monthly pattern of distribution and the spatial pattern of distribution over the main areas of the fishery with the far northern settlement (Shark Bay north) being an exception. The assessment also applied an optimizing technique to estimating some model parameters to fitting the puerulus settlement that is not often used in oceanographic larval models.

These sensitivity analyses have identified the following parameters as being important in this assessment: (a) wind effect on the water movement; (b) the level of puerulus swimming allowed in the model; (c) the month of larval release; (d) the abundance and spatial distribution of larval release and (e) larval duration before settlement. The correlation between model and actual puerulus settlement was significantly improved when the larval release was concentrated in the early months. This aspect is being examined further to understand the possible reasons of why annual settlement is more sensitive to early releases than later releases.

The analyses also identified areas where more improvement in larval model could occur: (a) the lack of model settlement in the far northern region does not fit with observed good settlement in that area; (b) the model fit to 2011/12 settlement affected by the marine heat wave is an outlier so the temperature effect on larval growth and survival at very high water temperatures needs to be examined; (c) model generally underestimated the settlement in the later months of settlement; (d) there was a conflict in the model between early larval releases providing the best fit to overall settlement but not fitting the monthly distribution, mostly due to the distortion of the annual cycle of settlements in some of the model runs; and (e) the pike in model settlement at the Abrolhos is not apparent in the actual settlement data.

Table 7.1.2. Raw (unweighted) number of successful settlements for each settlement season (e.g. 1994 indicates 1994/95 season) from each model run. The 2011 runs involve the 1994/95-2010/11 seasons whilst the 2012 runs also include the 2011/12 season. Only successful model settlements between 27°S and 34°S are included. The last row indicates the annual coast-wide puerulus index derived from the observed puerulus data at 8 locations across the fishery.

Model	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
2011g	799	1472	852	555	1452	1455	1709	761	835	455	1123	603	1212	681	1658	620	524	NA
2011h	71	514	433	149	630	602	635	179	393	163	270	272	286	302	399	268	1	NA
2011i	25	311	125	67	238	368	337	96	186	51	118	109	118	168	293	57	1	NA
2011j	107	484	154	161	289	667	514	229	249	91	222	181	297	215	614	98	86	NA
2011k	803	1480	923	545	1491	1549	1726	785	816	476	1089	638	1219	716	1628	632	509	NA
2011l	52	472	488	146	632	606	605	159	388	147	239	302	275	344	333	255	0	NA
2011m	450	1178	766	423	1201	1135	1337	597	685	347	780	527	894	550	1059	507	191	NA
2011n	44	353	177	125	224	445	348	191	218	65	160	195	194	205	392	91	28	NA
2011o	358	673	426	273	672	693	887	388	337	208	416	240	575	347	1014	280	243	NA
2011p	46	452	264	127	360	562	445	235	275	78	227	220	223	227	422	128	20	NA
2011q	113	634	429	173	528	645	637	360	278	178	389	258	386	294	642	192	56	NA
2011r	10	252	159	63	218	366	266	102	148	59	79	147	112	169	250	69	0	NA
2011s	36	335	306	117	374	429	581	133	351	71	135	212	179	268	277	136	1	NA
2011t	53	454	358	222	636	562	742	133	384	100	151	169	189	353	451	167	20	NA
2012a	467	2409	2318	425	726	1174	1443	569	1429	620	772	630	692	1175	1224	940	58	4045
2012b	792	3288	2646	702	1218	1856	1935	1012	1932	825	1169	929	971	1447	1752	1133	248	5410
2012c	209	1402	1331	259	264	749	887	385	608	266	327	403	341	616	714	395	42	2359
2012d	266	1761	1658	431	624	829	1336	404	982	292	556	586	428	955	730	723	87	2520
2012e	34	636	398	80	141	262	237	145	192	48	114	143	99	200	309	119	19	1268
2012f	7	193	76	22	39	71	59	34	52	4	23	37	33	40	123	27	3	564
2012g	4	177	63	11	50	96	62	35	45	7	22	49	26	39	93	20	3	497
2012h	88	1012	514	205	334	555	455	356	411	72	194	272	205	300	527	180	57	2125
2012i	171	882	955	249	815	686	668	262	631	231	258	360	157	422	422	512	5	1855
2012j	70	678	691	219	512	487	514	225	438	97	151	261	95	283	320	321	13	1408
Index	59	137	103	35	28	96	117	79	25	48	39	49	14	10	2	5	19	23

Table 7.1.3. Correlations of observed annual puerulus data with the annual modelled settlement numbers, concordance correlation of averaged monthly proportions of observed puerulus data with averaged modelled monthly proportions, and average difference in mean latitude of settlement from observed puerulus data and modelled settlements, from various experiments for the 2012 IBM with various wind, wave, swim, growth and maximum puerulus duration parameters, for the period 1994/95-2006/07 and the period 1994/95-2010/11. Only successful model settlements between 27°S and 34°S are included. Maximum correlation, or minimum absolute latitude difference, for each category is highlighted in grey.

Model	Annual Correlation		Monthly Concordance Correlation		Difference in Mean Latitude	
	1994/95-2006/07	1994/95-2010/11	1994/95-2006/07	1994/95-2010/11	1994/95-2006/07	1994/95-2010/11
2011g	0.440	0.355	0.901	0.900	0.088	0.161
2011h	0.452	0.443	0.654	0.638	0.175	0.265
2011i	0.572	0.448	0.572	0.569	0.053	0.117
2011j	0.553	0.369	0.699	0.690	-0.087	-0.022
2011k	0.467	0.388	0.884	0.889	0.040	0.111
2011l	0.430	0.437	0.601	0.586	0.223	0.288
2011m	0.476	0.454	0.837	0.836	0.038	0.091
2011n	0.584	0.416	0.627	0.617	-0.100	-0.027
2011o	0.513	0.278	0.836	0.826	-0.101	-0.050
2011p	0.576	0.483	0.622	0.607	-0.016	0.054
2011q	0.620	0.486	0.634	0.618	-0.032	0.012
2011r	0.565	0.445	0.536	0.518	-0.010	0.084
2011s	0.495	0.470	0.591	0.572	0.152	0.234
2011t	0.447	0.389	0.622	0.579	0.363	0.432
2012a	0.708	0.581	0.251	0.217	0.481	0.550
2012b	0.741	0.631	0.294	0.264	0.358	0.442
2012c	0.816	0.677	0.257	0.225	0.323	0.415
2012d	0.743	0.623	0.349	0.299	0.427	0.530
2012e	0.776	0.618	0.380	0.352	0.150	0.221
2012f	0.717	0.491	0.511	0.491	-0.117	-0.081
2012g	0.733	0.583	0.506	0.498	-0.149	-0.081
2012h	0.755	0.635	0.557	0.544	0.047	0.121
2012i	0.579	0.533	0.781	0.754	-0.023	0.146
2012j	0.653	0.596	0.774	0.740	-0.134	0.026

Table 7.1.4. Linear correlation of raw (unweighted) and weighted (by timing of larval release) model settlements and puerulus data for period 1994/95-2006/07 as well as extended period 1994/95-2010/11. Weighting by time of hatching involves the categories: Early, Average, Late or Individual by Monthly or Daily Weightings. Individual years were classified as early average or late by timing index. Monthly hatchings were also considered by north or south as well as individual periods (Sep-Oct, Oct-Nov, Dec-Jan, Feb-Mar). Maximum correlations were considered including all weightings, and secondly including all weightings other than by the four periods (No periods). Maximum correlation of each category is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined.

	Maximum Annual Correlation 1994-2006					Maximum Annual Correlation 1994-2010				
Model	Raw	Wt	Category	No Periods	Category	Raw	Wt	Category	No Periods	Category
2011g	0.440	0.560	Oct-Nov	0.395	Early(Monthly)	0.355	0.450	Oct-Nov	0.309	Early(Monthly)
2011h	0.452	0.575	Oct-Nov	0.387	Early(Daily)	0.443	0.524	Oct-Nov	0.397	Early(Daily)
2011i	0.572	0.668	Oct-Nov	0.507	Early(Daily)	0.448	0.557	Oct-Nov	0.394	Early(Daily)
2011j	0.553	0.641	Oct-Nov	0.500	Early(Daily)	0.369	0.486	Oct-Nov	0.316	Early(Monthly)
2011k	0.467	0.625	Oct-Nov	0.408	Early(Monthly)	0.388	0.524	Oct-Nov	0.338	Early(Monthly)
2011l	0.430	0.525	Oct-Nov	0.374	Early(Daily)	0.437	0.515	Oct-Nov	0.392	Early(Daily)
2011m	0.476	0.616	Oct-Nov	0.429	Early(Monthly)	0.454	0.564	Oct-Nov	0.415	Early(Monthly)
2011n	0.584	0.691	Oct-Nov	0.517	Early(Daily)	0.416	0.559	Oct-Nov	0.346	Early(Monthly)
2011o	0.513	0.615	Oct-Nov	0.449	Early(Monthly)	0.278	0.389	Oct-Nov	0.202	Early(Monthly)
2011p	0.576	0.700	Oct-Nov	0.503	Early(Daily)	0.483	0.618	Oct-Nov	0.417	Early(Daily)
2011q	0.620	0.747	Oct-Nov	0.546	Early(Daily)	0.486	0.610	Oct-Nov	0.416	Early(Daily)
2011r	0.565	0.648	Oct-Nov	0.493	Early(Daily)	0.445	0.544	Oct-Nov	0.387	Early(Monthly)
2011s	0.495	0.570	Oct-Nov	0.444	Early(Daily)	0.470	0.534	Oct-Nov	0.426	Early(Monthly)
2011t	0.447	0.482	Oct-Nov	0.451	N-Early,S-Late	0.389	0.412	Oct-Nov	0.378	N-Early,S-Late
2012a	0.708	0.791	Oct-Nov	0.724	Early(Daily)	0.581	0.643	Oct-Nov	0.584	N-Early,S-Late
2012b	0.741	0.836	Oct-Nov	0.783	Early(Monthly)	0.631	0.711	Oct-Nov	0.659	Early(Monthly)
2012c	0.816	0.837	Early(Monthly)	0.837	Early(Monthly)	0.677	0.667	Oct-Nov	0.666	Early(Monthly)
2012d	0.743	0.729	Oct-Nov	0.723	Early(Monthly)	0.623	0.584	Early(Monthly)	0.584	Early(Monthly)
2012e	0.776	0.775	Oct-Nov	0.772	Early(Monthly)	0.618	0.609	Sep-Oct	0.494	Early(Monthly)
2012f	0.717	0.697	Early(Monthly)	0.697	Early(Monthly)	0.491	0.577	Sep-Oct	0.267	Early(Monthly)
2012g	0.733	0.658	Sep-Oct	0.651	Early(Monthly)	0.583	0.621	Sep-Oct	0.379	Early(Monthly)
2012h	0.755	0.686	Oct-Nov	0.667	Early(Monthly)	0.635	0.616	Sep-Oct	0.493	Early(Monthly)
2012i	0.579	0.578	Feb-Mar	0.521	N-Early,S-Late	0.533	0.528	Feb-Mar	0.513	N-Early,S-Late
2012j	0.653	0.612	Sep-Oct	0.501	Early(Monthly)	0.596	0.530	Sep-Oct	0.480	Early(Monthly)

Table 7.1.5. Concordance correlation of monthly proportions of raw and weighted (by timing of larval release) model settlements and puerulus data for period 1994/95-2006/07 as well as extended period 1994/95-2010/11. Weighting by time of hatching involves the categories: Early, Average, Late or Individual by Monthly (M) or Daily (D) Weightings. Individual years were classified as early average or late by timing index. Monthly hatchings were also considered by north or south as well as individual periods (Sep-Oct, Oct-Nov, Dec-Jan, Feb-Mar). Maximum correlations were considered including all weightings, and secondly including all weightings other than by period. Maximum correlation of each category is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined.

	Maximum Monthly Concordance Correlation 1994-2006					Maximum Monthly Concordance Correlation 1994-2010				
Model	**Raw**	**Wt**	**Category**	**No Periods**	**Category**	**Raw**	**Wt**	**Category**	**No Periods**	**Category**
2011g	0.901	<u>0.926</u>	N-Early,S-Late	<u>0.926</u>	N-Early,S-Late	0.900	<u>0.923</u>	N-Early,S-Late	<u>0.923</u>	N-Early,S-Late
2011h	0.654	<u>0.699</u>	Late(M)	<u>0.699</u>	Late(M)	0.638	<u>0.697</u>	Late(M)	<u>0.697</u>	Late(M)
2011i	0.572	<u>0.643</u>	Late(M)	<u>0.643</u>	Late(M)	0.569	<u>0.661</u>	Late(M)	<u>0.661</u>	Late(M)
2011j	0.699	<u>0.795</u>	Late(M)	<u>0.795</u>	Late(M)	0.690	<u>0.784</u>	Late(M)	<u>0.784</u>	Late(M)
2011k	0.884	<u>0.911</u>	N-Early,S-Late	<u>0.911</u>	N-Early,S-Late	0.889	<u>0.918</u>	N-Early,S-Late	<u>0.918</u>	N-Early,S-Late
2011l	0.601	<u>0.636</u>	Late(M)	<u>0.636</u>	Late(M)	0.586	<u>0.642</u>	Late(M)	<u>0.642</u>	Late(M)
2011m	0.837	<u>0.884</u>	Late(M)	<u>0.884</u>	Late(M)	0.836	<u>0.890</u>	Late(M)	<u>0.890</u>	Late(M)
2011n	0.627	<u>0.744</u>	Late(M)	<u>0.744</u>	Late(M)	0.617	<u>0.743</u>	Late(M)	<u>0.743</u>	Late(M)
2011o	0.836	<u>0.914</u>	Late(M)	<u>0.914</u>	Late(M)	0.826	<u>0.910</u>	Late(M)	<u>0.910</u>	Late(M)
2011p	0.622	<u>0.705</u>	Late(M)	<u>0.705</u>	Late(M)	0.607	<u>0.706</u>	Late(M)	<u>0.706</u>	Late(M)
2011q	0.634	<u>0.743</u>	Late(M)	<u>0.743</u>	Late(M)	0.618	<u>0.733</u>	Late(M)	<u>0.733</u>	Late(M)
2011r	0.536	<u>0.598</u>	Late(M)	<u>0.598</u>	Late(M)	0.518	<u>0.599</u>	Late(M)	<u>0.599</u>	Late(M)
2011s	0.591	<u>0.630</u>	N-Early,S-Late	<u>0.630</u>	N-Early,S-Late	0.572	<u>0.626</u>	Late(M)	<u>0.626</u>	Late(M)
2011t	0.622	<u>0.702</u>	Late(M)	<u>0.702</u>	Late(M)	0.579	<u>0.669</u>	Late(M)	<u>0.669</u>	Late(M)
2012a	0.251	<u>0.602</u>	Feb-Mar	<u>0.491</u>	Late(M)	0.217	<u>0.628</u>	Feb-Mar	<u>0.462</u>	Late(D)
2012b	0.294	<u>0.620</u>	Feb-Mar	<u>0.538</u>	Late(M)	0.264	<u>0.646</u>	Feb-Mar	<u>0.526</u>	Late(M)
2012c	0.257	<u>0.678</u>	Feb-Mar	<u>0.467</u>	Late(M)	0.225	<u>0.671</u>	Feb-Mar	<u>0.448</u>	Late(D)
2012d	0.349	<u>0.647</u>	Feb-Mar	<u>0.552</u>	Late(D)	0.299	<u>0.643</u>	Feb-Mar	<u>0.525</u>	Late(D)
2012e	0.380	<u>0.600</u>	Late(M)	<u>0.600</u>	Late(M)	0.352	<u>0.580</u>	Late(M)	<u>0.580</u>	Late(M)
2012f	0.511	<u>0.730</u>	Dec-Jan	<u>0.691</u>	Late(D)	0.491	<u>0.696</u>	Dec-Jan	<u>0.674</u>	Late(D)
2012g	0.506	<u>0.675</u>	Late(Monthly)	<u>0.675</u>	Late(M)	0.498	<u>0.708</u>	Late(M)	<u>0.708</u>	Late(M)
2012h	0.557	<u>0.721</u>	Late(M)	<u>0.721</u>	Late(M)	0.544	<u>0.713</u>	Late(M)	<u>0.713</u>	Late(M)
2012i	0.781	<u>0.838</u>	Late(M)	<u>0.838</u>	Late(M)	0.754	<u>0.851</u>	Late(M)	<u>0.851</u>	Late(M)
2012j	0.774	<u>0.841</u>	N-Early,S-Late	<u>0.841</u>	N-Early,S-Late	0.740	<u>0.839</u>	Late(M)	<u>0.839</u>	Late(M)

Table 7.1.6. Linear correlation of raw and weighted (by latitude of larval release) model settlements and puerulus data for period 1994/95-2006/07 as well as extended period 1994/95-2010/11. Weighting by latitudinal hatching was based on 1-degree bands of latitude, with an average for all years (Average), and also individually for each season (Individual). Maximum correlation of each category is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined. The weighting category displaying the highest correlation for each model run is indicated in bold.

Model	1994-2006			1994-2010		
	Raw	Average	Individual	Raw	Average	Individual
2011g	0.440	0.539	**0.553**	0.355	0.383	**0.480**
2011h	0.452	0.530	**0.540**	0.443	0.514	**0.554**
2011i	0.572	0.668	**0.668**	0.448	0.503	**0.575**
2011j	0.553	**0.622**	0.615	0.369	0.385	**0.470**
2011k	0.467	0.577	**0.583**	0.388	0.471	**0.547**
2011l	0.430	0.515	**0.527**	0.437	0.516	**0.558**
2011m	0.476	0.582	**0.590**	0.454	0.535	**0.595**
2011n	0.584	**0.559**	0.554	0.416	0.369	**0.463**
2011o	0.513	0.654	**0.671**	0.278	0.337	**0.449**
2011p	0.576	**0.653**	0.639	0.483	0.572	**0.622**
2011q	0.620	0.742	**0.743**	0.486	0.576	**0.644**
2011r	0.565	**0.680**	0.659	0.445	0.519	**0.588**
2011s	0.495	**0.526**	0.512	0.470	0.505	**0.536**
2011t	0.447	**0.553**	0.544	0.389	0.448	**0.496**
2012a	0.708	0.764	**0.795**	0.581	0.670	**0.729**
2012b	0.741	0.794	**0.822**	0.631	0.702	**0.763**
2012c	0.816	0.812	**0.839**	0.677	0.710	**0.773**
2012d	0.743	0.744	**0.770**	0.623	0.648	**0.712**
2012e	0.776	0.760	**0.793**	0.618	0.617	**0.691**
2012f	0.717	0.718	**0.751**	0.491	0.431	**0.523**
2012g	0.733	0.715	**0.727**	0.583	0.597	**0.656**
2012h	0.755	0.759	**0.784**	0.635	0.629	**0.702**
2012i	0.579	0.680	**0.697**	0.533	0.608	**0.648**
2012j	0.653	0.680	**0.694**	0.596	0.601	**0.646**

Table 7.1.7. Concordance correlation of monthly proportions of unweighted and weighted (by latitude of larval release) model settlements and puerulus data for period 1994/95-2006/07 as well as extended period 1994/95-2010/11. Weighting by latitudinal hatching was based on 1-degree bands of latitude, with an average for all years (Average), and also individually for each season (Individual). Maximum correlation of each category is highlighted in grey. No weighting category showed an increase from the correlation with raw settlements. The weighting category displaying the highest correlation for each model run is indicated in bold.

Model	1994-2006			1994-2010		
	Raw	Average	Individual	Raw	Average	Individual
2011g	0.901	0.855	**0.855**	0.900	0.856	**0.857**
2011h	0.654	**0.625**	0.622	0.638	**0.613**	0.608
2011i	0.572	**0.555**	0.554	0.569	**0.545**	0.543
2011j	0.699	0.666	**0.667**	0.690	0.658	**0.661**
2011k	0.884	0.837	**0.838**	0.889	0.851	**0.852**
2011l	0.601	**0.577**	0.576	0.586	**0.566**	0.563
2011m	0.837	**0.791**	0.790	0.836	**0.787**	0.786
2011n	0.627	**0.607**	0.606	0.617	**0.595**	0.592
2011o	0.836	**0.770**	0.769	0.826	0.775	**0.777**
2011p	0.622	**0.613**	0.609	0.607	**0.590**	0.587
2011q	0.634	0.583	**0.584**	0.618	**0.580**	0.579
2011r	0.536	**0.525**	0.524	0.518	**0.509**	0.507
2011s	0.591	**0.582**	0.581	0.572	**0.566**	0.563
2011t	0.622	0.593	**0.593**	0.579	0.554	**0.558**
2012a	0.251	0.172	**0.174**	0.217	0.145	**0.147**
2012b	0.294	0.201	**0.204**	0.264	0.175	**0.178**
2012c	0.257	0.211	**0.214**	0.225	0.197	**0.198**
2012d	0.349	0.317	**0.321**	0.299	0.266	**0.270**
2012e	0.380	0.336	**0.341**	0.352	0.297	**0.303**
2012f	0.511	0.452	**0.455**	0.491	0.438	**0.441**
2012g	0.506	0.491	**0.497**	0.498	0.482	**0.487**
2012h	0.557	0.496	**0.502**	0.544	0.488	**0.491**
2012i	0.781	0.748	**0.749**	0.754	0.716	**0.718**
2012j	0.774	0.739	**0.741**	0.740	0.698	**0.702**

Table 7.1.8. Linear correlation of unweighted and weighted (by mortality) model settlements and puerulus data for period 1994/95-2006/07 as well as extended period 1994/95-2010/11. Weighting by mortality involved pelagic larval duration (PLD), duration in Category A (Category A) or daily mortality with temperature loading (Daily Temp). Maximum correlation of each category is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined. The weighting category displaying the highest correlation for each model run is indicated in bold.

Model	1994-2006				1994-2010			
	Raw	Cat A	PLD	Daily Temp	Raw	Cat A	PLD	Daily Temp
2011g	0.440	0.490	**0.508**	0.488	0.355	0.303	0.370	**0.419**
2011h	0.452	**0.528**	0.519	0.482	0.443	**0.462**	0.447	0.459
2011i	0.572	0.536	**0.634**	0.589	0.448	0.338	0.453	**0.472**
2011j	0.553	0.520	**0.588**	0.587	0.369	0.227	0.367	**0.441**
2011k	0.467	0.493	0.505	**0.517**	0.388	0.300	0.407	**0.465**
2011l	0.430	**0.515**	0.520	0.439	0.437	0.445	**0.468**	0.442
2011m	0.476	0.504	**0.507**	0.504	0.454	0.391	0.454	**0.504**
2011n	0.584	0.518	**0.627**	0.606	0.416	0.200	0.436	**0.480**
2011o	0.513	0.536	0.541	**0.556**	0.278	0.206	0.297	**0.362**
2011p	0.576	0.558	**0.635**	0.595	0.483	0.357	0.515	**0.533**
2011q	0.620	0.599	**0.706**	0.671	0.486	0.379	0.546	**0.561**
2011r	0.565	0.539	**0.645**	0.594	0.445	0.302	0.448	**0.489**
2011s	0.495	0.503	**0.535**	0.466	0.470	0.414	0.448	**0.466**
2011t	0.447	0.492	**0.524**	0.435	0.389	0.374	**0.402**	0.388
2012a	0.708	**0.779**	0.740	0.723	0.581	**0.610**	0.601	0.592
2012b	0.741	**0.815**	0.785	0.761	0.631	0.642	**0.660**	0.654
2012c	0.816	**0.843**	0.841	0.840	0.677	0.632	0.687	**0.689**
2012d	0.743	0.711	**0.752**	0.740	0.623	0.545	0.602	**0.609**
2012e	0.776	0.790	**0.821**	0.767	0.618	0.342	0.559	**0.622**
2012f	0.717	0.726	**0.793**	0.693	0.491	0.218	0.357	**0.507**
2012g	0.733	0.704	**0.765**	0.701	0.583	0.218	0.520	**0.590**
2012h	0.755	0.699	**0.779**	0.737	0.635	0.344	0.576	**0.647**
2012i	0.579	0.587	**0.653**	0.589	0.533	**0.519**	0.495	0.504
2012j	0.653	0.548	**0.684**	0.643	0.596	0.475	0.533	**0.564**

Table 7.1.9. Concordance correlation of monthly proportions of unweighted and weighted (by mortality) model settlements and puerulus data for period 1994/95-2006/07 as well as extended period 1994/95-2010/11. Weighting by mortality involved pelagic larval duration (PLD), duration in Category A (Category A) or daily mortality with temperature loading (Daily Temp). Maximum correlation of each category is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined. The weighting category displaying the highest correlation for each model run is indicated in bold.

Model	1994-2006				1994-2010			
	Raw	Cat A	PLD	Daily Temp	Raw	Cat A	PLD	Daily Temp
2011g	0.901	**<u>0.923</u>**	0.606	0.806	0.900	**<u>0.915</u>**	0.594	0.803
2011h	0.654	**0.632**	0.500	0.599	0.638	**0.622**	0.467	0.574
2011i	0.572	**<u>0.606</u>**	0.479	0.530	0.569	**<u>0.598</u>**	0.447	0.518
2011j	0.699	**<u>0.748</u>**	0.513	0.621	0.690	**<u>0.737</u>**	0.502	0.611
2011k	0.884	**<u>0.893</u>**	0.582	0.783	0.889	**<u>0.901</u>**	0.576	0.786
2011l	0.601	**0.592**	0.476	0.556	0.586	**0.582**	0.447	0.534
2011m	0.837	**<u>0.839</u>**	0.546	0.739	0.836	**<u>0.836</u>**	0.527	0.728
2011n	0.627	**<u>0.692</u>**	0.459	0.557	0.617	**<u>0.688</u>**	0.450	0.545
2011o	0.836	**<u>0.847</u>**	0.536	0.728	0.826	**<u>0.826</u>**	0.518	0.716
2011p	0.622	**<u>0.670</u>**	0.489	0.563	0.607	**<u>0.663</u>**	0.475	0.545
2011q	0.634	**<u>0.652</u>**	0.461	0.565	0.618	**<u>0.637</u>**	0.443	0.547
2011r	0.536	**<u>0.569</u>**	0.445	0.496	0.518	**<u>0.561</u>**	0.415	0.472
2011s	0.591	**<u>0.599</u>**	0.476	0.547	0.572	**<u>0.583</u>**	0.447	0.523
2011t	0.622	**0.617**	0.427	0.568	0.579	**0.561**	0.385	0.529
2012a	0.251	**<u>0.288</u>**	0.153	0.179	0.217	**<u>0.253</u>**	0.118	0.145
2012b	0.294	**<u>0.344</u>**	0.184	0.214	0.264	**<u>0.314</u>**	0.148	0.181
2012c	0.257	**<u>0.333</u>**	0.185	0.193	0.225	**<u>0.302</u>**	0.149	0.157
2012d	0.349	**<u>0.441</u>**	0.241	0.262	0.299	**<u>0.392</u>**	0.190	0.213
2012e	0.380	**<u>0.467</u>**	0.261	0.328	0.352	**<u>0.434</u>**	0.227	0.296
2012f	0.511	**0.498**	0.398	0.477	0.491	**<u>0.504</u>**	0.369	0.456
2012g	0.506	**<u>0.535</u>**	0.408	0.471	0.498	**<u>0.569</u>**	0.391	0.456
2012h	0.557	**<u>0.643</u>**	0.379	0.477	0.544	**<u>0.635</u>**	0.352	0.456
2012i	0.781	**<u>0.802</u>**	0.445	0.651	0.754	**<u>0.788</u>**	0.356	0.600
2012j	0.774	**<u>0.814</u>**	0.459	0.640	0.740	**<u>0.797</u>**	0.388	0.590

Table 7.1.10. Linear correlation of unweighted and weighted model settlements and puerulus data for period 1994/95-2006/07. Weighting involved a combination of weights based on timing of release, latitude of release and mortality. The combination of weighting categories used to obtain the maximum correlation with annual settlement are indicated. Maximum correlation achieved for raw and weighted settlements over all models is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined.

Model	Correlation with Raw	Maximum Correlation	Timing of release	Latitude of release	Mortality
2011g	0.440	0.564	Early(Monthly)	Individual	Category A
2011h	0.452	0.482	Early(Monthly)	Individual	Daily Temp
2011i	0.572	0.640	Early(Daily)	Individual	PLD
2011j	0.553	0.568	Early(Daily)	Individual	PLD
2011k	0.467	0.560	Early(Monthly)	Individual	Daily Temp
2011l	0.430	0.509	Early(Daily)	Individual	PLD
2011m	0.476	0.541	Early(Monthly)	Individual	Daily Temp
2011n	0.584	0.500	Early(Daily)	Individual	PLD
2011o	0.513	0.672	Early(Monthly)	Individual	Category A
2011p	0.576	0.644	Early(Monthly)	Average	PLD
2011q	0.620	0.738	Early(Monthly)	Individual	Category A
2011r	0.565	0.651	Early(Monthly)	Average	PLD
2011s	0.495	0.493	Early(Daily)	Average	PLD
2011t	0.447	0.614	N-Early, S-Late	Average	PLD
2012a	0.708	0.852	Early(Monthly)	Individual	Category A
2012b	0.741	0.887	N-Early, S-Average	Individual	Category A
2012c	0.816	0.821	Early(Monthly)	Average	Daily Temp
2012d	0.743	0.733	Early(Monthly)	Average	PLD
2012e	0.776	0.756	Early(Monthly)	Average	PLD
2012f	0.717	0.674	Early(Monthly)	Individual	Daily Temp
2012g	0.733	0.539	Early(Monthly)	Individual	Daily Temp
2012h	0.755	0.709	Early(Monthly)	Average	PLD
2012i	0.579	0.627	N-Early, S-Late	Individual	Daily Temp
2012j	0.653	0.615	Early(Monthly)	Average	PLD

Table 7.1.11. Concordance correlation of monthly proportions of unweighted and weighted model settlements and puerulus data for period 1994/95-2006/07. Weighting involved a combination of weights based on timing of release, latitude of release and mortality. The combination of weighting categories used to obtain the maximum concordance correlation are indicated. Maximum correlation achieved for raw and weighted settlements over all models is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined.

Model	Correlation with Raw	Maximum Correlation	Timing of release	Latitude of release	Mortality
2011g	0.901	0.897	Late(Daily)	Average	Category A
2011h	0.654	0.637	Late(Monthly)	Average	Daily Temp
2011i	0.572	<u>0.684</u>	Late(Monthly)	Average	Category A
2011j	0.699	<u>0.775</u>	Late(Daily)	Average	Category A
2011k	0.884	<u>0.894</u>	Late(Daily)	Individual	Category A
2011l	0.601	<u>0.607</u>	Late(Monthly)	Average	Category A
2011m	0.837	<u>0.851</u>	Late(Monthly)	Average	Category A
2011n	0.627	<u>0.716</u>	Late(Daily)	Individual	Category A
2011o	0.836	<u>0.899</u>	Late(Monthly)	Individual	Category A
2011p	0.622	<u>0.692</u>	Late(Daily)	Average	Category A
2011q	0.634	<u>0.736</u>	Late(Monthly)	Average	Category A
2011r	0.536	<u>0.566</u>	Late(Monthly)	Average	Category A
2011s	0.591	<u>0.593</u>	Individual(Daily)	Average	Category A
2011t	0.622	<u>0.655</u>	Late(Monthly)	Average	Category A
2012a	0.251	<u>0.455</u>	Late(Monthly)	Individual	Category A
2012b	0.294	<u>0.508</u>	Late(Daily)	Individual	Category A
2012c	0.257	<u>0.482</u>	Late(Daily)	Average	Category A
2012d	0.349	<u>0.544</u>	Late(Daily)	Average	Category A
2012e	0.380	<u>0.577</u>	Late(Monthly)	Average	Category A
2012f	0.511	<u>0.607</u>	Late(Daily)	Individual	Daily Temp
2012g	0.506	<u>0.622</u>	Late(Monthly)	Average	Daily Temp
2012h	0.557	<u>0.706</u>	Late(Monthly)	Average	Category A
2012i	0.781	<u>0.829</u>	Late(Monthly)	Average	Category A
2012j	0.774	<u>0.817</u>	N-early, S-Late	Average	Category A

Table 7.1.12. Linear correlation of unweighted and weighted model settlements and puerulus data for 1994/95-2010/11. Weighting involved a combination of weights based on timing of release, latitude of release and mortality. The combination of weighting categories used to obtain the maximum annual puerulus correlation are indicated. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined. The monthly concordance correlation and mean latitude difference for the weighting is also shown.

Model	Correlation with Raw	Weighted Correlation	Timing of release	Latitude of release	Mortality	Month Conc. Cor	Mean Diff Lat
2011g	0.355	0.466	Early(M)	Individual	PLD	0.558	-0.049
2011h	0.443	0.500	Early(M)	Individual	Daily Temp	0.559	-0.276
2011i	0.448	0.525	Early(M)	Individual	Daily Temp	0.502	-0.171
2011j	0.369	0.456	Early(D)	Individual	Daily Temp	0.578	0.065
2011k	0.388	0.557	Early(M)	Individual	Daily Temp	0.725	-0.024
2011l	0.437	0.512	Early(D)	Individual	PLD	0.457	-0.294
2011m	0.454	0.572	Early(D)	Individual	Daily Temp	0.680	-0.065
2011n	0.416	0.423	Early(M)	Individual	Daily Temp	0.542	0.053
2011o	0.278	0.427	Early(D)	Individual	Daily Temp	0.668	0.122
2011p	0.483	0.588	Early(D)	Individual	PLD	0.476	-0.078
2011q	0.486	0.621	Early(D)	Individual	PLD	0.448	-0.114
2011r	0.445	0.541	Early(M)	Individual	Daily Temp	0.478	-0.033
2011s	0.470	0.489	Early(M)	Individual	Daily Temp	0.526	-0.201
2011t	0.389	0.515	NeSl	Individual	PLD	0.431	-0.091
2012a	0.581	0.751	NeSa	Individual	PLD	0.202	-0.462
2012b	0.631	0.801	Early(M)	Individual	Daily Temp	0.220	-0.371
2012c	0.677	0.750	Early(M)	Individual	Daily Temp	0.200	-0.358
2012d	0.623	0.680	Early(M)	Individual	Daily Temp	0.252	-0.388
2012e	0.618	0.636	Early(M)	Individual	Daily Temp	0.369	-0.088
2012f	0.491	0.389	Early(M)	Individual	Daily Temp	0.427	0.189
2012g	0.583	0.420	Early(M)	Individual	Daily Temp	0.532	0.115
2012h	0.635	0.595	Early(M)	Individual	Daily Temp	0.507	-0.045
2012i	0.533	0.587	Early(M)	Individual	Daily Temp	0.667	-0.138
2012j	0.596	0.557	Early(M)	Individual	Daily Temp	0.631	-0.122

Table 7.1.13. Concordance correlation of monthly proportions of unweighted and weighted model settlements and puerulus data for extended period 1994/95-2010/11. Weighting involved a combination of weights based on timing of release, latitude of release and mortality. The combination of weighting categories used to obtain the maximum concordance correlation is indicated. Maximum correlation of each category is highlighted in grey. Correlations for weighted settlements which showed an increase from the correlation with raw settlements are underlined.

Model	Correlation with Raw	Maximum Correlation	Timing of release	Latitude of release	Mortality
2011g	0.900	0.894	Late(Daily)	Individual	Category A
2011h	0.638	0.644	Late(Monthly)	Average	Category A
2011i	0.569	0.677	Late(Monthly)	Individual	Category A
2011j	0.690	0.782	Late(Daily)	Individual	Category A
2011k	0.889	0.898	Late(Daily)	Individual	Category A
2011l	0.586	0.631	Late(Monthly)	Average	Category A
2011m	0.836	0.857	Late(Monthly)	Average	Category A
2011n	0.617	0.727	Late(Daily)	Average	Category A
2011o	0.826	0.887	Late(Monthly)	Individual	Category A
2011p	0.607	0.699	Late(Daily)	Average	Category A
2011q	0.618	0.742	Late(Monthly)	Individual	Category A
2011r	0.518	0.566	Late(Monthly)	Average	Category A
2011s	0.572	0.609	Late(Daily)	Average	Category A
2011t	0.579	0.627	Late(Monthly)	Individual	Category A
2012a	0.217	0.431	Late(Monthly)	Individual	Category A
2012b	0.264	0.496	Late(Daily)	Individual	Category A
2012c	0.225	0.480	Late(Daily)	Average	Category A
2012d	0.299	0.533	Late(Daily)	Average	Category A
2012e	0.352	0.585	Late(Monthly)	Average	Category A
2012f	0.491	0.583	Late(Monthly)	Individual	Category A
2012g	0.498	0.728	Late(Monthly)	Average	Category A
2012h	0.544	0.693	Late(Monthly)	Average	Category A
2012i	0.754	0.838	Late(Monthly)	Average	Category A
2012j	0.740	0.838	Individual(Monthly)	Average	Category A

Table 7.1.14. Optimised weightings of correlations with annual settlement and concordance correlation of monthly proportions for daily survival parameter and 3 parameters associated with time of hatching (see Figure 7.1.4) for years up to and including 2006/07

Model	Maximise Annual Settlement Correlation					Maximise Average Monthly Correlation				
	Daily Surv	Mean Early	SD	Diff.	Corr.	Daily Mort	Mean Early	SD	Diff.	Corr.
2011g	0.988	-5.000	23.455	45.000	0.657	0.999	70.000	40.924	65.000	0.952
2011h	0.956	-5.000	21.308	45.000	0.696	0.999	70.000	22.990	45.000	0.801
2011i	0.992	-5.000	20.000	45.000	0.743	0.999	70.000	20.000	54.286	0.784
2011j	0.985	-5.000	20.181	45.000	0.709	0.999	70.000	20.000	52.313	0.864
2011k	0.990	-5.000	20.763	45.000	0.689	0.999	70.000	40.219	65.000	0.952
2011l	0.963	-5.000	21.196	45.000	0.688	0.999	70.000	22.795	45.000	0.770
2011m	0.987	-5.000	21.967	45.000	0.707	0.999	70.000	31.396	53.367	0.921
2011n	0.994	-5.000	20.000	45.000	0.627	0.999	70.000	20.000	50.244	0.827
2011o	0.999	-5.000	24.110	45.000	0.746	0.999	70.000	32.061	56.046	0.920
2011p	0.983	-5.000	20.017	45.000	0.740	0.999	70.000	20.740	52.902	0.808
2011q	0.974	-5.000	22.873	45.000	0.845	0.999	70.000	20.000	45.000	0.831
2011r	0.996	-5.000	20.000	45.000	0.736	0.999	70.000	20.000	45.000	0.707
2011s	0.950	-5.000	20.000	65.000	0.640	0.999	70.000	23.282	51.194	0.760
2011t	0.950	31.699	20.000	50.661	0.671	0.999	70.000	20.000	45.000	0.758
2012a	0.970	13.719	20.000	45.000	0.871	0.999	70.000	20.000	45.000	0.569
2012b	0.979	9.130	20.147	45.000	0.891	0.999	70.000	20.000	45.000	0.633
2012c	0.996	2.628	22.038	49.028	0.859	0.999	70.000	20.000	51.128	0.613
2012d	0.986	-3.261	50.000	47.267	0.788	0.999	70.000	20.000	50.248	0.659
2012e	0.978	-5.000	20.000	49.108	0.841	0.999	70.000	20.000	45.000	0.716
2012f	0.988	-5.000	23.375	45.000	0.783	0.999	70.000	20.000	45.000	0.752
2012g	0.993	-5.000	20.000	50.137	0.713	0.999	70.000	20.000	46.686	0.829
2012h	0.981	-5.000	20.000	65.000	0.815	0.999	70.000	20.000	52.915	0.815
2012i	0.960	-5.000	29.097	45.000	0.790	0.999	70.000	34.008	51.094	0.894
2012j	0.958	-5.000	50.000	64.986	0.719	0.999	70.000	31.175	52.317	0.903

Table 7.1.15. Optimised weightings of correlations with annual settlement and concordance correlation of monthly proportions for daily survival parameter and 3 parameters associated with time of hatching (see Figure 7.1.4) for years up to and including 2010/11

Model	Maximise Annual Correlation					Maximise Average Monthly Correlation				
	Daily Mort	Mean Early	SD	Diff.	Corr.	Daily Mort	Mean Early	SD	Diff.	Corr.
2011g	0.993	-5.000	20.000	45.000	0.603	0.999	70.000	43.257	65.000	0.953
2011h	0.993	-5.000	20.000	45.000	0.639	0.999	70.000	31.949	50.768	0.807
2011i	0.999	-5.000	20.000	45.000	0.684	0.999	70.000	24.720	59.502	0.775
2011j	0.999	-5.000	20.000	45.000	0.587	0.999	70.000	27.784	56.600	0.873
2011k	0.994	-5.000	20.000	45.000	0.678	0.999	70.000	40.037	61.720	0.949
2011l	0.982	-5.000	20.000	45.000	0.652	0.999	70.000	29.245	48.990	0.775
2011m	0.994	-5.000	20.704	45.000	0.707	0.999	70.000	34.443	55.217	0.926
2011n	0.999	-5.000	20.000	45.000	0.585	0.999	70.000	24.684	53.718	0.834
2011o	0.993	-5.000	20.000	45.000	0.583	0.999	70.000	33.696	54.237	0.930
2011p	0.993	-5.000	20.000	45.000	0.717	0.999	70.000	27.630	55.938	0.817
2011q	0.984	-5.000	20.000	45.000	0.765	0.999	70.000	21.651	46.424	0.843
2011r	0.999	-5.000	20.000	45.000	0.701	0.999	70.000	23.091	45.000	0.726
2011s	0.999	-5.000	20.000	45.000	0.585	0.999	70.000	30.069	55.058	0.768
2011t	0.987	-5.000	20.000	45.000	0.531	0.999	70.000	26.916	47.057	0.786
2012a	0.972	-5.000	20.000	45.000	0.784	0.999	70.000	20.000	45.000	0.627
2012b	0.984	-5.000	20.000	45.000	0.801	0.999	70.000	20.000	45.000	0.670
2012c	0.993	-5.000	20.000	45.000	0.817	0.999	70.000	20.000	50.045	0.646
2012d	0.992	-5.000	20.000	45.000	0.729	0.999	70.000	20.000	51.027	0.704
2012e	0.999	-5.000	20.000	45.000	0.730	0.999	70.000	20.880	45.000	0.739
2012f	0.999	-5.000	20.000	45.000	0.517	0.999	70.000	20.000	45.000	0.789
2012g	0.999	-5.000	20.000	65.000	0.646	0.999	70.000	30.025	55.322	0.783
2012h	0.999	-5.000	20.000	45.000	0.741	0.999	70.000	23.878	51.759	0.823
2012i	0.999	-5.000	20.000	65.000	0.596	0.999	70.000	39.938	54.352	0.894
2012j	0.999	-5.000	20.000	65.000	0.606	0.999	70.000	37.828	56.494	0.899

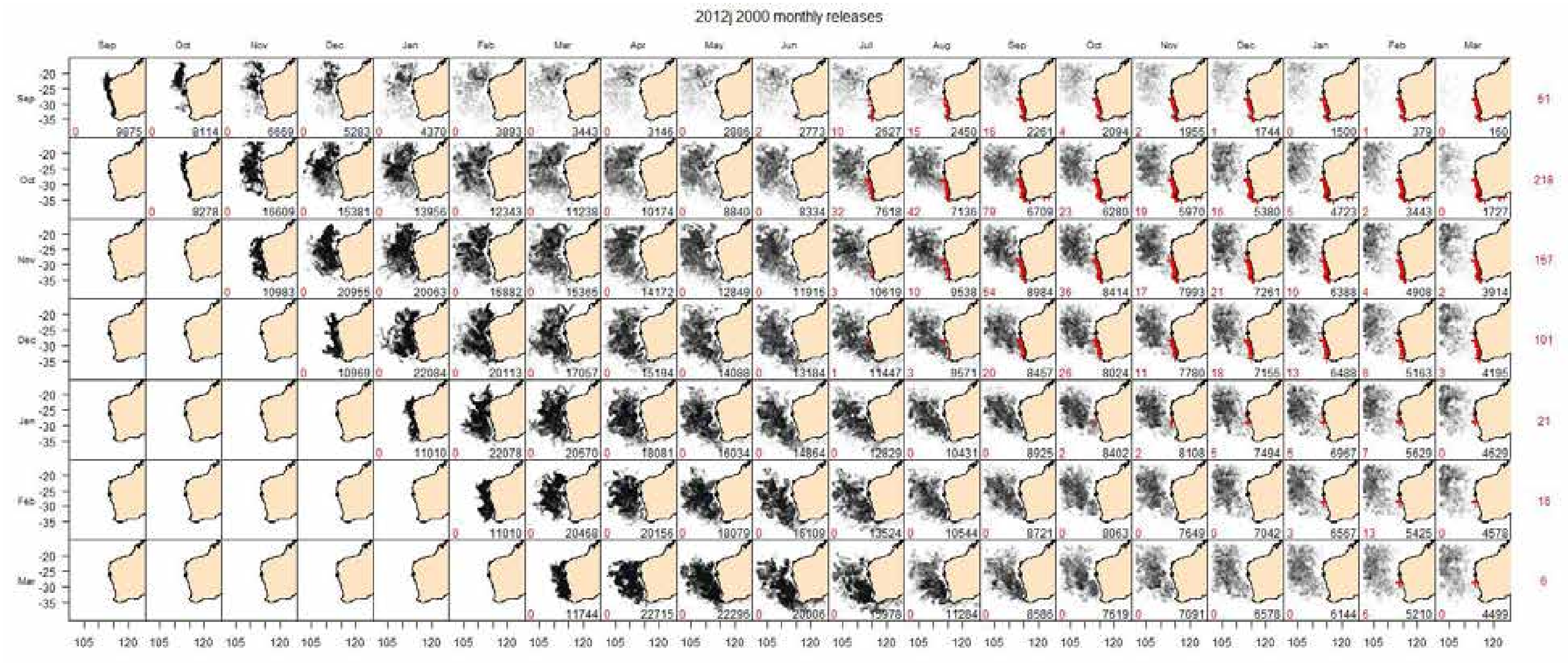


Figure 7.1.8. Spatial distribution of the phyllosoma larvae released each month (September to March) from the 2012j model run for the 2000/01 season. Each row represents the larvae associated with that month of release, from the earliest month of release (September 1999) to the end of the settlement season (March 2001). Each column is a snapshot of the distribution of larvae on the 15th day of that month. The black number in the lower right hand corner indicates the number of larvae present on that day whilst the red number in the lower left hand corner indicates the number of puerulus settling in the past month. The red number in the right hand margin of each row indicates the total number of puerulus settling from those particles released in that month.

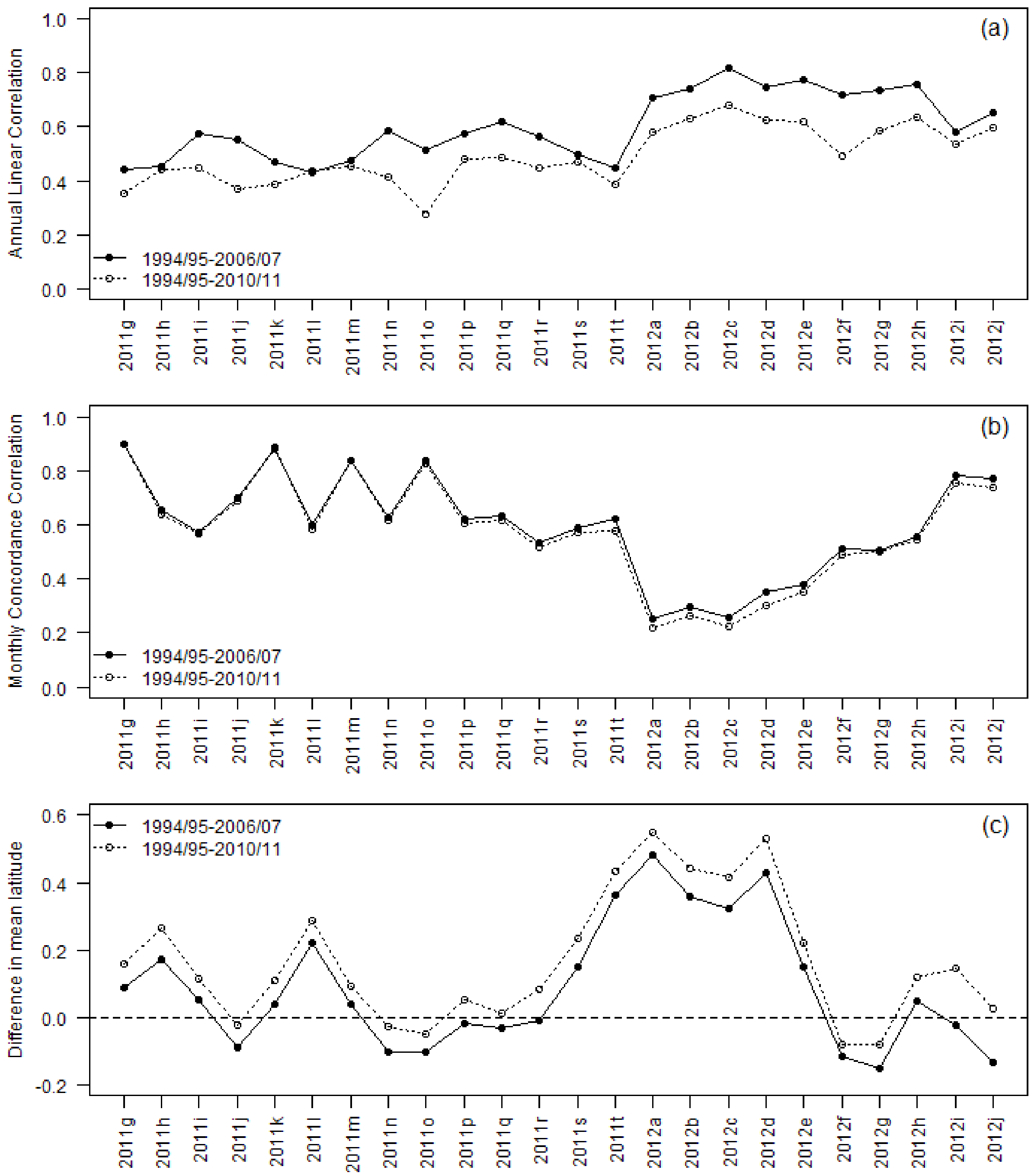


Figure 7.1.9. (a) Linear correlation of annual numbers of unweighted model settlements and coast-wide puerulus index, (b) concordance correlation of averaged observed and modelled monthly proportions, and (c) difference in mean latitude of observed and modelled settlement for period 1994/95-2006/07 and for period 1994/95-2010/11 for 24 model runs. Only successful settlements between 27-34°S are considered.

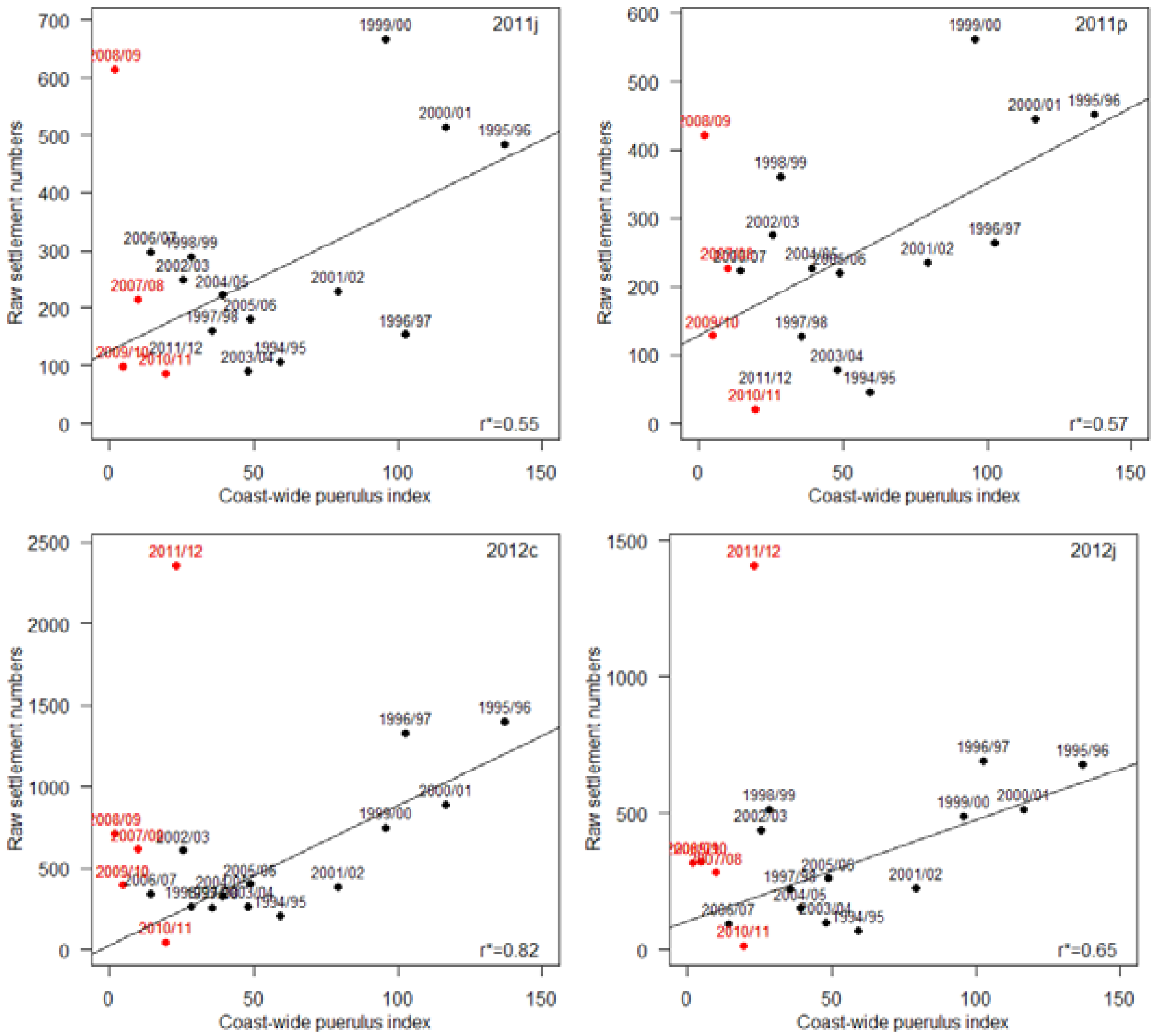


Figure 7.1.10. Unweighted annual settlement numbers from model versus coast-wide puerulus index for settlement seasons in model 2011j (top left), 2011p (top right), 2012c (bottom left) and 2012j (bottom right). Linear regression model fitted for seasons up to and including 2006/07, and settlement seasons after 2006/07 indicated in red. Linear correlation of modelled and observed data up to and including season 2006/07 is shown in bottom right hand corner.

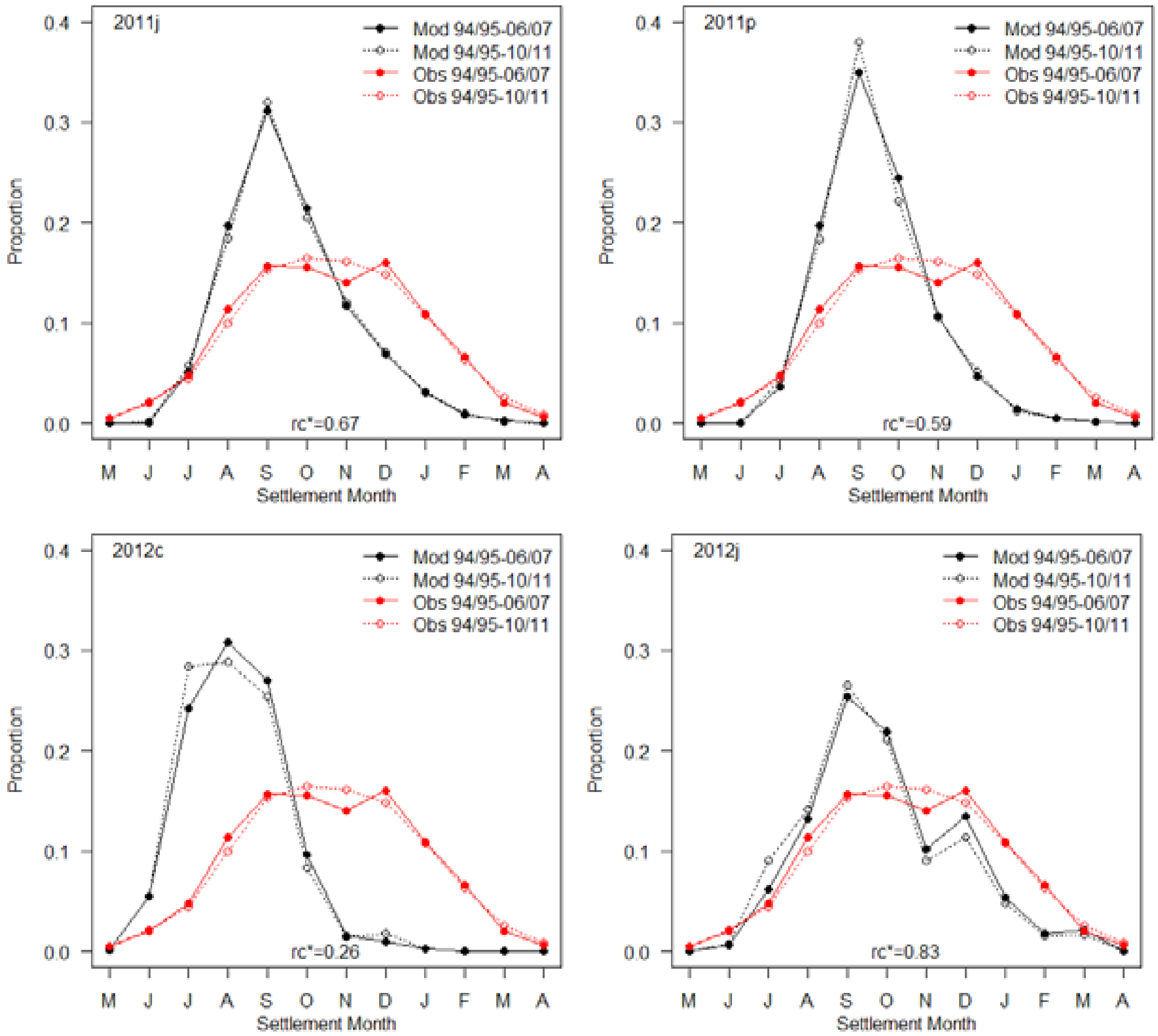


Figure 7.1.11. Unweighted monthly modelled settlement proportions and monthly coast-wide puerulus index proportions by settlement month averaged over the settlement seasons 1994/95-2006/07 and 1994/95-2010/11 for model 2011j (top left), 2011p (top right), 2012c (bottom left) and 2012j (bottom right). Concordance correlation of modelled and observed data up to and including season 2006/07 is shown above horizontal axis.

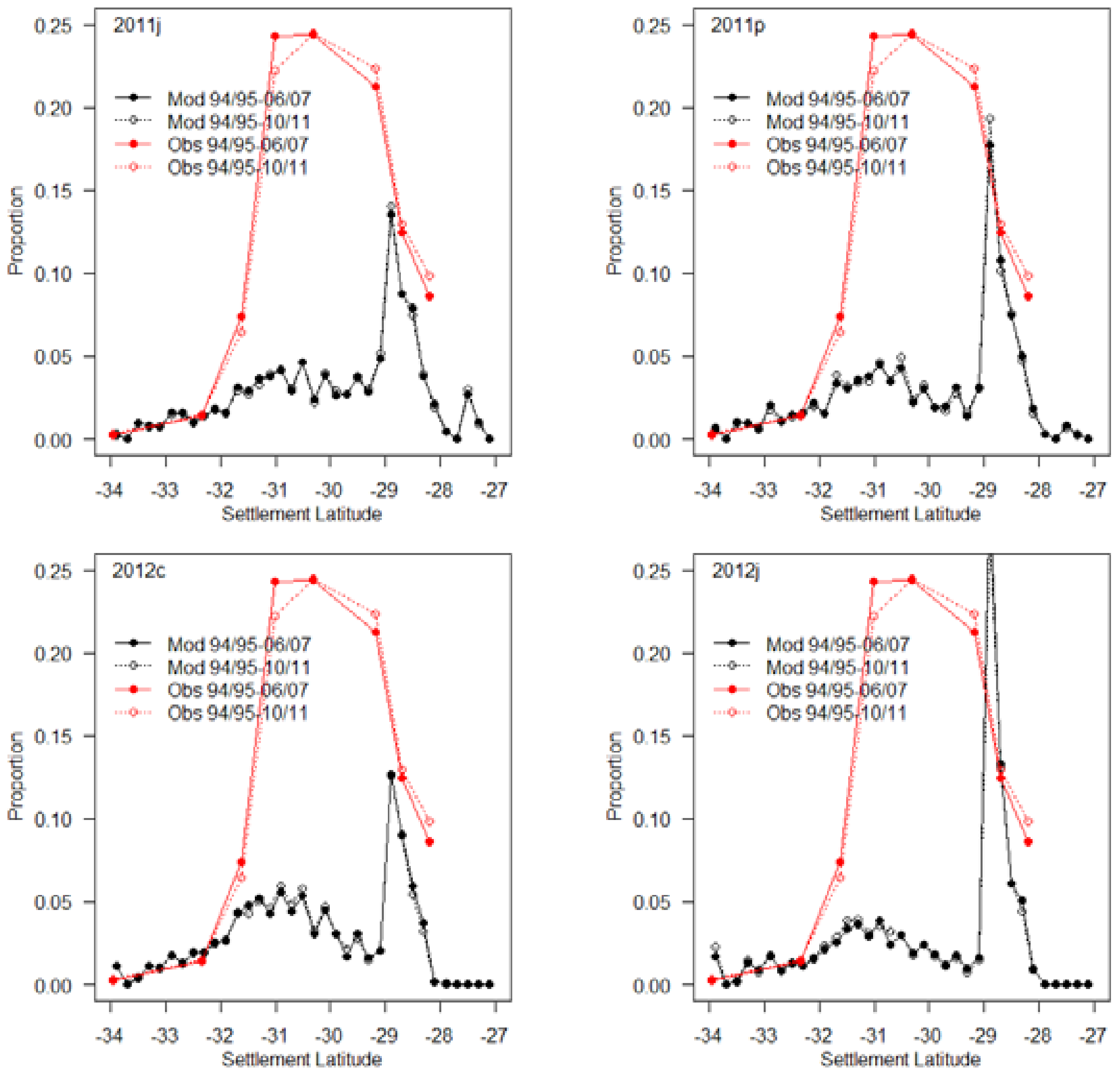


Figure 7.1.12. Distribution of unweighted modelled settlement proportions by 0.2° settlement latitude and annual puerulus indices by proportion for 8 locations across fishery by latitude averaged over the settlement seasons 1994/95-2006/07 and 1994/95-2010/11 for model 2011j (top left), 2011p (top right), 2012c (bottom left) and 2012j (bottom right).

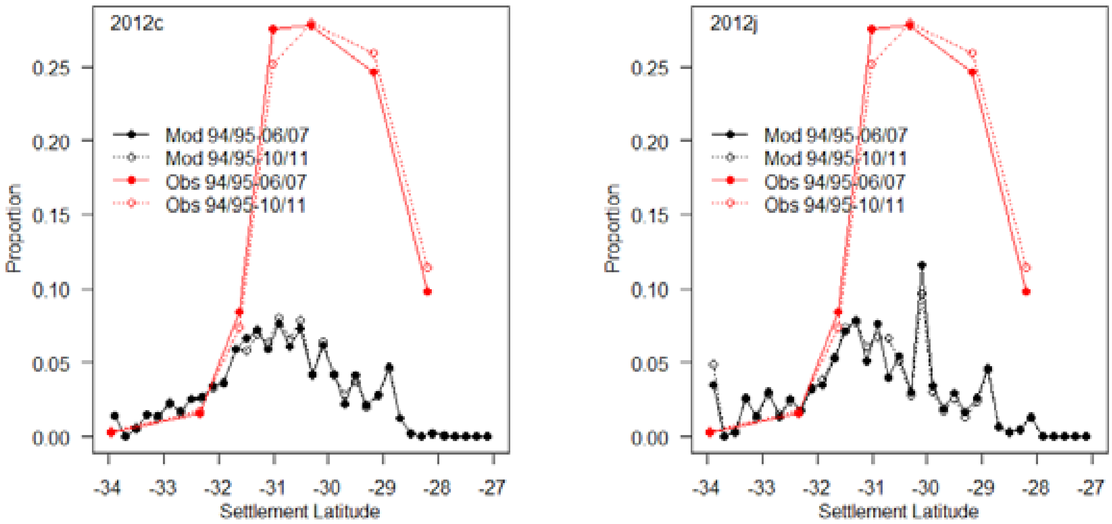


Figure 7.1.13. Same as figure above but removing settlement numbers for Abrolhos Island.

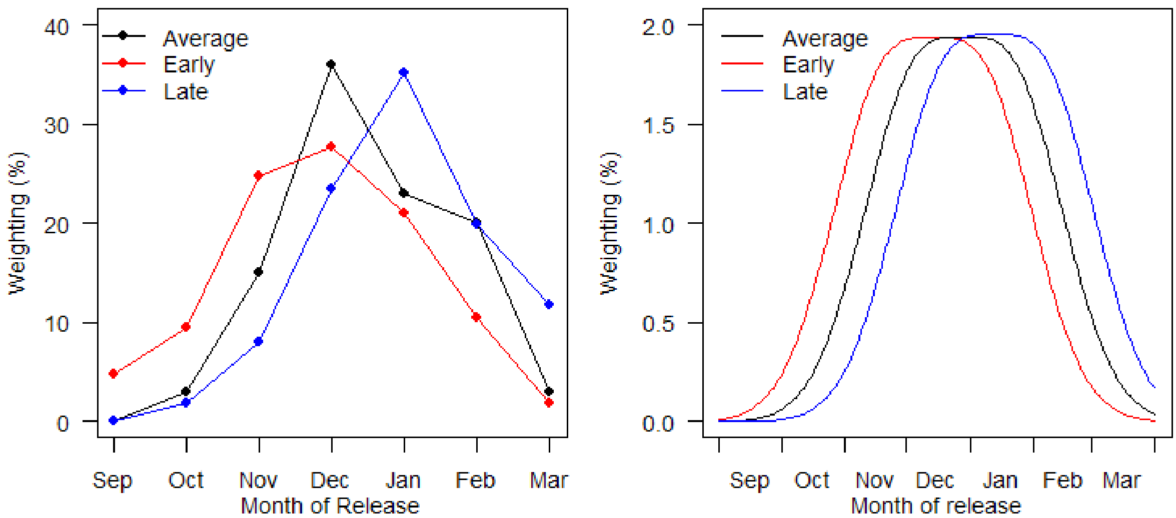


Figure 7.1.14. Monthly hatching weightings for average, early and late releases (left) and daily hatching weighting (right) based on combination of 2 Normal distributions (right).

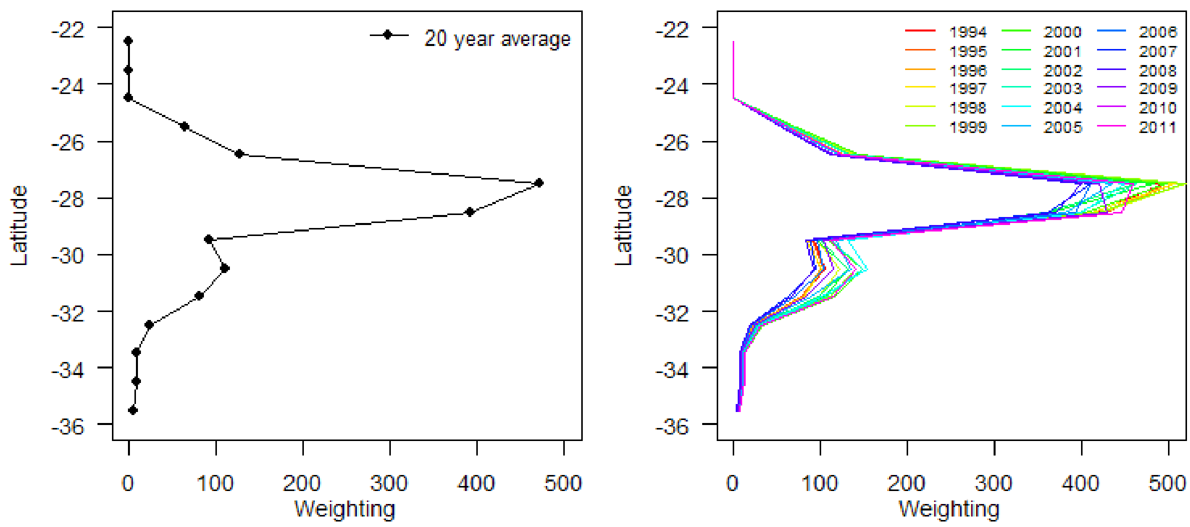


Figure 7.1.15. Latitudinal hatching weightings from stock assessment model for 20-year average (left) and individual years (right).

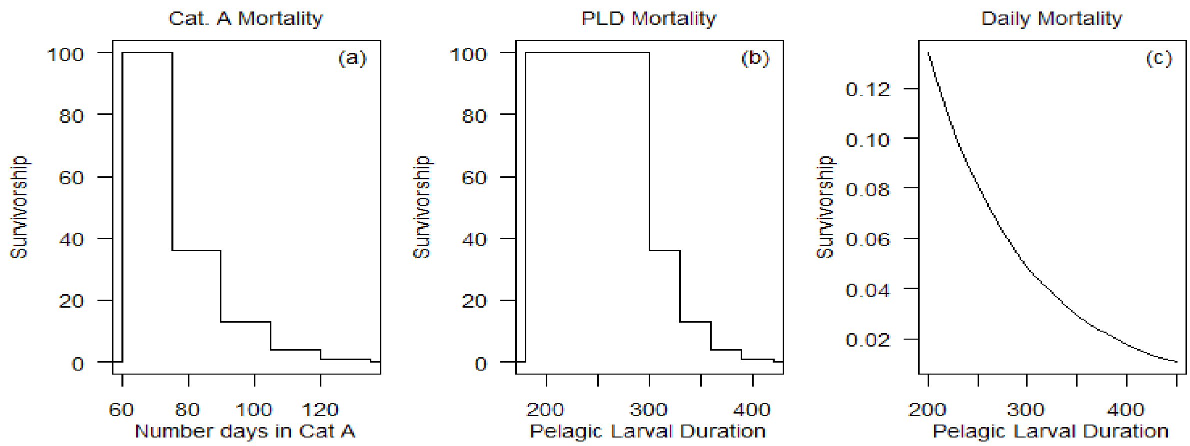


Figure 7.1.16. Mortality (survivorship) weightings for (a) larval category A, (b) pelagic larval duration, and (c) daily survivorship rate.

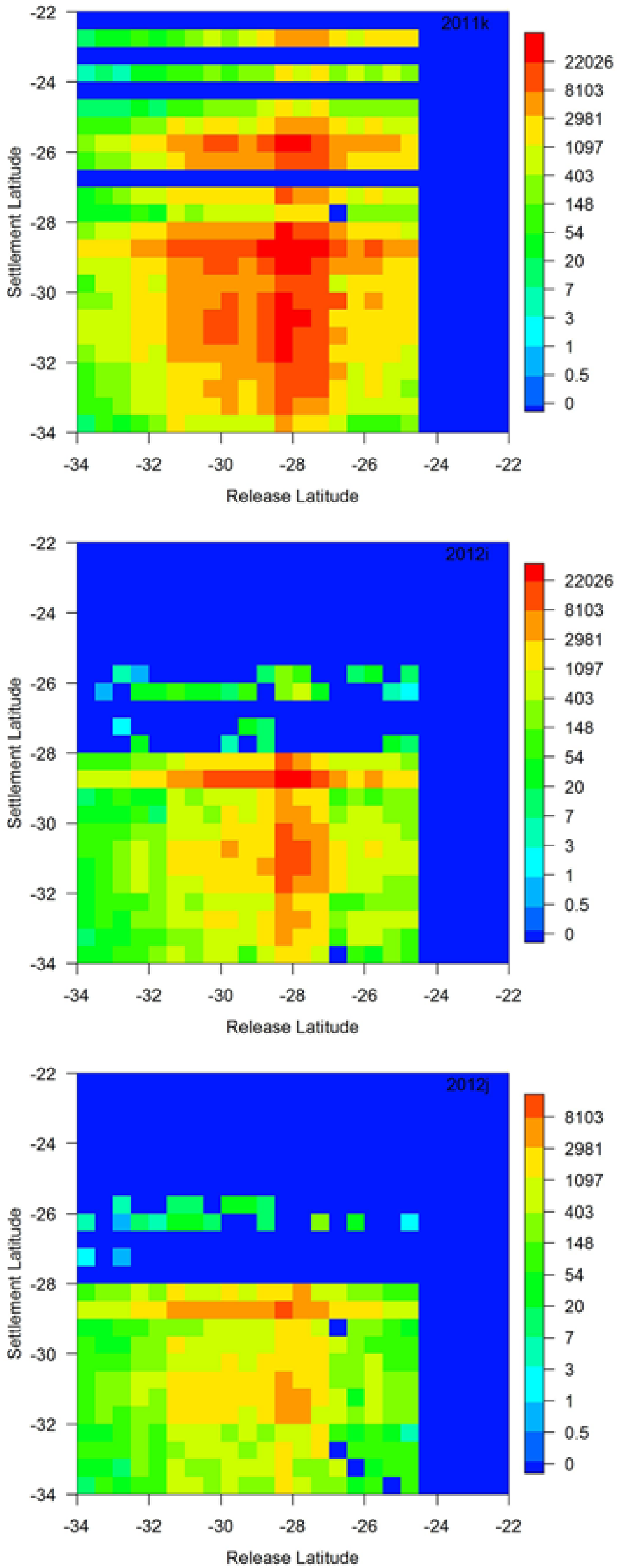


Figure 7.1.17. Source-sink relationships for 3 weighted model runs 2011k (top), 2012i (middle) and 2012j (bottom).

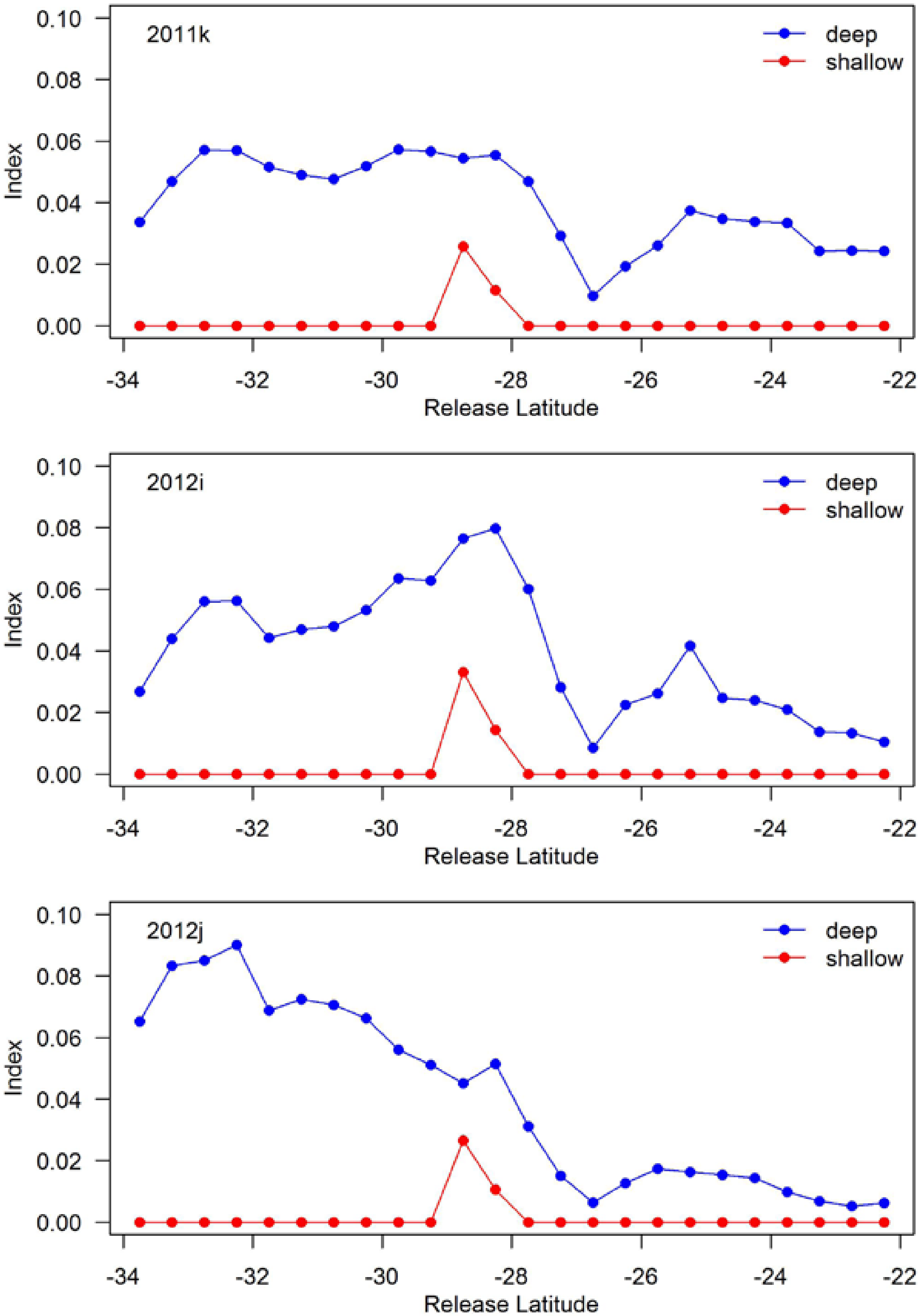


Figure 7.1.18. Relative mean success of larvae released at different latitudes for all years analysed for 3 model runs (unweighted) 2011k (top), 2012i (middle) and 2012j (bottom).

7.2 Drifter buoys

The drifters were released along the mid- and outer continental shelf between Cliff Head and Lancelin in late December 2010 (Table 6.2.1), and clearly showed the high variability in the current system (Figure 7.2.1a to e), with drifters released in close proximity often travelling in different directions.

Drifters #0680 and #4120

Released at the shelf break off Cliff Head on 21st December 2010 (Figure 7.2.1a), drifter #0680 moved slowly southwards for a few days then drifted offshore into the Leeuwin Current which carried it rapidly southwards along the shelf break to Cape Naturaliste by mid-January. At this stage, it moved westwards out of the Leeuwin Current and headed north-westwards where it became trapped for over 3 months in a complex eddy system west of the Abrolhos Islands, before finally escaping northwards and westwards into the central Indian Ocean. (It eventually ran aground at Knysna on the east coast of South Africa 22 months later; Pearce and Jackson, in prep.).

Drifter #4120 was released on the same day as #0680 but nearer the coast (Figure 7.2.1b). It was carried steadily northwards along the inner shelf in the Capes Current except for a minor reversal off Kalbarri, eventually running aground at the northern tip of Dirk Hartog Island on 17th January 2011.

Drifters #5170 and #3670

These drifters were released in close proximity on the outer shelf off Leeman on 21st December (Figures 7.2.1c and d). They moved briefly southward along the shelf before reversing and heading northward to Shark Bay, with #5170 inshore of (and moving faster than) #3670, with a week-long reversal early in January that matched the flow reversal of #4120. Off Shark Bay, both drifters moved westward off the shelf where their paths diverged.

#5170 was caught up into a complex system of mesoscale eddies up to 300 km from the coast between Shark Bay and North West Cape. It drifted back onto the shelf at the end of July, finally running aground on the coast near Shark Bay in early August 2011, having been trapped in the eddy system for about 8 months -- effectively replicating the oceanic migration of rock lobster larvae and their subsequent return to the coast. By contrast, #3670 was carried southwards in the Leeuwin Current, becoming trapped in a very large anticlockwise eddy system south of Shark Bay for almost 6 months. It finally moved north-westward into the central Indian Ocean in October.

Drifter #8120

The southern-most drifter, #8120, was released on the outer shelf off Lancelin on 23rd December. It was immediately entrained into the Leeuwin Current, then circulated briefly in an anticlockwise eddy before heading westward into the central Indian Ocean.

Summary

The drifters (together with other drifting buoys released off Western Australia by the fin-fish program) have improved our understanding of the variability of the current system both along and across the continental shelf, with obvious implications for the transport of pelagic larvae. While some drifters remained on the shelf for periods of days to weeks, most eventually moved offshore into the Leeuwin Current and were either carried southwards or were trapped in eddy systems, recirculating repeatedly before either escaping to the northwest into the central Indian Ocean or (in one case) returning to the continental shelf. The movement of the drifters, which were released in the hatching depth zones for rock lobster larvae along the coast, has confirmed that the surface water movement during the hatching period will generally assist the movement off the shelf by category A larvae. Noting that the phyllosoma larvae also undertake diurnal movements that are likely to magnify this offshore transport, the drifter data suggests that most phyllosoma are likely to exit the continental shelf waters soon after hatching. These results correspond to the data from the field studies by Rimmer (1980), which suggested a rapid offshore movement of early stage phyllosoma.

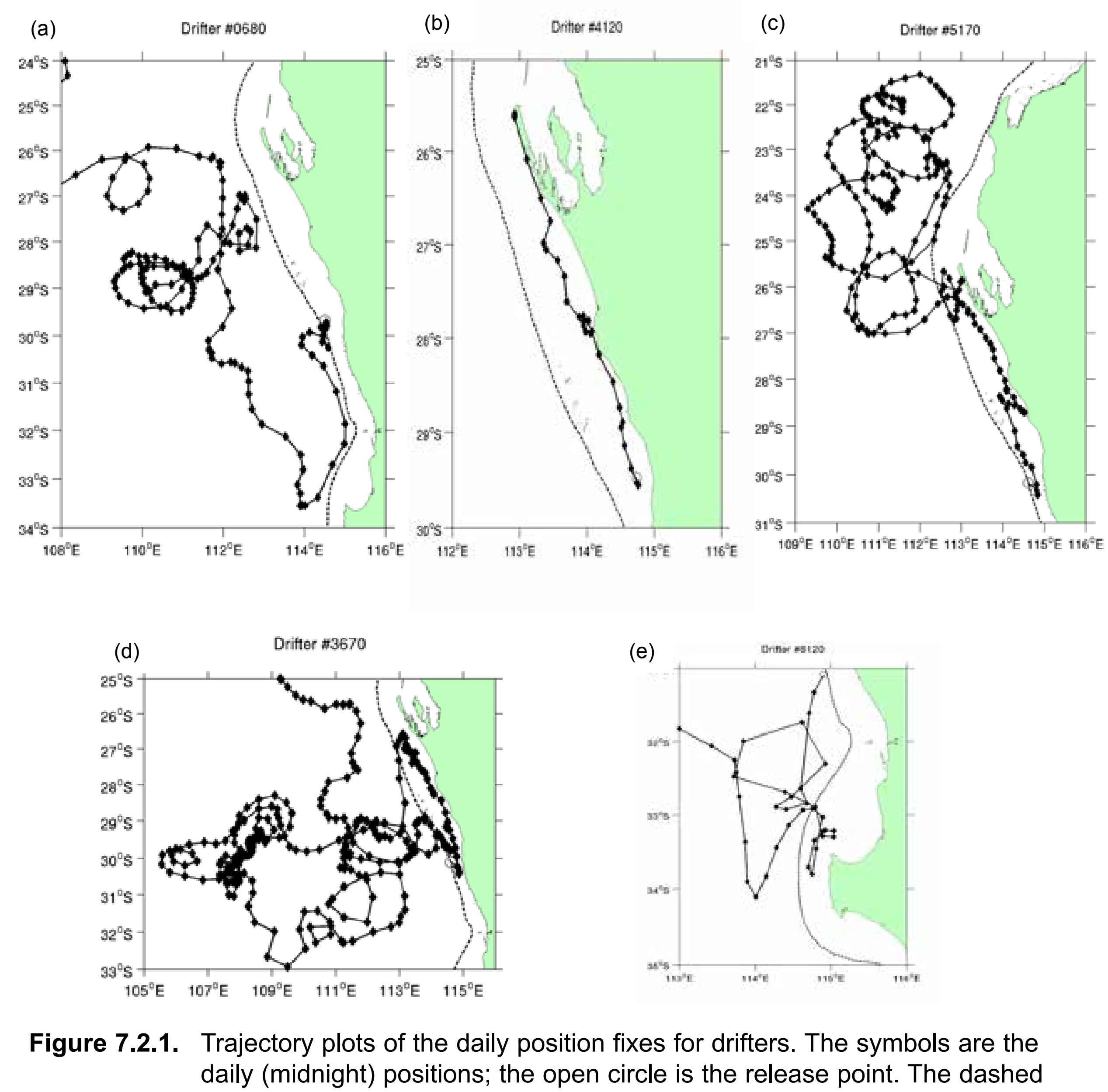


Figure 7.2.1. Trajectory plots of the daily position fixes for drifters. The symbols are the daily (midnight) positions; the open circle is the release point. The dashed line represents the 200 m contour, the nominal edge of the continental shelf. (a) Drifter #0680 released off Cliff Head on 21st December 2010. (b) Drifter #4120 released off Cliff Head on 21st December 2010. (c) Drifter #5170 released off Leeman on 21st December 2010. (d) Drifter #3670 released off Leeman on 21st December 2010. (e) Drifter #8120 released off Lancelin on 23rd December 2010.

7.3 IOD/ENSO effect on SST and wind

An assessment of the effects of ENSO events, Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) on the environment (sea surface temperatures and winds) off WA has been examined by Weller *et al.* (2012). This paper showed that off the WA coast, interannual variations of wind regime during the austral winter and spring are significantly correlated with the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) variability (Figure 7.3.1). ENSO events mostly affect the sea surface temperature variations off the Western Australia coast. Atmospheric General Circulation Model experiments forced by an idealised IOD sea surface temperature anomaly field suggest that the IOD generated deep atmospheric convection anomalies trigger a Rossby wave train in the upper troposphere that propagates into the southern extratropics and induces positive geopotential height anomalies over southern Australia. The positive geopotential height anomalies from the upper troposphere to the surface, south of the Australian continent, and their associated blocking result in easterly wind anomalies off the Western Australia coast and a reduction of the high frequency synoptic storm events that deliver the majority of southwest Australia rainfall during austral winter and spring. In the marine environment, the wind anomalies and reduction of storm events may hamper the movement of western rock lobster larvae and affect the puerulus recruitment process.

The annular modes are hemispheric scale patterns of climate variability. SAM explains more of the week-to-week, month-to-month, and year-to-year variance in the extratropical atmospheric flow than any other climate phenomenon (Marshall 2003). The annular modes owe their existence to internal atmospheric dynamics in the middle latitudes. In the wind field, the annular modes describe north-south vacillations in the extratropical zonal wind with centres of action located ~55-60 and ~30-35 degrees latitude. To first order, the time series of the annular modes are consistent with a normally distributed red-noise process with an e-folding timescale of ~10 days.

SAM has exhibited trends towards their high index polarities over the past few decades. The trend in the SAM is largest in the SH summer season. Observations and model results suggest the trend in the SAM is at least partially driven by Antarctic ozone depletion. Climate models forced with increasing greenhouse gases consistently simulate a trend towards the high index polarity of the SAM.

In fact, there is also an upward trend towards high index in SAM during the austral winter since late 1990s (Figure 7.3.2). This trend has induced much weakened westerly winds in the 30-35°S latitude band in 2008 and 2010, which were two years with low puerulus settlement.

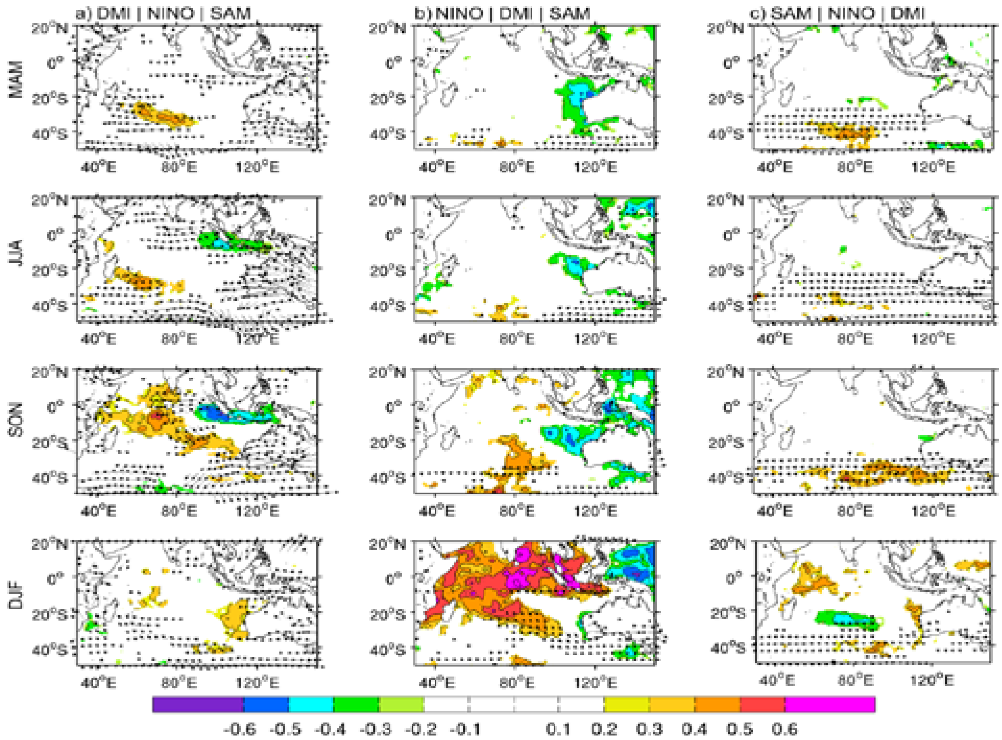


Figure 7.3.1. (a) Lag/lead partial correlation of SST (shading) on the dipole mode index (DMI, September-November) and partial regression of surface wind stress on DMI (September-November), independent of Niño-3.4 and Southern Annular Mode (SAM). Areas where the explained variance is significant (90%) are shaded and magnitudes of wind correlations smaller than 5 x 10-3 N m-2 per index unit are not plotted. (b) Same as (a), but for Niño-3.4 (November-January) independent of DMI and SAM. (c) Same as (a), but for SAM (concurrent) independent of Niño-3.4 and IOD.

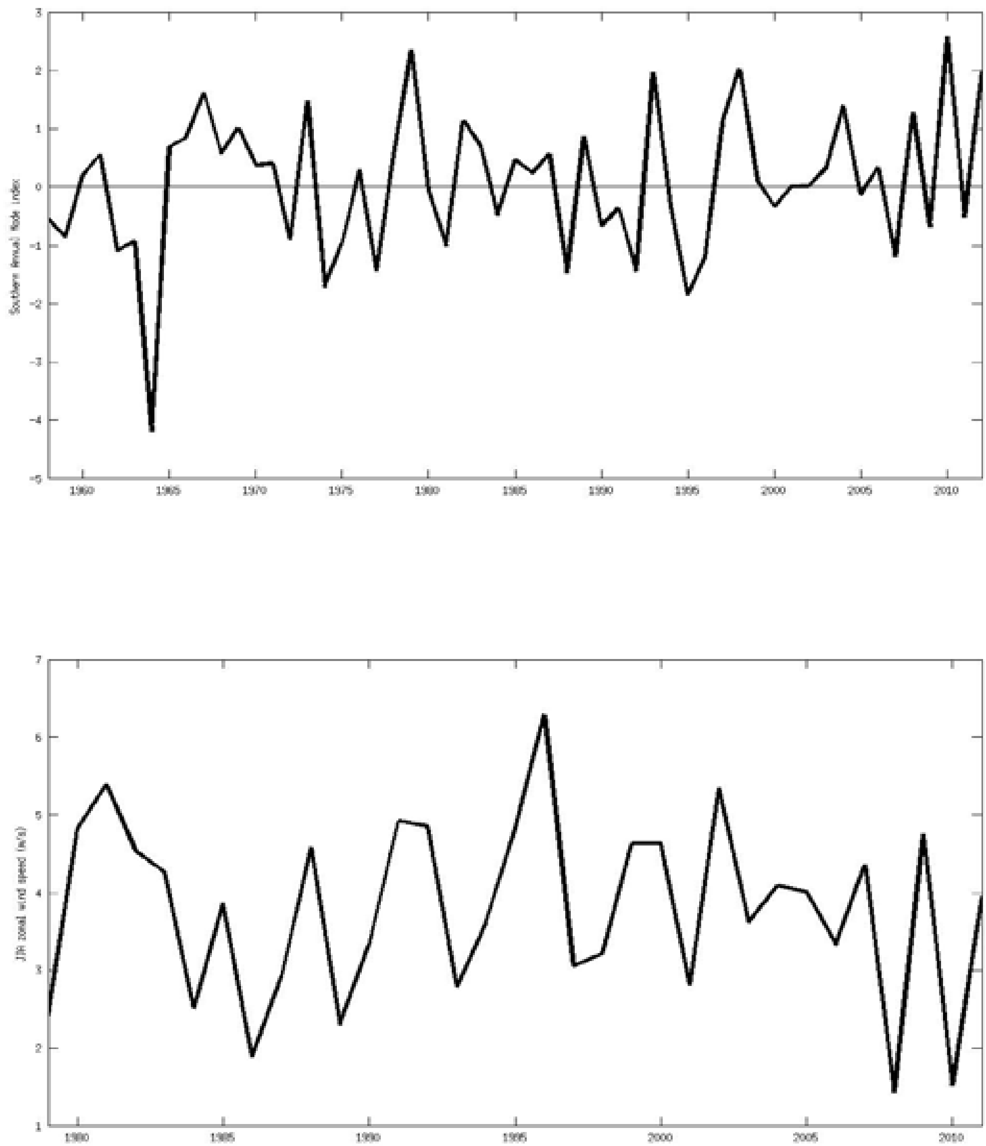


Figure 7.3.2. (upper panel) SAM index averaged in June-July-August, and (lower panel) average zonal wind speed in June-July-August in the area 35-30°S, 100-115°E off southwest Australia.

7.4 Environmental effects on puerulus settlement

This section examines the relationship between a number of environmental variables and puerulus settlement. Some key environmental variables identified in this section and 7.5 and 7.6 are examined in combination with spawning stock in Section 7.7 to assess the stock-recruitment-environment relationship. Any climate change implications associated with the key environmental variable are examined in Section 7.8.

Puerulus settlement

The puerulus settlement time series highlights the significant decline in abundance from 2005/06 to 2008/09 with an improved settlement since then but still below average (Figure 3.2). The settlement in the most southern sites, south of Alkimos show a longer time series of low settlement since about 2002/03 while the more northern sites generally showed a peak in 2004/05 and/or 2005/06 before declining in 2006/07.

The monthly distribution of puerulus settlement for the period before and after the recent period of low settlement in 2006/07 indicates that settlement during the early part of the normal peak period, August to October, was more affected by the downturn (Figure 7.4.1). The peak in Dongara has moved back two months to November, while the peak in Lancelin that generally occurred over August to December has moved to January. The peak settlement at the Abrolhos has historically occurred a couple of months after the peak settlement at the coastal locations in December and this has been maintained in recent years.

The relationship between the timing of peak settlement and the level of settlement showed that in years of good settlement the peak settlement occurred at about mid-late October while in years of poor settlement the peak was about one month later towards the end of November (Figure 7.4.2).

Sea surface temperatures

Historically sea surface temperatures (SST) during the early larval phase (February to April) have been a good indicator of strength of puerulus settlement that occurs later in the year, peaking over August to December (Figure 7.4.3) (Caputi *et al*. 2001). The low puerulus settlement in 2006/07, which was the first of the six consecutive low settlement years, was associated with cooler water temperatures and was therefore expected. However during the subsequent three years there was an increase in water temperatures but continued low settlement. This culminated with the strong Leeuwin Current in 2008 and very high water temperatures but the lowest settlement on record for 2008/09. The low settlement in 2010/11 was again well related with cooler water temperature of that year, however the settlement in 2011/12 was well below that expected with the very strong Leeuwin Current and record warm water temperatures during that year (Figure 7.4.3). The settlement to date for the 2012/13 season (December 2012) indicates another low settlement season occurring despite above average temperatures.

The correlation between monthly SST in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement up to 2006/07 showed that SST during February and March-April for the two southern locations, Jurien and Alkimos, was strongly correlated with settlement (Figure 7.4.4).

The analysis of monthly SST by the three settlement monthly periods (early, peak and late) indicated that the SST mostly affected the settlement in the early period, Aug-Sept, with a reduced effect on the settlement after this period (Figure 7.4.5). In years of good settlement the peak month of settlement usually occurs earlier compared to the peak month in years of average or below-average settlement (Figure 7.4.2). The above result thus illustrates that the variation in the early settlement is more sensitive to the SST earlier in the year. Therefore a warm SST results in a good puerulus settlement, particularly in the early months of August-September.

When the above analyses between SST and settlement were conducted for data including settlement data after 2006/07 there were no significant correlations observed due to the influence of anomalous data as illustrated by the relationship in Figure 7.4.3. This highlights that variations in the SST during the larval phase do not explain the cause of the recent poor settlement.

Wind strength and direction

NCEP wind stress was correlated with the log-transformed annual puerulus index by considering the meridional (North-South) and zonal (East-West) component vectors. A number of patches of significant negative and positive correlations were identified with the North-South (Figure 7.4.6) and East-West (Figure 7.4.7) components when considering the puerulus indices of seasons up to and including 2006/07. The zonal analysis showed some negative relationships for some locations in November and March which indicates that there may be some positive effect on puerulus settlement associated with offshore movement of the early larval stages. However these were not consistent across puerulus collector locations. Also, the location of these patches of correlation did not persist when the recent years of low puerulus settlement were included in the analysis. The meridional and zonal wind stress components were also considered together in a multiple linear regression model but did not show any consistency in behaviour across puerulus collector locations (Figure 7.4.8).

Wave height

The linear correlation between significant wave height and log-transformed puerulus for settlement seasons 1997/98 to 2006/07 indicated some isolated patches of significant positive and negative correlation but the locations of the patches were not consistent across the puerulus collector locations. When the recent seasons 2007/08 to 2009/10 corresponding to lower puerulus settlement were included in the analysis, a common patch of negative correlation was noticed offshore in the January preceding settlement for the coast-wide annual puerulus index (Figure 7.4.9) as well as the various puerulus collector locations (Figure 7.4.10). The wave height at some offshore locations south of 30°S in March was also identified as having a negative correlation with settlement. This identified that an increase in wave height in this offshore area in January was associated with poorer puerulus settlement.

Water movement

The zonal and meridional components of the BRAN ocean surface current were compared with the log-transformed annual puerulus index (1993/94 to 2007/08) on a monthly basis. This analysis revealed only individual grid locations with significant correlation, but no areas of significant correlation were observed.

The zonal and meridional components of the water movement vector combining the ocean current, the surface water movement and the surface current correction to replicate the actual forces of movement experienced by particles in the oceanographic model (Section 6.1.3) were examined with the log-transformed annual puerulus indices (1993/94 to 2007/08). These were on a finer scale grid (0.1 degree) than the previous current and wind data. The region north of 30°S during May-July could be a significant region that needs to be examined further by its components and with additional years of data (Figure 7.4.11 and 7.4.12).

Rainfall

The relationship between rainfall at five southern coastal locations (Mandurah to Lancelin) during May to October with annual puerulus settlement was not significant. However this factor is examined further in combination with other environmental variables in Section 7.7.

Indian Ocean Dipole

The Indian Ocean Dipole (IOD) appears to have a significant influence on levels of puerulus settlement, with a positive index being related to poor settlement levels. The effect of the IOD appears to be associated with the strength of the westerly winds and storm activity in winter/spring near the period that settlement is occurring.

The plots of the IOD during June to November with the annual puerulus settlement generally indicate that above average settlement occurs during years with negative IOD values, particularly during September to November (Figure 7.4.13). However not all negative IODs are associated with above average settlement.

The Indian Ocean Dipole index remained positive for four consecutive years from 2006 to 2009, for the first time (Figure 7.4.14). Moreover, 2008 was the first time in 30 years that a positive IOD index has occurred at the same time as an evolution of a La Niña event. However settlement remained relatively low in 2009/10 despite the IOD moving back to a neutral position in 2009 indicating again that other factors are involved.

Fremantle Sea Level

The Leeuwin Current flows poleward against the prevailing winds and transports warm-fresh tropical waters southward along the west coast of WA. The Current can be monitored by the sea level anomaly at Fremantle, with high sea level implying a strong current. An index of the strength of the Leeuwin Current is provided by the mean annual Fremantle sea level (Pearce and Phillips 1988).

A linear relationship was fitted to the mean annual Fremantle sea level (FSL) time series available from 1897 to 2011 which showed a long-term rate of increase of 1.62 mm/year (Figure 7.4.15) which is slightly higher than an earlier estimate obtained by Pearce and Feng (2007). The FSL anomaly highlights the strong Leeuwin Currents in 1999-2000, 2008 and 2011 with the latter having the highest anomaly in over 100 years.

Self-organising weather maps (A. Denham, P. Hope, K. Keay, N. Caputi)

Counts of each of the 35 weather patterns were provided by Pandora Hope and Kevin Keay from the Bureau of Meteorology, Melbourne for each month of the year (January-December) from 1968 to 2010. The SOM weather patterns were derived for two periods January to June July to December. The weather patterns for both periods show similarities (Figure 7.4.16), with the identification codes shown in Figure 7.4.17. Counts of each weather type were produced for the period January to June and for the period July to December, by combining the counts of the individual months in each period.

The linear correlations of the natural logarithm of the annual puerulus index with the SOM counts of each period are shown (Table 7.4.1). Scatterplots are shown of the SOM counts against the annual log puerulus index (Figure 7.4.18 and 7.4.19).

A stepwise regression procedure was used to add one SOM count variable at a time to the model based on the AIC value whilst requiring significance of the added variable at the 0.05 level (Table 7.4.2). This resulted in 6 of the SOM count variables to be added to the model. These were X00 and X10 from the January-June Period and X45, X10, X03 and X06 from the July-December period, resulting in an R-squared value of 0.6121 ($p < 0.001$). Of the six variables selected, four had correlations of magnitude greater than 0.25 with the puerulus.

The AIC, likelihood of each model and Akaike weights demonstrate that there is strong evidence for the model using all 6 factors outlined previously (Table 7.4.2). The fit of each stage of the fitted model is shown in Figure 7.4.20, with the 5 recent low years of settlement highlighted in red. The SOM weather types associated with each of these SOM categories is shown in Figure 7.4.21.

The relationship between the natural logarithm of the puerulus index and each of the variables included in the model is shown in Figure 7.4.22, and correlations indicated. All of the 6 variables show a weak negative correlation with the puerulus index. There is no obvious pattern of the SOM counts for the 5 recent years of low settlement indicated in red.

Altimeter – onshore larval flow

Examination of the altimeter data revealed a general pattern of weak onshore flow progressively increasing throughout the calendar year to maximum levels in winter, before again declining towards the end of the year (Figure 7.4.25). Over the 19 years examined (1992 – 2011), 13 years reported a maximum negative slope occurring in either June or July. The remaining six years had maximums occurring in two months either side of these peak months, with the exception of 1992, where a full year examination was not possible.

The timing of the annual maximum onshore flow always occurred prior to the timing of peak puerulus settlement. The peak of settlement occurred on average 119 days after the maximum onshore flow but varied between 32 and 207 days. No significant relationship was found to exist between the timing of onshore flow and the timing of settlement (Figure 7.4.26). There was also no relationship between the timing of onshore flow and the magnitude of puerulus settlement, with good puerulus settlement years intermixed with the more recent poor settlement years (Figure 7.4.26)

The altimeter-derived magnitude of onshore flow was examined relative to the magnitude of puerulus settlement (Figure 7.4.27). No significant relationship was found to exist between these factors. For example, the highest annual settlement that was recorded during this period (1995: 206) had a similar magnitude of onshore flow to that of 1993 which only had a settlement of 24 (Figure 7.4. 27).

The average latitude of puerulus settlement was located further towards the south in years of good puerulus settlement (Figure 7.4.28). This trend was not explained by variation in the latitude of peak onshore flow, with peak settlement occurring above and below the location of peak onshore flow in different years (Figure. 7.4.28).

Based on altimeter data there appears to be a period of high annual onshore flow that occurs just prior to the settlement season of western rock lobster puerulus. This onshore flow peaks predominantly in June and July. On average, 119 days later a peak in puerulus settlement occurs on the West Australian coast. There appears to be no relationships between the timing, magnitude and latitude of this onshore flow and the magnitude or fine scale timing of puerulus settlement. As the altimeter transect was located offshore of the continental shelf, onshore flows detected may not always represent flows across the shelf break onto the shore. The variation in the timing, location and temperature of water being moved onto the continental shelf and its association with puerulus settlement still requires further investigation, as patterns are not apparent at this broader scale.

Chlorophyll A

The linear correlation between log-transformed Chlorophyll data and log-transformed coast-wide puerulus index for settlement seasons 1998/99 to 2008/09 is shown in Fig 7.4.23. A high correlation is apparent off the mid-west coast about February and March which is the period when the Leeuwin Current strengthens and the locations where eddies usually form. Results from the indices of individual collector locations displayed similar patches of significant correlations. Additional years of recent data need to be examined to assess effect on ChlA on the recent years of low settlement.

Environmental effect on latitudinal distribution

The relationship between the strength of the south-flowing Leeuwin Current and mean latitude of puerulus settlement showed that in years of strong current the mean latitude moved south (Figure 7.4.24). Prior to the 2007/08 season (i.e. 1985/86 – 2006/07) this relationship was highly significant (R^2=0.65; P<0.001), however when post 2006/07 data was added to the long-term data series, this relationship started to break down (R^2=0.14; P=0.054). A good example of this change in the relationship was the mean latitude of settlements in 2008/09, and 2011/12 which were two years of strong Leeuwin Current that would historically have resulted in good settlement overall and the mean latitude occurring in the south; these both appear as outliers (Figure 7.4.24).

Summary

The key points from this statistical assessment are:

- The low settlement in recent years has been associated with a peak in settlement that is about two months after the historical average peak settlement month and further to the north than would have been expected based on the strength of the Leeuwin Current.
- ENSO events, which are associated with weak Leeuwin Currents and cooler water temperatures during the larval phase, have long been associated with low puerulus settlement (Figure 7.4.3).
- The correlation between monthly SST off the WA coast during the spawning and larval period with the subsequent annual puerulus settlement up to 2006/07 at 4 locations showed that SST during February and March-April for the two southern locations, Jurien and Alkimos, was strongly correlated with settlement (Figure 7.4.4).
- Examination of this correlation between monthly SST and Jurien puerulus settlement broken down into 3 periods indicated that the SST mostly affected the settlement in the early period, Aug-Sept, with a reduced effect on the settlement after this period (Figure 7.4.5).
- Weak westerly winds (associated with fewer storms and lower rainfall) in late winter/spring have also been historically associated with lower puerulus settlement.
- The environmental conditions in the first year of low settlement (2006/07) had very cold water in February-April 2006 and hence a low settlement was expected. In 2008 and 2011, above-average water temperatures (due to strong Leeuwin Currents associated with La Nina events) were associated with low settlements indicating that other factors are involved.
- The Indian Ocean Dipole (IOD) also appears to have a significant influence on levels of puerulus settlement, with a positive index, particularly September-November, being related to poor settlement levels. The effect of the IOD appears to be associated with the strength of the westerly winds and storm activity in winter/spring near the period that settlement is occurring.
- The Indian Ocean Dipole remained positive for four consecutive years from 2006 to 2009, the first time three consecutive years have been recorded. Moreover, 2008 was the first time in 30 years that a positive IOD index has occurred at the same time as a La Niña event.
- Westerly wind patterns during the 2010/11settlement season have been extremely unusual, with the westerly component being far weaker than average. This is reflected by the second lowest winter/spring rainfall on record in 2010 with 2006 having the lowest rainfall on record. It is likely that this was adverse for the 2010/11 puerulus settlement.

- Self-organising maps identified some weather patterns that may be affecting the puerulus settlement.

Table 7.4.1. Linear correlations of the natural logarithm of the annual puerulus index with the SOM counts of each period are shown. Negative correlations indicated in red and positive in green with magnitudes greater than 0.3 indicated in bold.

Jan-Jun	0_	1_	2_	3_	4_	Jul-Dec	0_	1_	2_	3_	4_
_0	**-0.43**	**-0.34**	-0.12	-0.02	0.12	_0	0.03	-0.05	0.07	0.06	0.09
_1	0.06	0.04	-0.01	-0.12	-0.24	_1	0.11	**0.30**	0.22	0.20	0.15
_2	0.02	0.04	-0.09	0.03	-0.19	_2	0.15	0.04	0.24	0.02	-0.24
_3	**0.25**	-0.01	0.24	-0.03	-0.10	_3	**-0.28**	0.03	-0.07	0.24	-0.05
_4	-0.12	-0.01	0.23	-0.10	0.12	_4	-0.24	0.09	-0.10	0.08	0.16
_5	-0.01	0.08	0.20	0.28	-0.13	_5	-0.15	-0.22	-0.02	0.08	**-0.33**
_6	-0.1	-0.05	**0.34**	0.11	-0.03	_6	-0.24	0.06	0.08	-0.01	-0.24

Table 7.4.2. A stepwise regression procedure adding one SOM count variable at a time to the model based on the AIC value whilst requiring significance of the added variable at the 0.05 level. The AIC, likelihood of each model and Akaike weights in the stepwise analysis are shown. Note that the last digit of the variable is the period. X001 means variable X00 from 1st period i.e. January-June and X452 means variable X45 from 2nd period i.e. July –December.

```
log puerulus ~ X001 + X101 + X452 + X102 + X032 + X062

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  7.97121    0.63595  12.534 2.67e-14 ***
X001        -0.12500    0.03615  -3.458 0.001482 **
X101        -0.12583    0.04007  -3.140 0.003484 **
X452        -0.15101    0.04088  -3.694 0.000771 ***
X102        -0.18619    0.05457  -3.412 0.001680 **
X032        -0.12675    0.04301  -2.947 0.005765 **
X062        -0.08967    0.03531  -2.539 0.015852 *
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6646 on 34 degrees of freedom
Multiple R-squared: 0.6121,    Adjusted R-squared: 0.5436
F-statistic: 8.942 on 6 and 34 DF,  p-value: 7.008e-06
```

```
step    model                           AIC        Lh          aic.weights
   6    X001+X101+X452+X102+X032+X062    91.17202  -37.58601   0.9173792
   5    X001+X101+X452+X102+X032         96.29167  -41.14584   0.0709301
   4    X001+X101+X452+X102             100.21118  -44.10559   0.0099936
   3    X001+X101+X452                  103.95040  -46.97520   0.0015408
   2    X001+X101                       108.98071  -50.49036   0.0001246
   1    X001                            111.72144  -52.86072   0.0000316
```

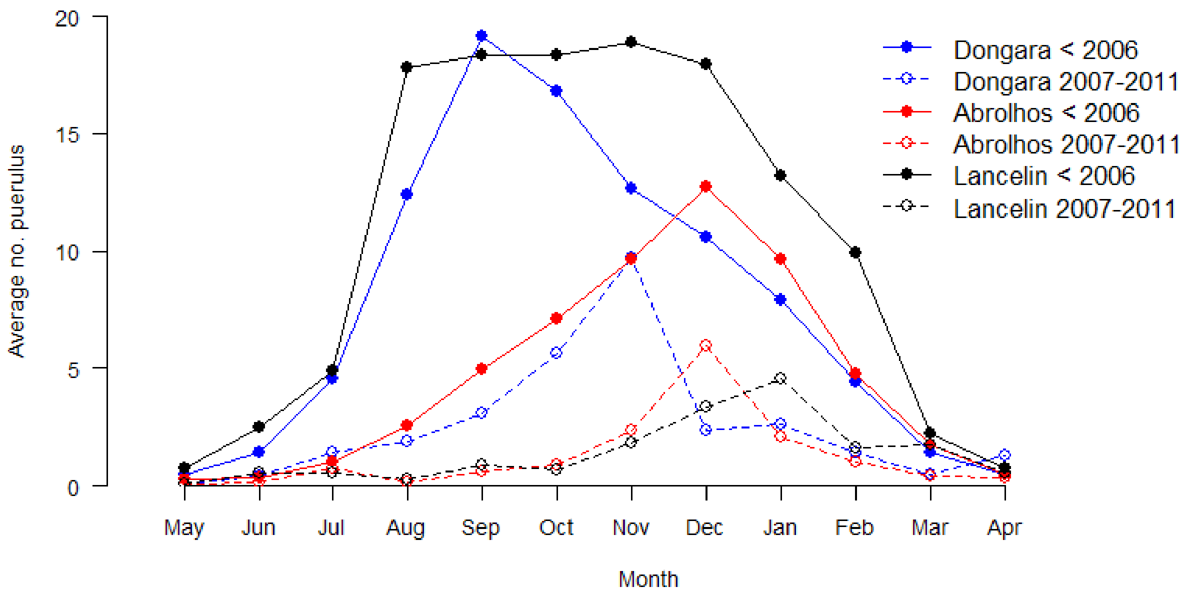


Figure 7.4.1. Average puerulus settlement by month for sites in the northern (Dongara), southern (Lancelin) and offshore (Abrolhos Islands) zones of the WRL fishery before and after 2006/07.

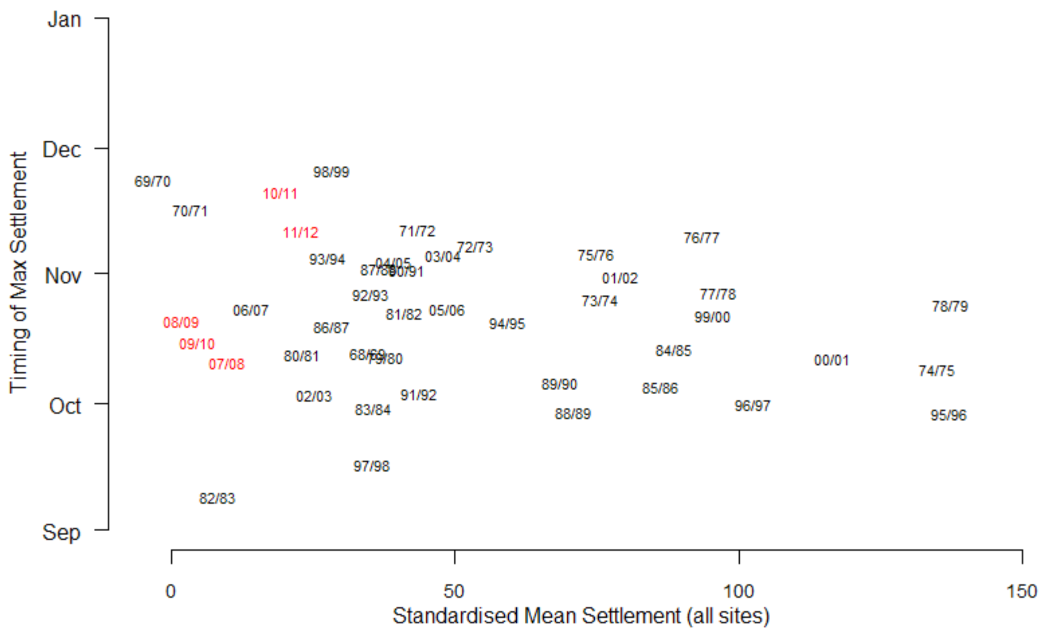


Figure 7.4.2. Relationship between timing of peak settlement (day of the settlement season) and puerulus settlement (coast-wide index). The years shown represent the puerulus settlement season from May - April, with all years after 2006/07 being highlighted in red. The months on the y-axis represent the midpoint of the month, i.e. 15th September.

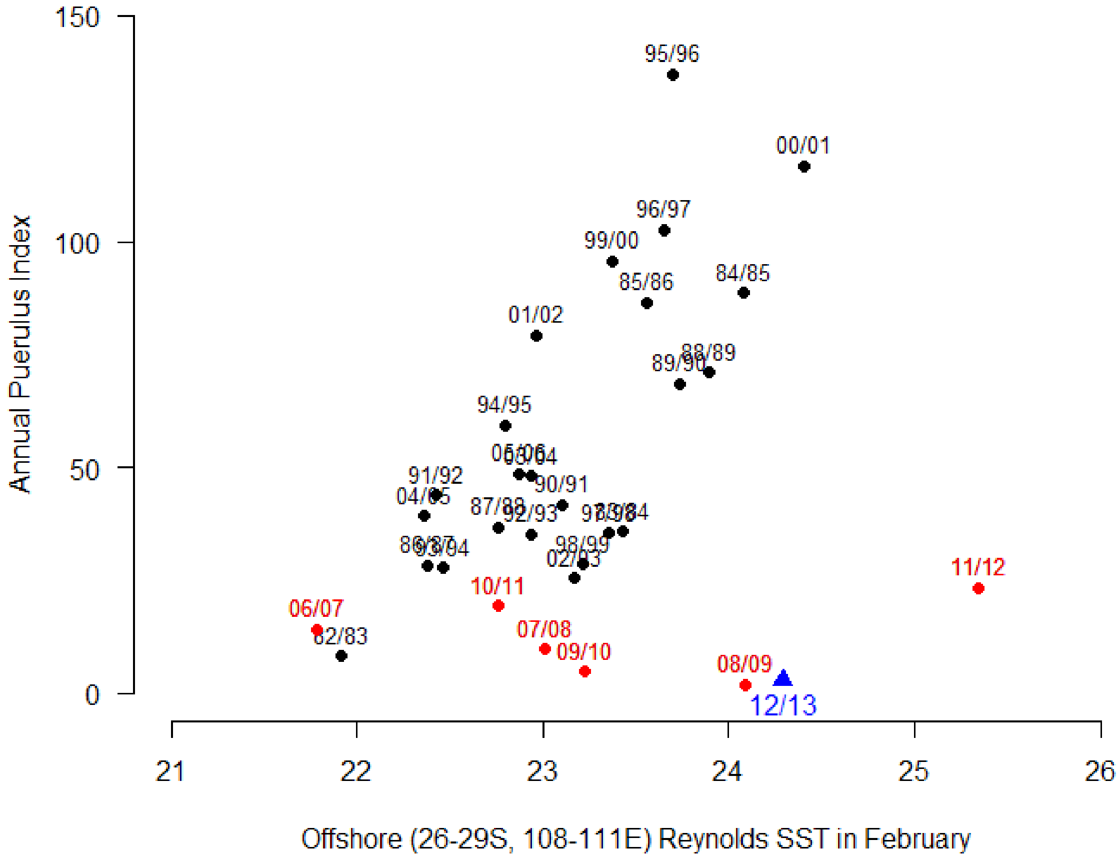


Figure 7.4.3. Relationship between the offshore SST in February with the coast wide puerulus settlement later for the season extending from May of that year to the following April. The season of the puerulus settlement is shown. Settlement seasons from 1982/83 to 2005/06 are indicated in black and the recent seasons of low settlement, 2006/07 to 2011/12, in red. The February SST in 2012 that is related to the 2012/13 settlement is shown in blue.

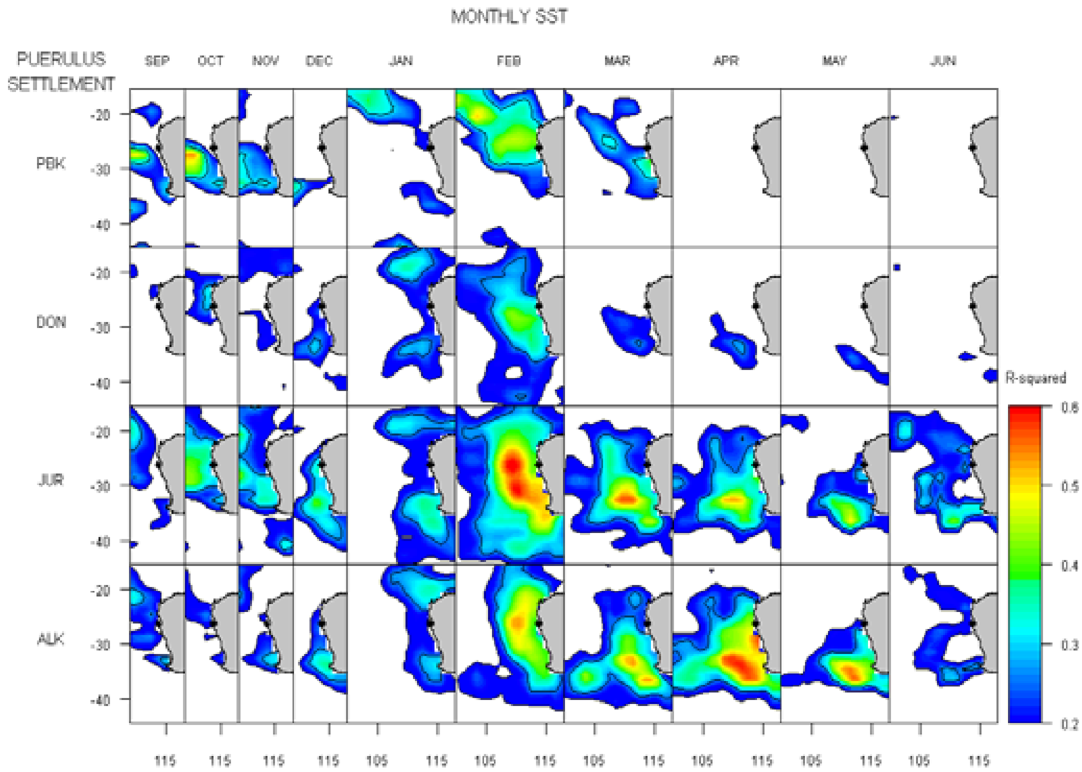


Figure 7.4.4. Correlation between monthly SST in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement up to 2006/07 at 4 locations: Port Gregory (PBK), Dongara (DON), Jurien (JUR) and Alkimos (ALK).

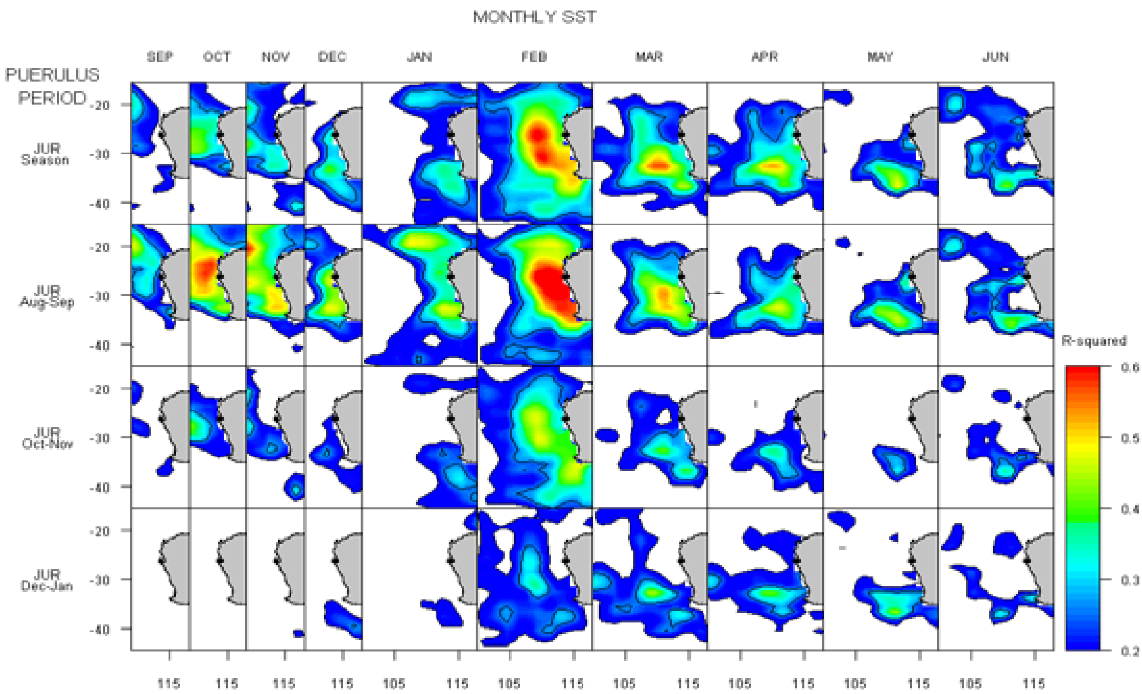


Figure 7.4.5. Correlation between monthly SST in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement up to 2006/07 at Jurien (JUR) and the Jurien settlement broken down into 3 periods: early (Aug-Sep), peak (Oct-Nov), and late (Dec-Jan).

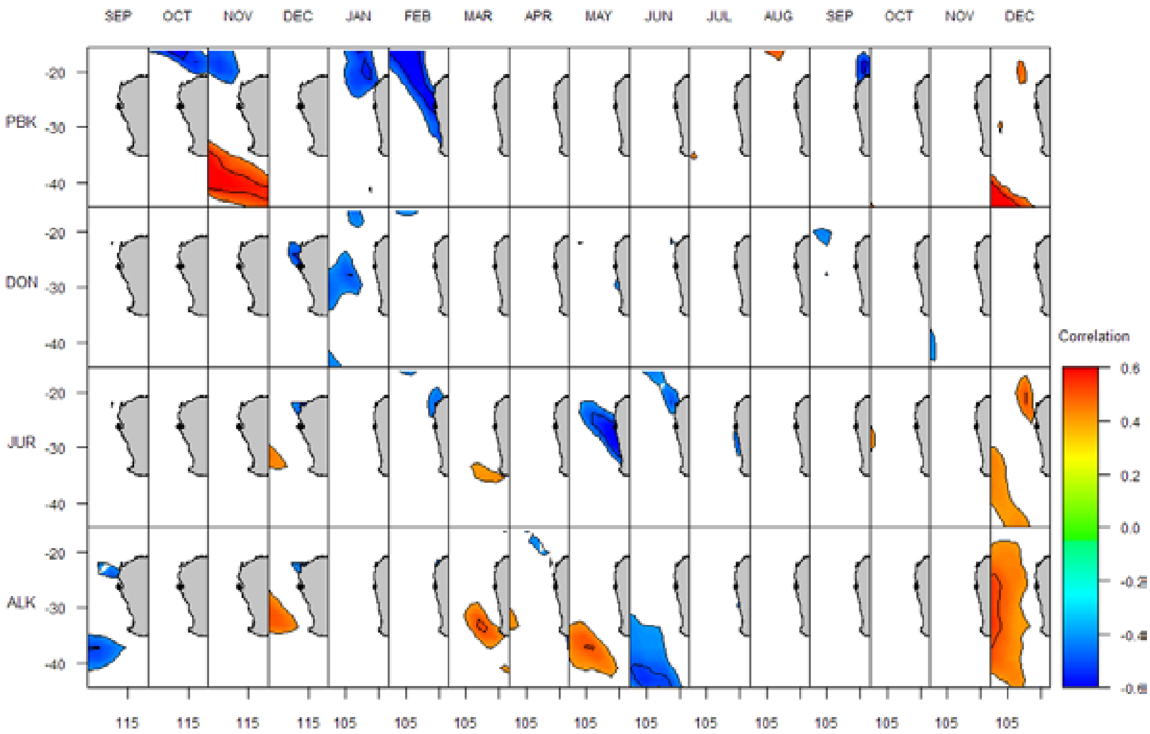


Figure 7.4.6. Correlation between monthly meridional (NS) wind stress in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement from 1982/83 to 2006/07 at 4 locations: Port Gregory (PBK), Dongara (DON), Jurien (JUR) and Alkimos (ALK). Only significant values shown.

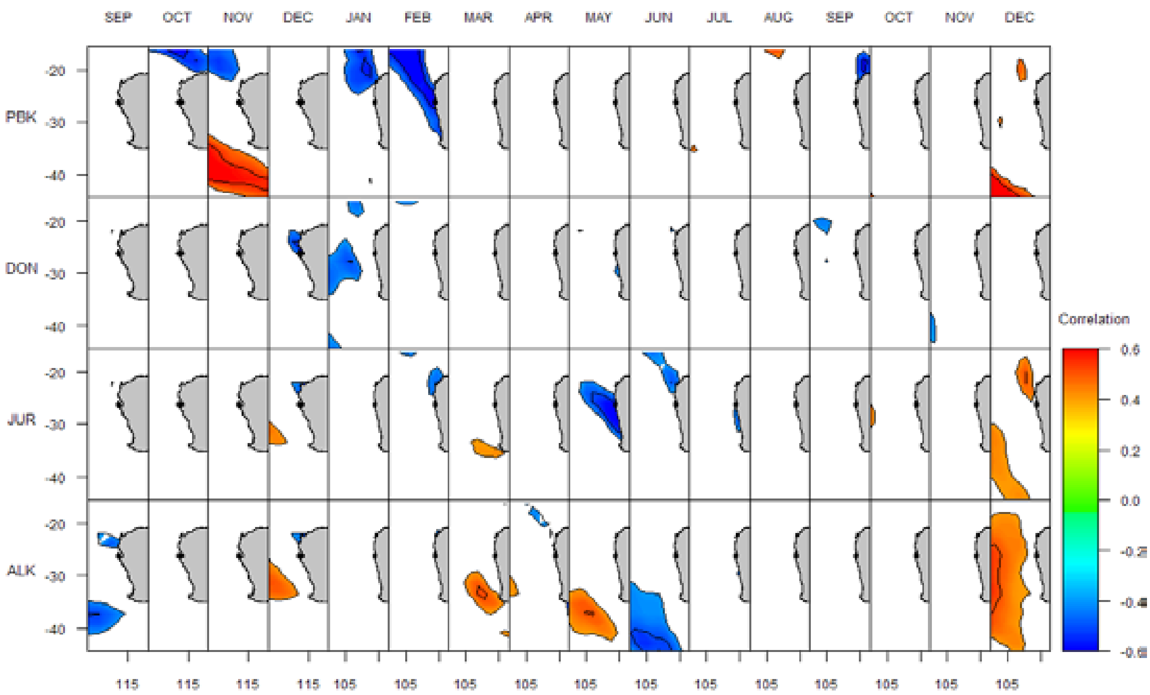


Figure 7.4.7. Correlation between monthly zonal (EW) wind stress in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement from 1982/83 to 2006/07 at 4 locations: Port Gregory (PBK), Dongara (DON), Jurien (JUR) and Alkimos (ALK).

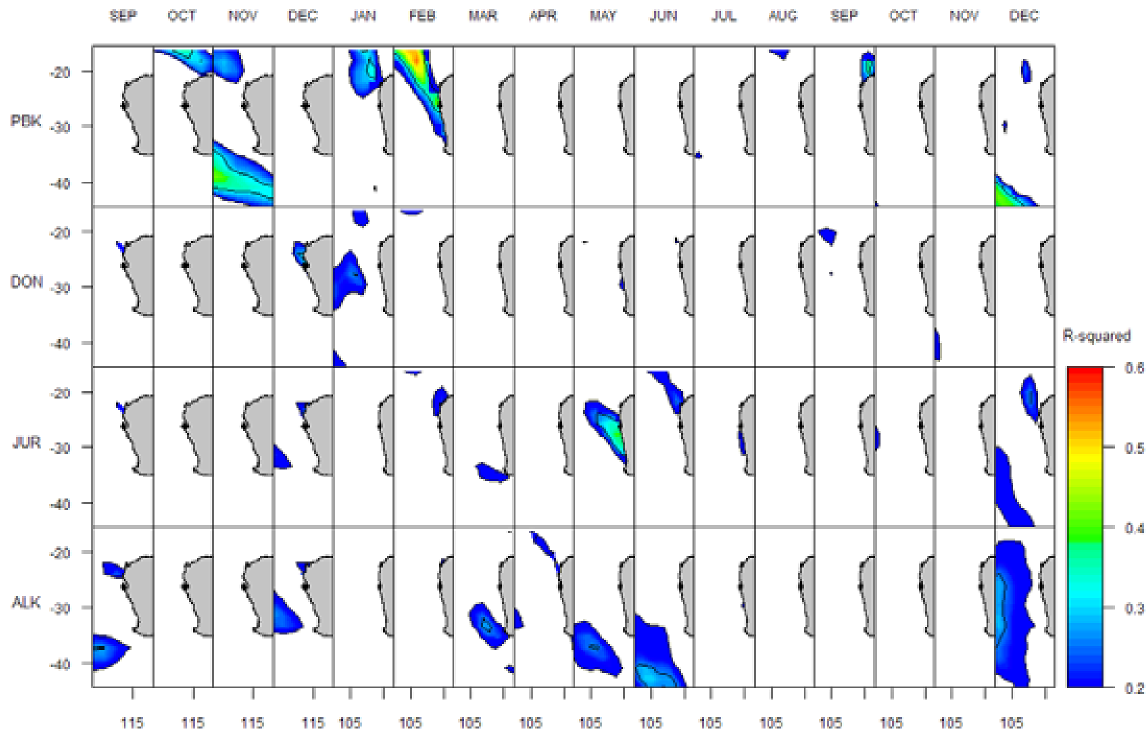


Figure 7.4.8. Multiple correlation (R^2 shown) between monthly meridional (NS) and zonal (EW) wind stress in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement from 1982/83 to 2006/07 at 4 locations: Port Gregory (PBK), Dongara (DON), Jurien (JUR) and Alkimos (ALK).

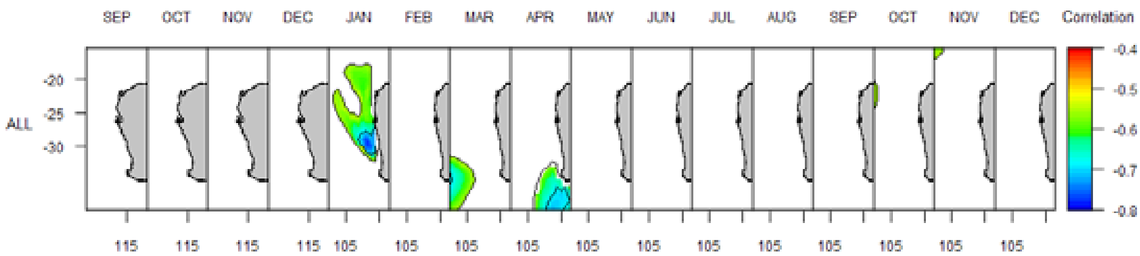


Figure 7.4.9. Correlation between monthly wave height in blocks of the WA coast during the spawning and larval period with the subsequent coast-wide annual puerulus settlement index from 1997/98 to 2009/10.

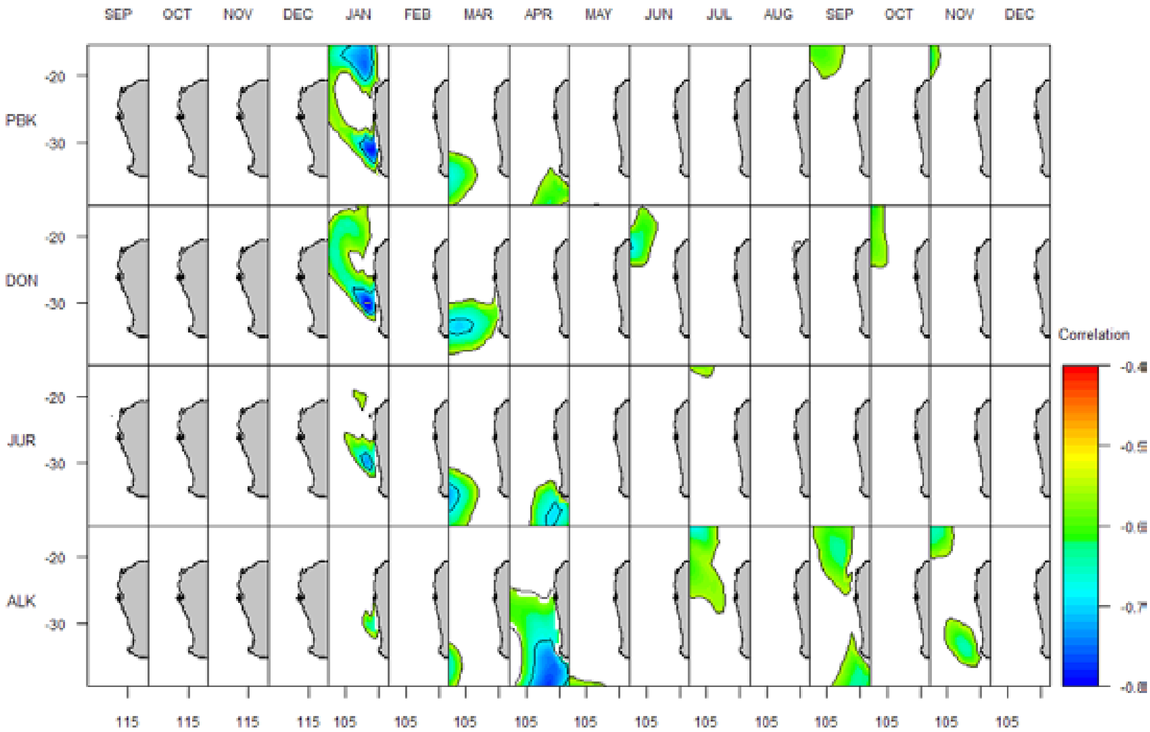


Figure 7.4.10. Correlation between monthly wave height in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement from 1997/98 to 2009/10 at 4 locations: Port Gregory (PBK), Dongara (DON), Jurien (JUR) and Alkimos (ALK).

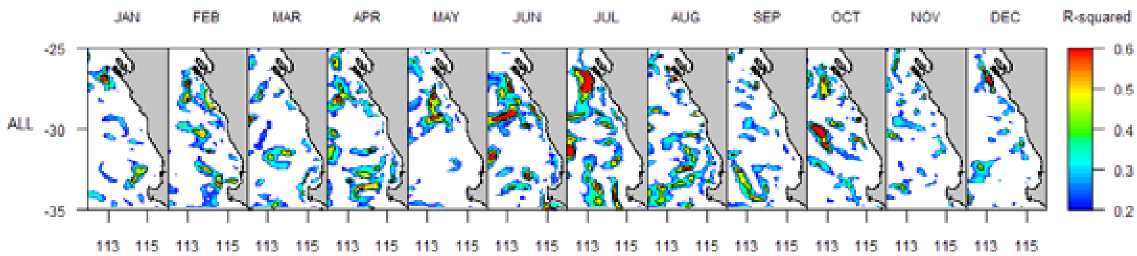


Figure 7.4.11. Correlation between monthly North-South and East-West water movement in blocks of the WA coast during the spawning and larval period with the subsequent annual coast-wide puerulus settlement index from 1993/94 to 2007/08.

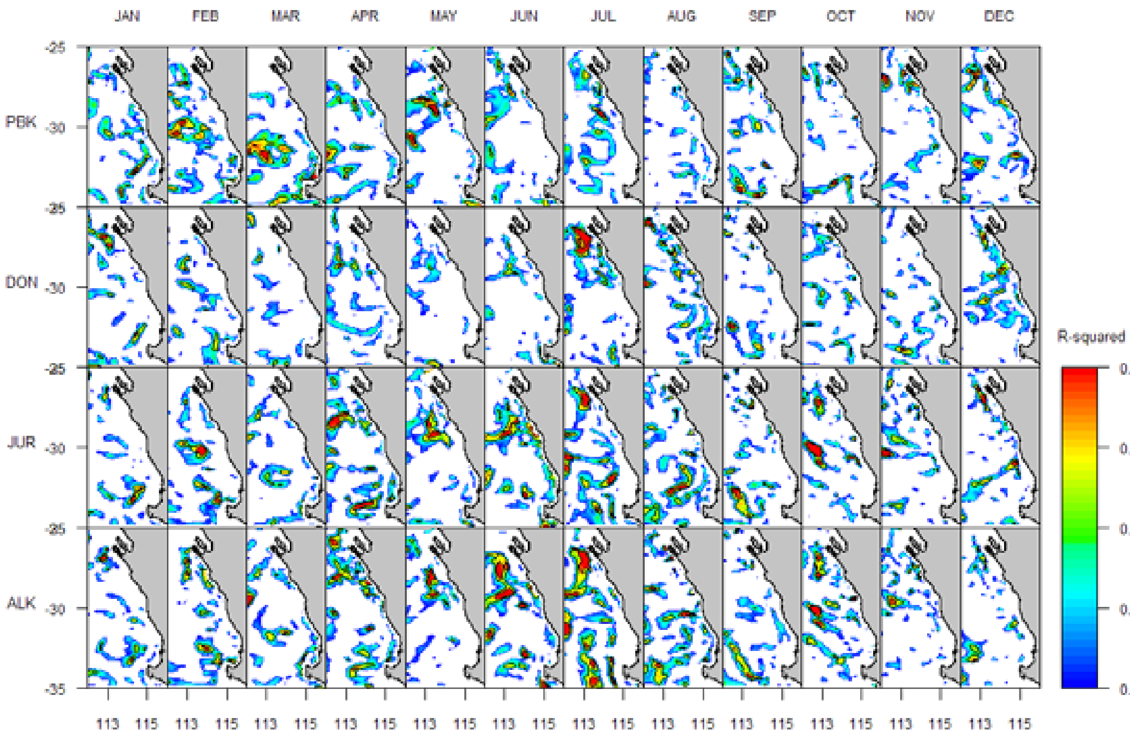


Figure 7.4.12. Correlation between monthly North-South and East-West water movement in blocks of the WA coast during the spawning and larval period with the subsequent annual puerulus settlement from 1993/94 to 2007/08 at 4 locations: Port Gregory (PBK), Dongara (DON), Jurien (JUR) and Alkimos (ALK).

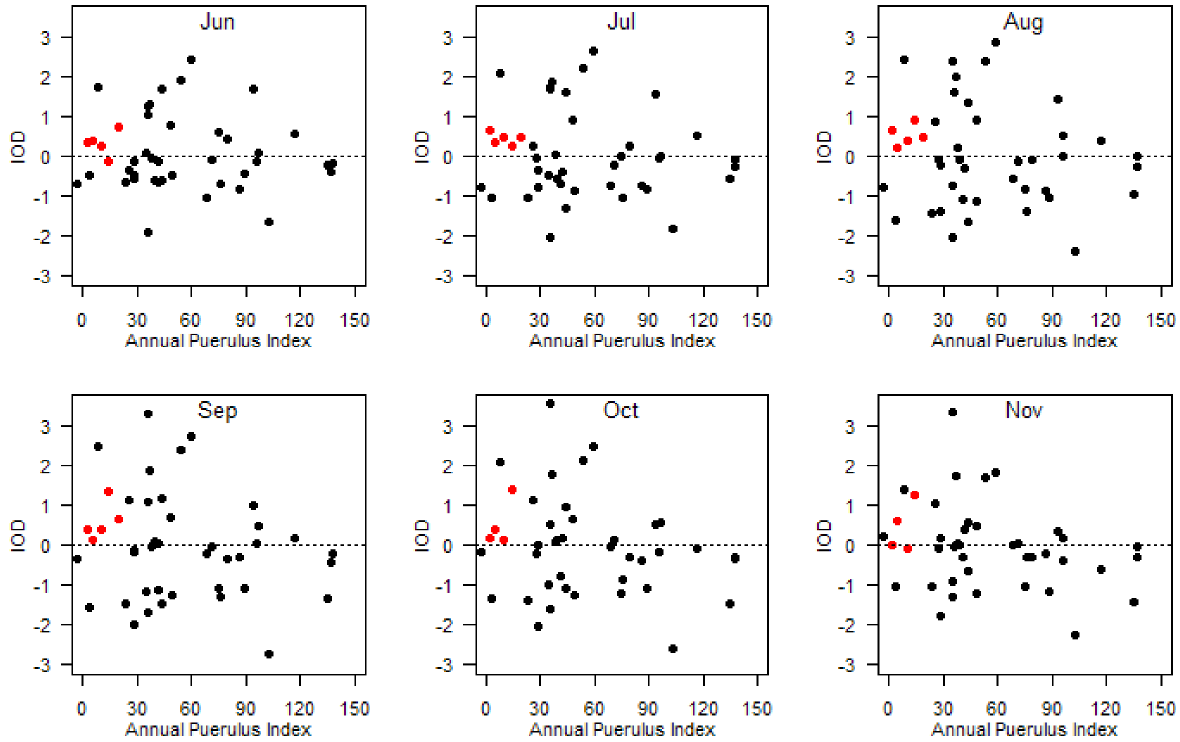


Figure 7.4.13. Correlation between Indian Ocean Dipole (IOD) for June to November with the annual coast-wide puerulus settlement. The five recent years to 2010/11 are shown in red.

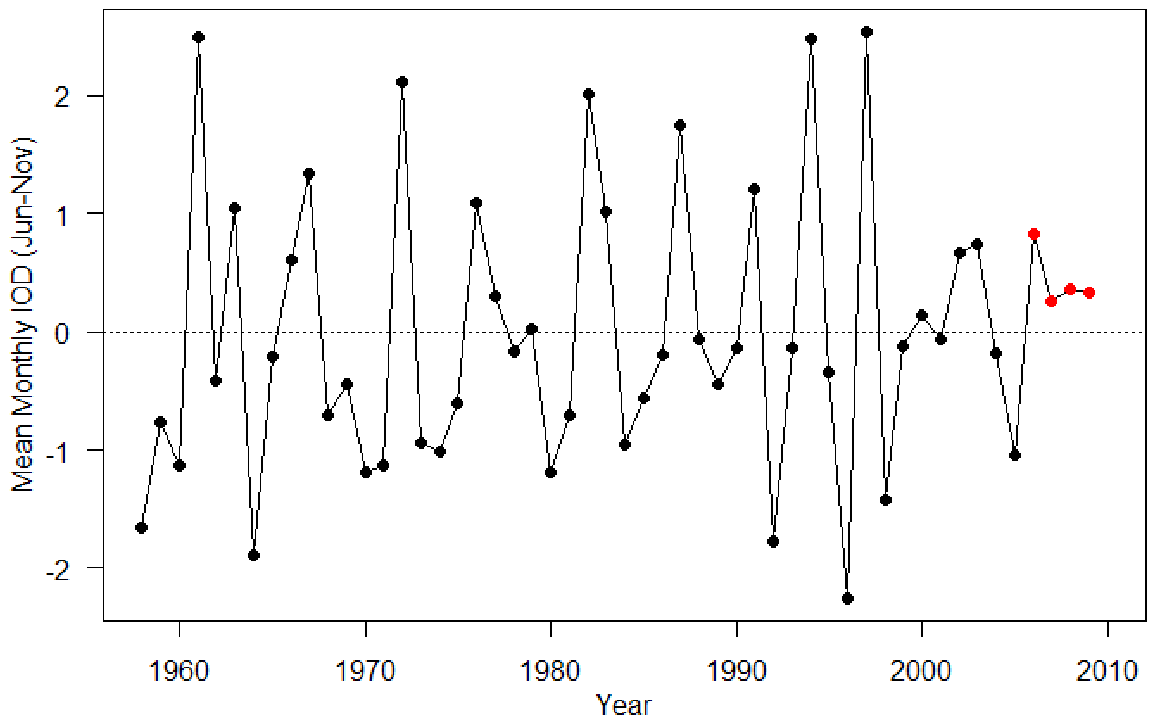


Figure 7.4.14. Average Indian Ocean Dipole (IOD) for June to November with the four recent years to 2009/10 shown in red.

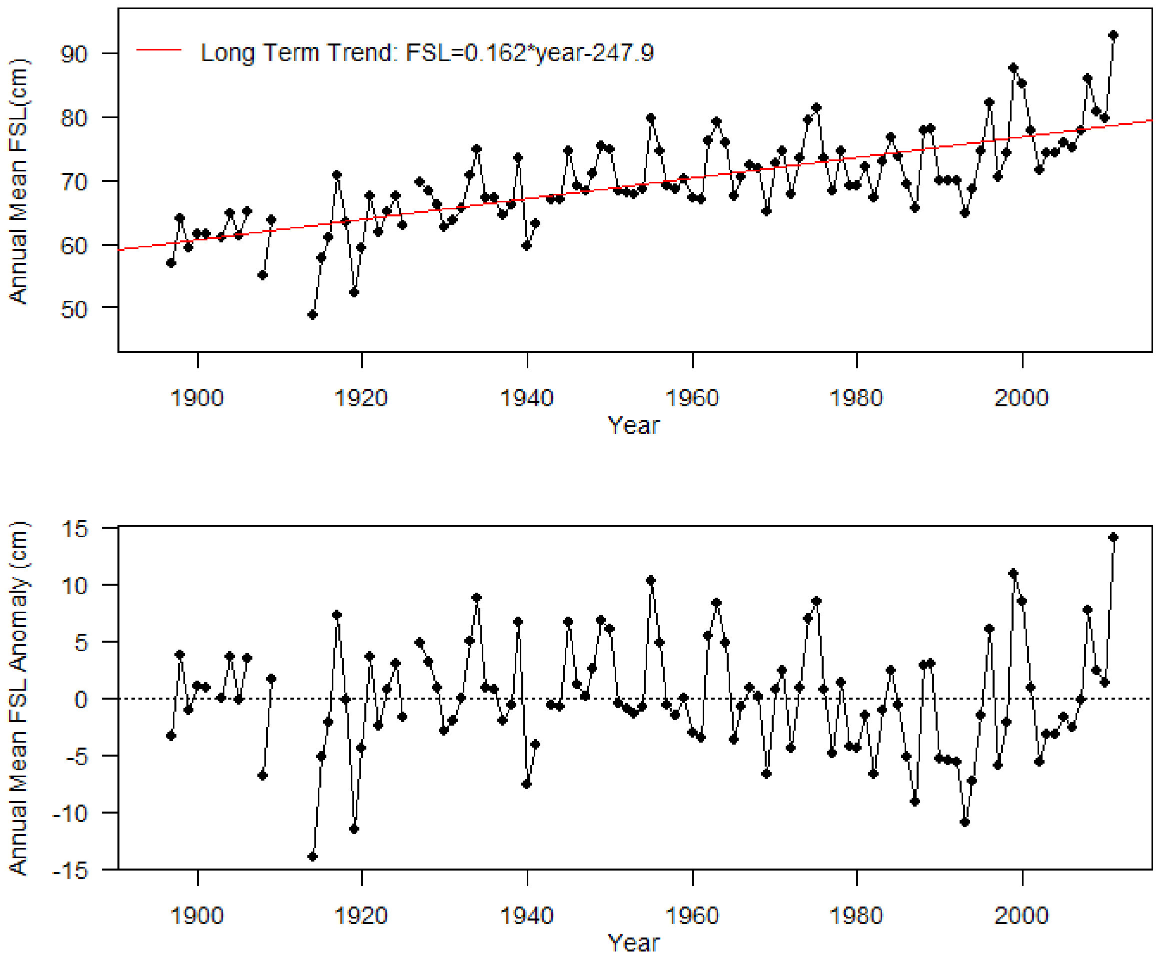


Figure 7.4.15. Annual mean Fremantle sea level (FSL) showing long-term trend (top) and with long-term trend removed (bottom).

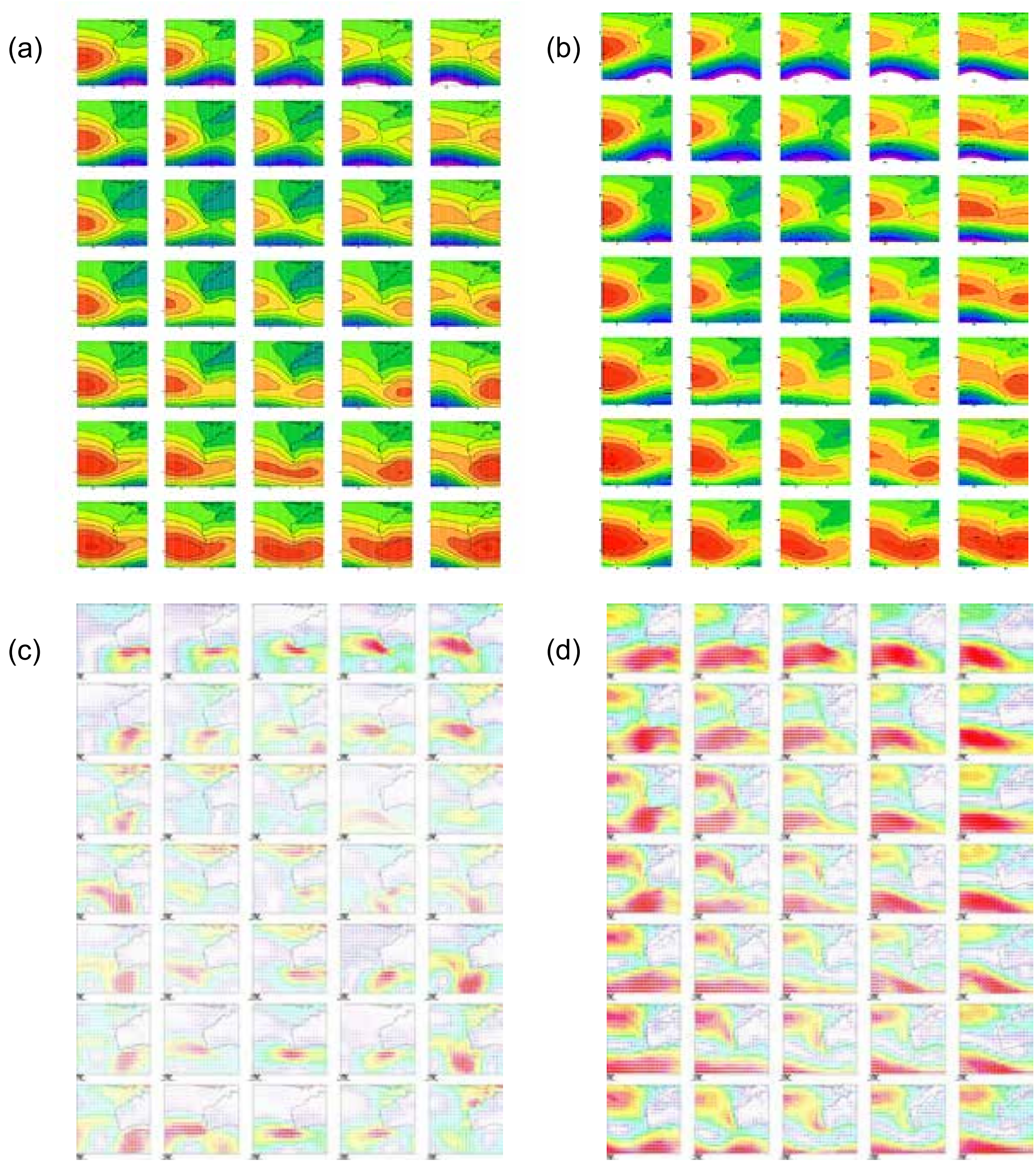


Figure 7.4.16. Array of SOM weather patterns for (a) Jan-Jun (b) Jul-Dec along with the corresponding wind patterns for (c) Jan-Jun (d) Jul-Dec. Shading of wind patterns corresponds to wind strength where blue is mild and red is strong. Note that the scale of the wind patterns for Jan-Jun and Jul-Dec are not identical.

00	10	20	30	40
01	11	21	31	41
02	12	22	32	42
03	13	23	33	43
04	14	24	34	44
05	15	25	35	45
06	16	26	36	46

Figure 7.4.17. Identification codes of SOM weather patterns.

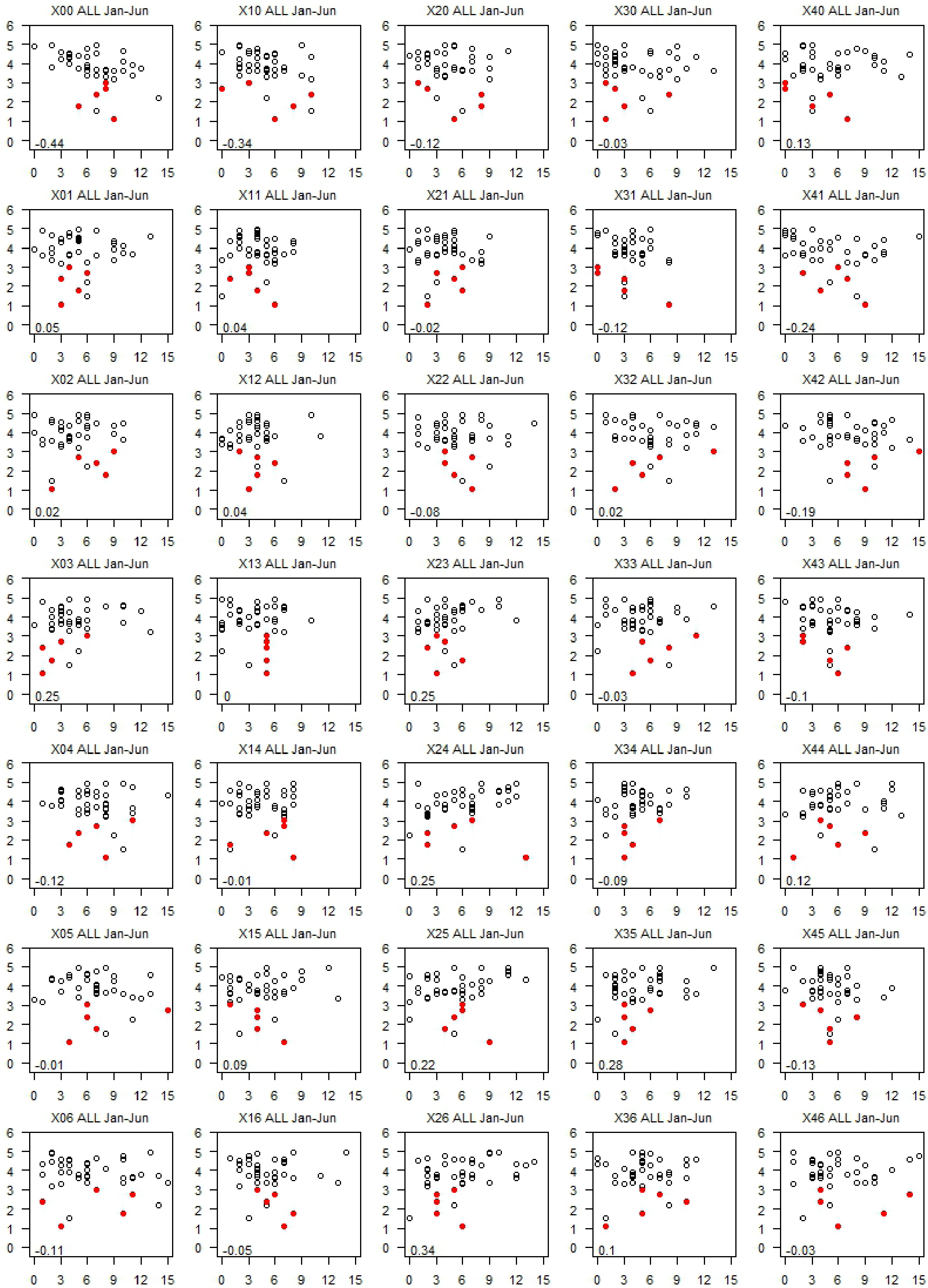


Figure 7.4.18. Plots of natural logarithm of puerulus (ALL) against the SOM counts for the 35 SOM types for January-June period for years 1970 to 2010. Red points indicate seasons 2007 to 2011. Correlations are indicated.

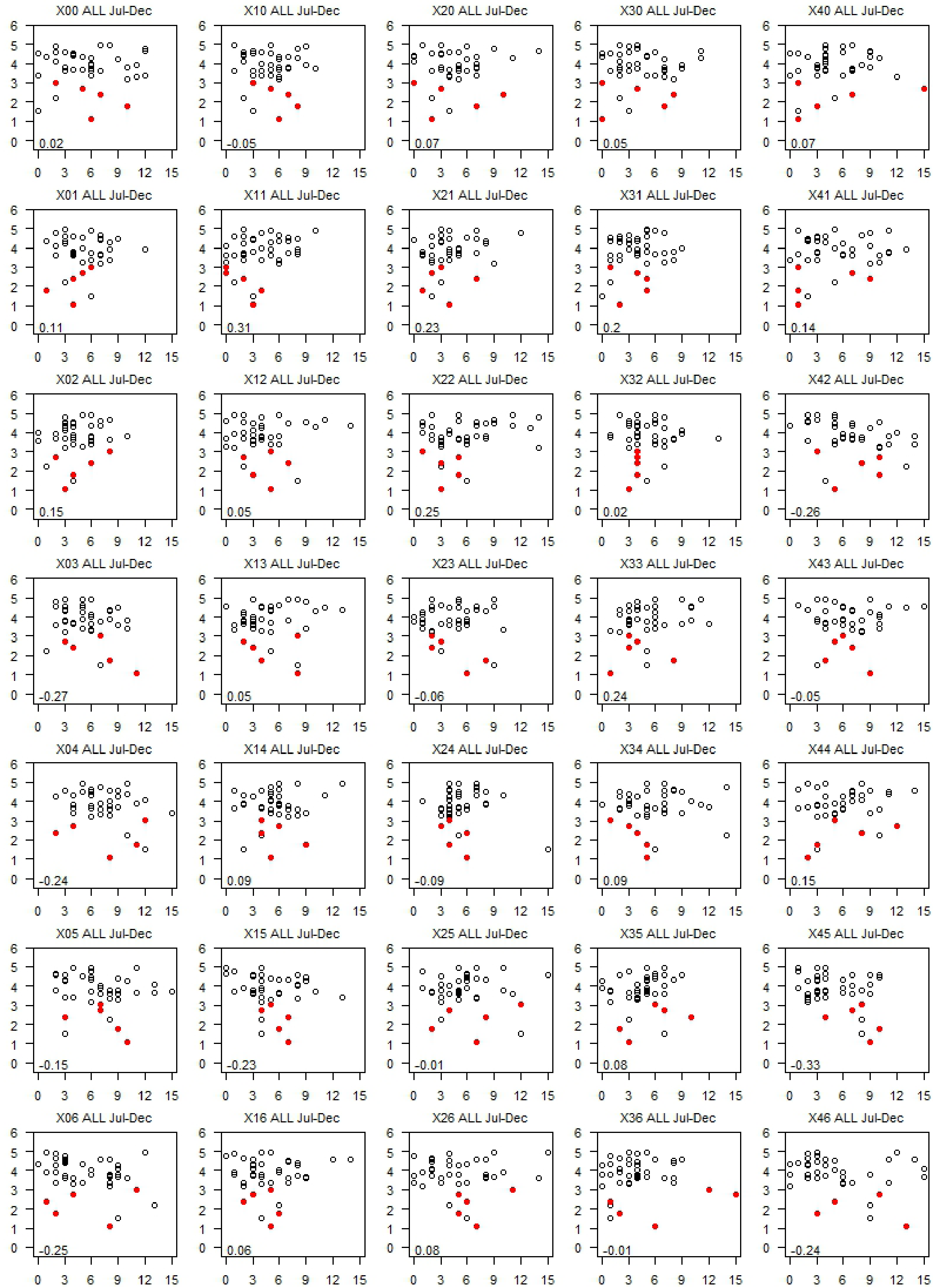


Figure 7.4.19. Plots of natural logarithm of puerulus (ALL) against the SOM counts for the 35 SOM types for July-December period for years 1970 to 2010. Red points indicate seasons 2007 to 2012. Correlations are indicated.

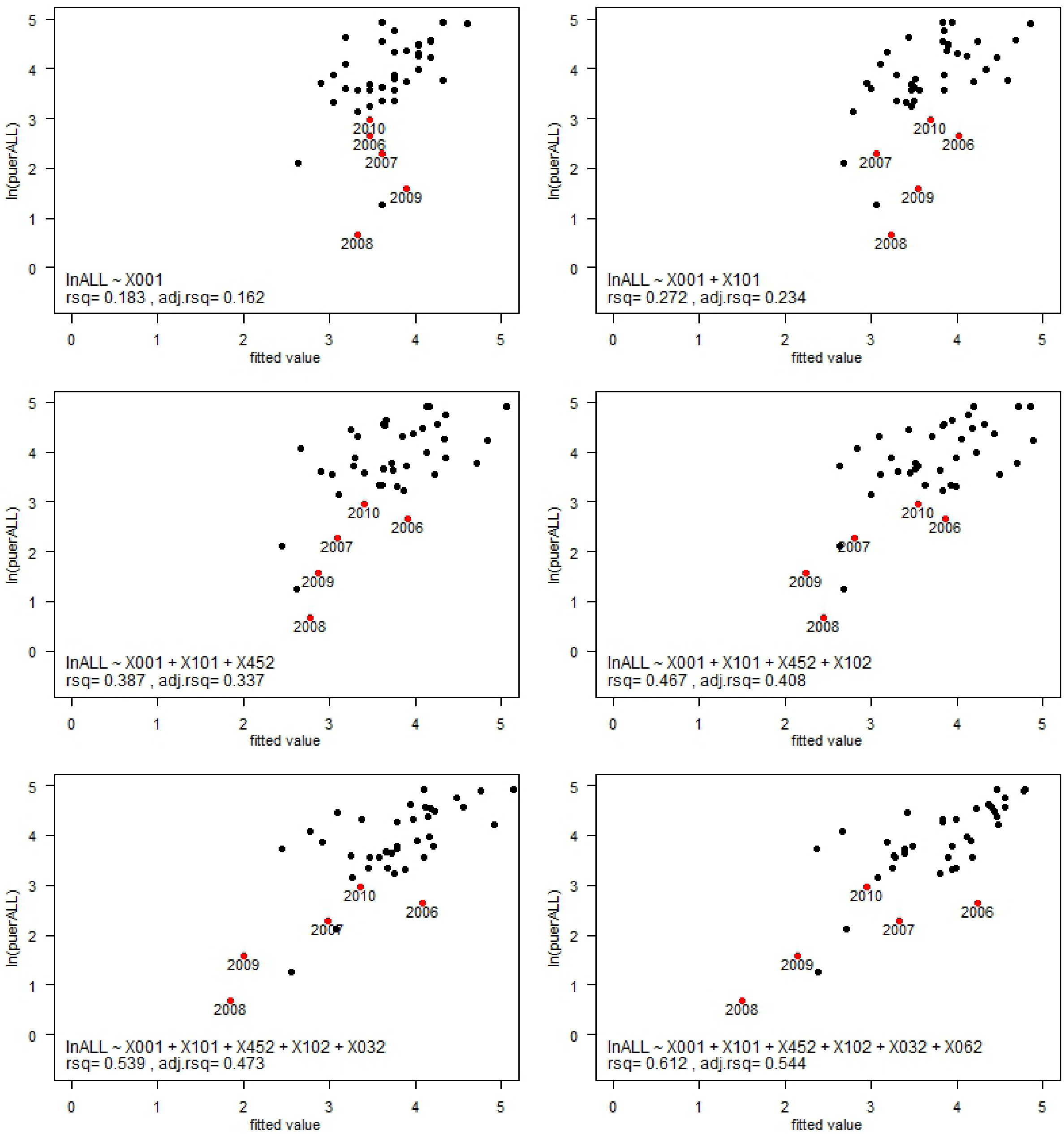


Figure 7.4.20. Natural log of annual puerulus index (ALL) versus the values from the fitted linear models.

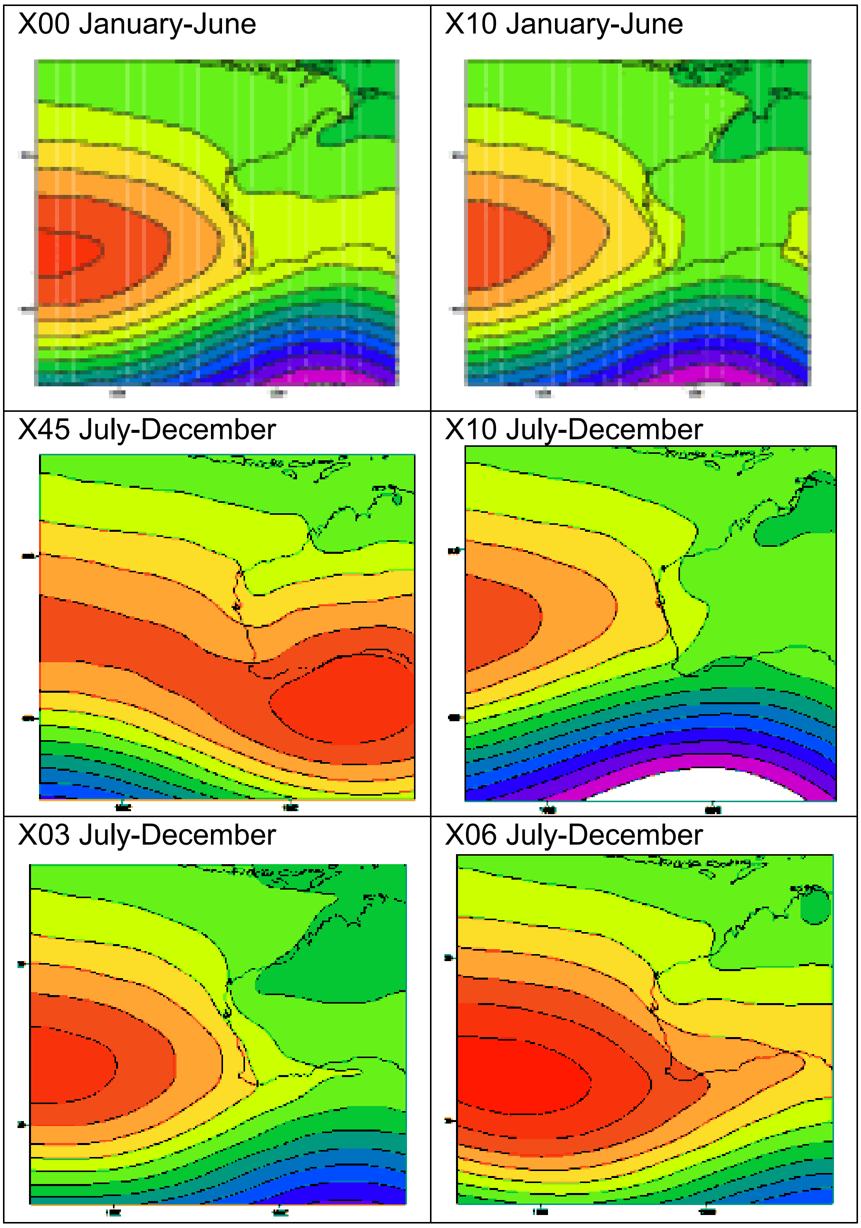


Figure 7.4.21. SOM weather patterns for the 6 variables of the fitted model.

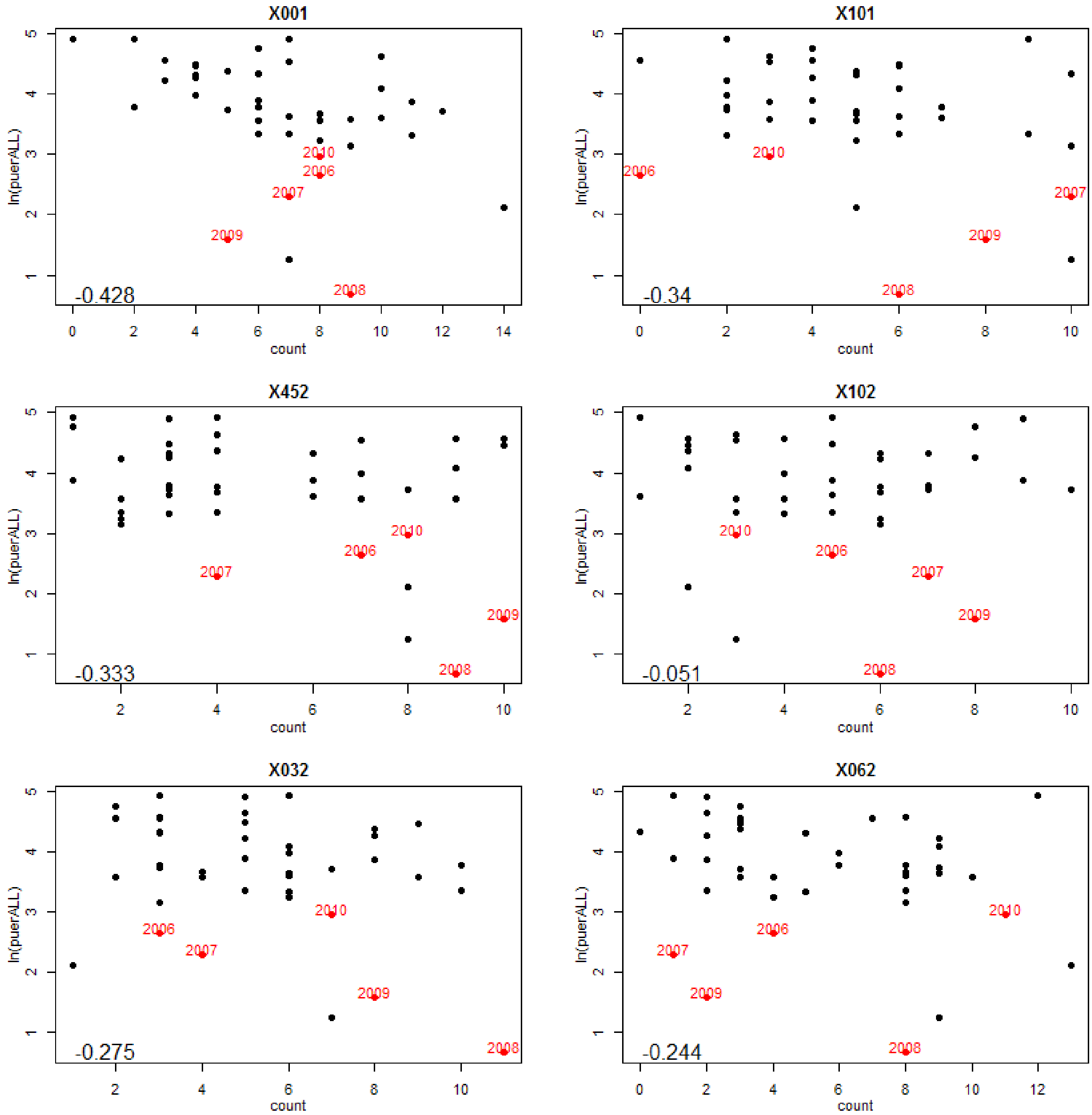


Figure 7.4.22. Relationship of SOM counts with annual puerulus index (ALL) for variables in fitted model. Correlation is shown in bottom left corner.

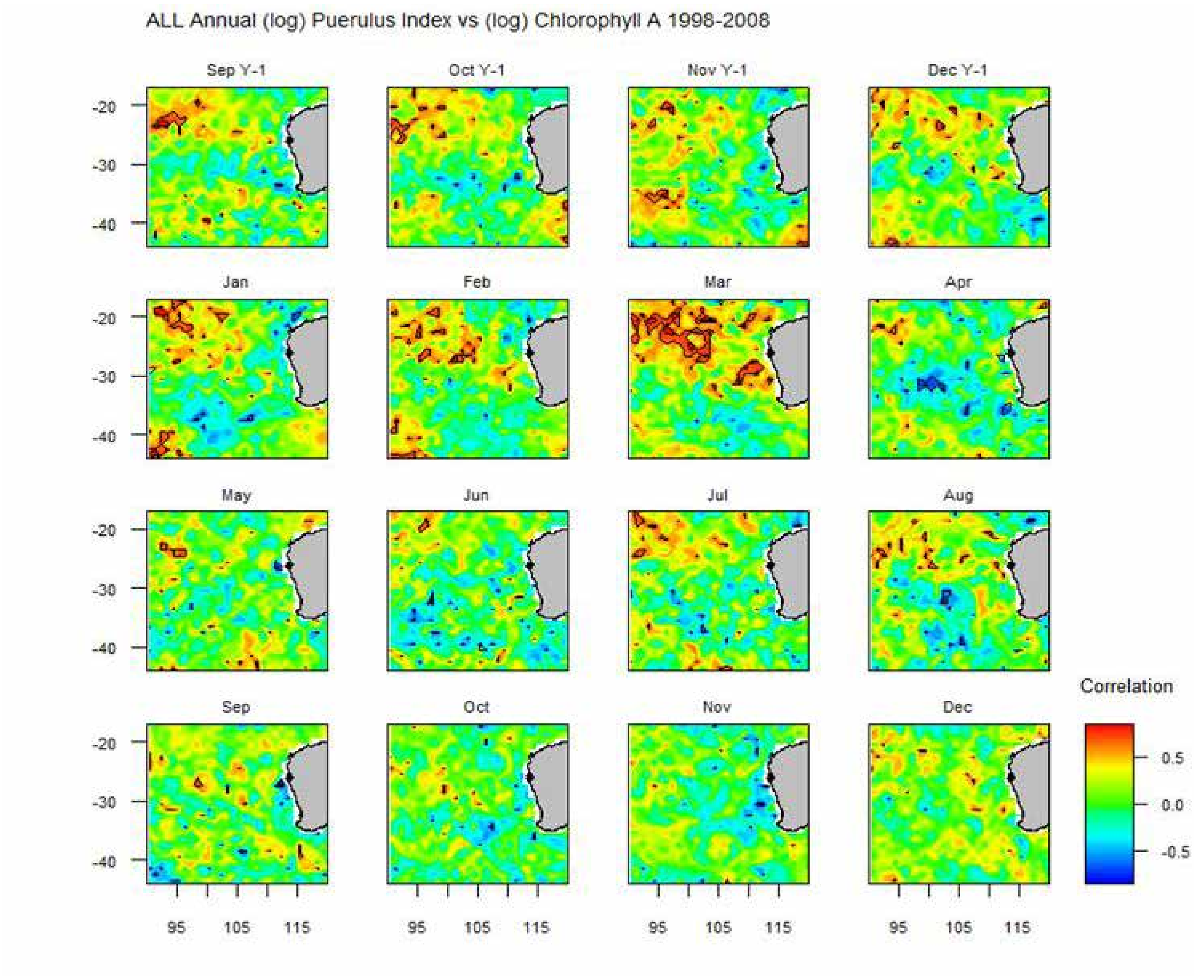


Fig 7.4.23. Correlation between monthly chlorophyll data in blocks of the WA coast with the subsequent annual puerulus settlement from 1998/99 to 2008/09. Areas of significant correlation (at the 0.05 level) are outlined in black. Note that January, February, March and July correlations do not include 2008 data as no Chlorophyll data available for these months.

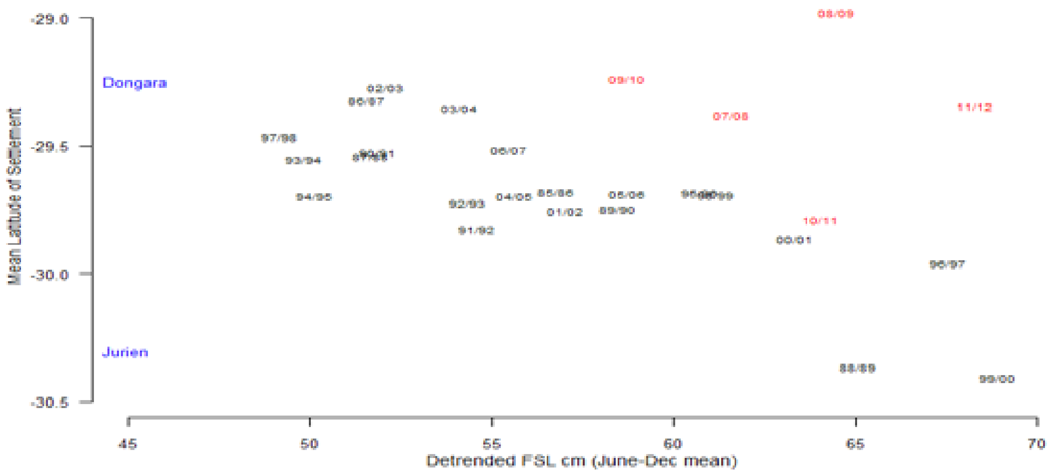


Figure 7.4.24. Relationship between the de-trended mean Fremantle sea level, June to December, and mean latitude of puerulus settlement. Updated from Caputi (2008).

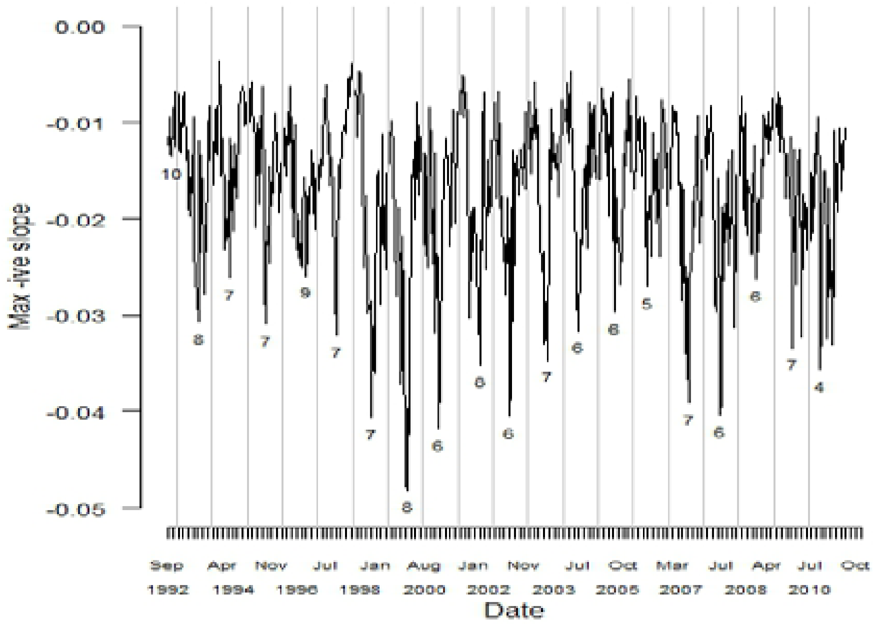


Figure 7.4.25. Maximum negative slope determined for each altimeter satellite pass every ~ 10 days from late 1992 until late 2011 with numbers indicating the month when the greatest negative slope was determined.

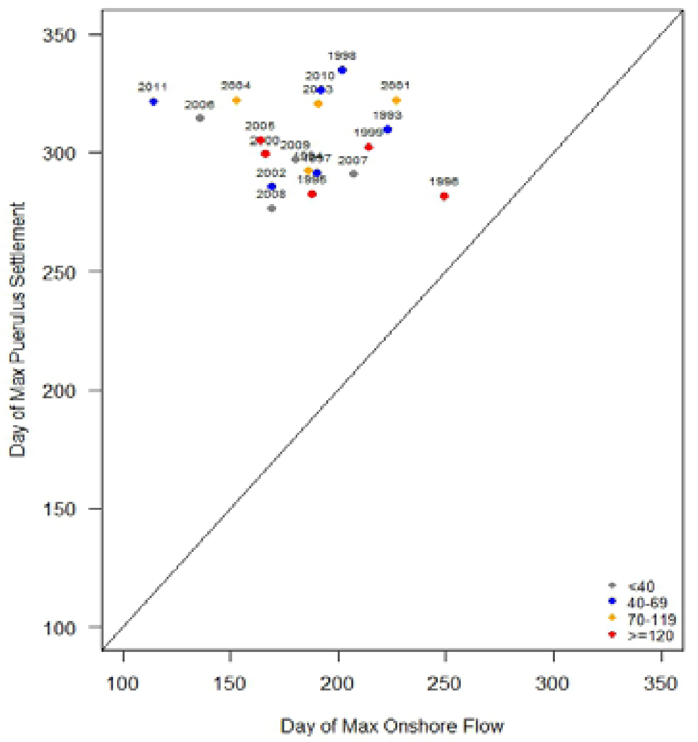


Figure 7.4.26. Day of maximum onshore flow from altimeter data and the day of peak puerulus settlement (weighted mean of Dongara/Jurien settlement index). The year is shown and colour indicates the magnitude of puerulus settlement (Dongara/Jurien).

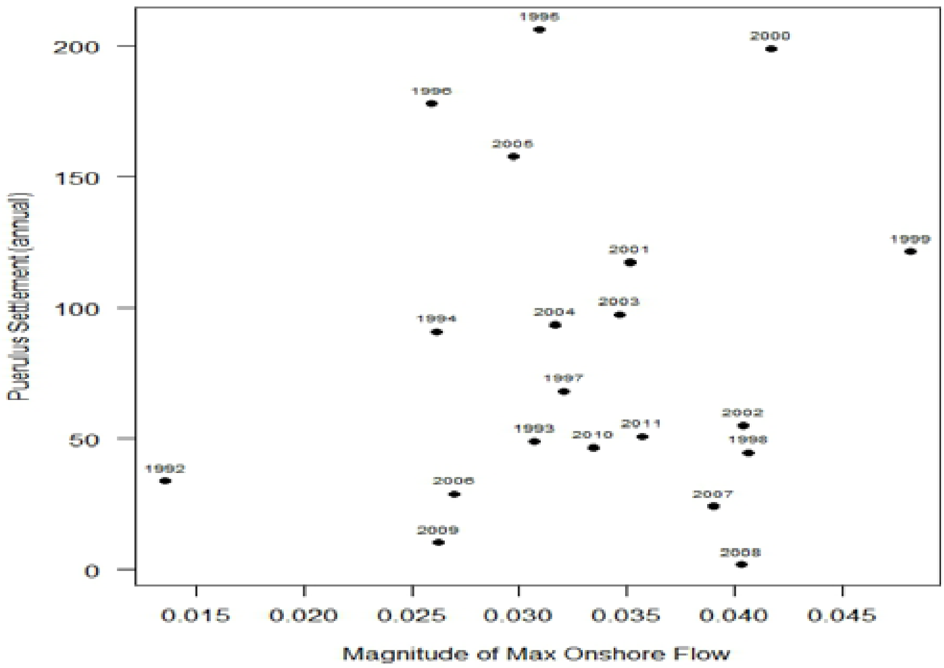


Figure 7.4.27. The magnitude of the maximum onshore flow derived from altimeter data and the corresponding magnitude of annual puerulus settlement (Dongara/Jurien).

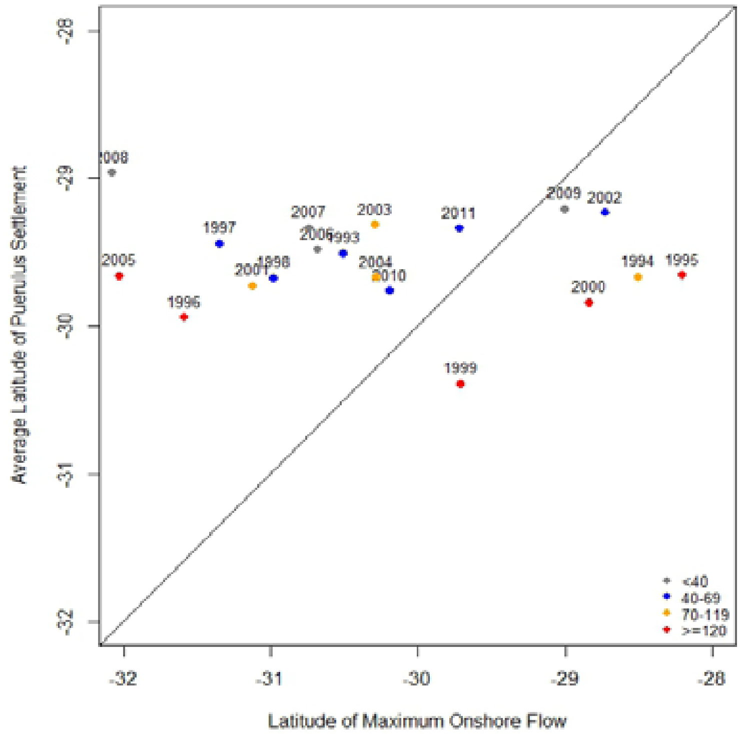


Figure 7.4.28. Latitude of maximum onshore flow from altimeter data and the average latitude of peak puerulus settlement. Text indicates the year of comparison and colour the magnitude of puerulus settlement (Dongara/Jurien).

7.5 Environmental effect on migrating lobsters

The mean latitude of migration, based on the catch rate of undersize lobsters in deep water, ranged from north of Kalbarri with a latitude just north of 27°S down to Dongara with a latitude of south of 29°S (Figure 7.5.1). This range in mean latitude of migration spanned a distance of about 300 km or half the coastal length of the fishery. In the first ten years of the time series (1990/91 – 1999/00) the mean latitude of migration declined slightly but remained in the northern end of the fishery, always north of 28°S. A marked southward decline occurred over the following six seasons down to about 29°S before the mean latitude of migration progressively increased back to north of 28°S by the 2007/08 fishing season (Figure 7.5.1). Due to a lack of fishing in deep-water locations the mean latitude of migration could not be determined after 2008/09.

The relationship between the mean latitude of migration and the two indices of puerulus settlement (abundance and mean latitude) three to four years previously without the environmental factors were highly significant ($P < 0.001$). These variables were then used in all subsequent models investigating the impact environmental factors may have had on the mean latitude of migration.

The relationships between the three environmental variables over the months encompassing the migration period (plus the puerulus indices three/four years previously) and mean latitude of migration were examined. Only the meridional current data showed significant multiple correlations with latitude of migration for any of the spatial locations examined. The other two environmental variables examined displayed consistently low contribution to the multiple R^2 values, below 0.1, with all models being not significant.

All increases in the multiple R^2 values from the log-linear models between the mean latitude of migration with the addition of the meridional ocean currents in January (to the puerulus settlement three and four years previously) for areas east of the shelf break were plotted on a bathymetric map of the fishery (Figure 7.5.2).

The resultant map generally identified that the area between 100-200 m had the highest correlation with meridional current strength, particularly the area north of the Abrolhos Islands. Therefore the current data within this region was chosen to further develop the average annual index of current strength for future comparisons. Within this area the highest ten R^2 values determined were located (shown as open circles in Figure 7.5.2). The meridional current velocities at these locations during the peak month of correlation (January) were then used to develop the average measure of meridional current strength for further analysis (Figure 7.5.3).

Over the 18-year time series, the current meridional index (average of ten locations) ranged from southward flow of 1 to 10 cms^{-1} (Figure 7.5.3). At the start of the time series current velocities remained between 1-5 cms^{-1} before strengthening southward in 2001-2004 to a peak southward flow of 8-10 cms^{-1} and then varying between 5-10 cms^{-1} over the subsequent seven years except for the weak current strength of about 3 cms^{-1} in 2009.

The model describing the relationship between the mean latitude of settlement and the average (ten locations) meridional current velocity with abundance and distribution of puerulus settlement three and four years previously was highly significant ($P<0.001$; $R^2 = 0.95$) (Table 7.5.1, Figure 7.5.4). Meridional current velocity was a highly significant factor in the model ($P<0.001$) and exhibited a negative relationship with the mean latitude of migration, i.e. increasing southward (negative) current velocities being correlated with increased latitude (southward) of migration. The mean latitude of puerulus settlement 3-4 years earlier was highly significant with southward location of the settlement being associated with the southward location of the migration. The magnitude of puerulus settlement 3-4 years earlier was also a significant factor in the model ($P<0.001$) and was also a negative relationship, indicating that increasing numbers of puerulus resulted in a more southern (higher latitude) migration. The fishing seasons where the mean latitude of settlement could not be determined due to limited data (i.e. from 2008/09) are estimated by the model to have been years when the mean latitudes of migration was towards the centre of the fishery, i.e. both estimated to have occurred just north of 30°S (Figure 7.5.4).

Both the mean latitude of migration (based on undersize lobsters) and the index of meridional current velocity were incorporated into catch-prediction models to determine whether either or both of these indices were significant factors in the magnitude of commercial catches of legal lobsters in the Big Bank region of the fishery (Table 7.5.2 and 7.5.3, Figure 7.5.5). Of the two indices, the mean latitude of migration represented a slightly longer time series by three years, beginning in 1990/01 vs 1993/94. Both of the catch prediction models accounted for over 63-82% of the variation reported in commercial catches in the Big-Bank region (Figure 7.5.5). Big Bank catches were dominated by three main peaks, in 1994/95, 1999/00 and 2004/05, all of which were well replicated by the catch predictions from the two models. The model based on average meridional current strength was positively related to catch and performed better than that based on mean latitude of undersize migration (Table 7.5.2 and 7.5.3). Puerulus settlement abundance four years earlier and mean latitude of settlement to a lesser extent both had a significant effect on the Big Bank catch.

This study has shown that the northward migration of *P. cygnus* over the past 20 years has generally resulted in lobsters moving to the north of the Abrolhos Islands and into the northern Big Bank region of the fishery. Such a long and energy-demanding activity presumably may have an important biological basis behind it, i.e. contranatant migration.

This study has also shown that there has been a marked departure from the normal pattern of migration, i.e. movement into the northern Big Bank region of the fishery, over the last 20 years. The departure occurred between 2000/01 and 2005/06. On its own it seems unlikely that this departure would have impacted on the overall larval production and recruitment of this population: *Panulirus cygnus* experiences a relatively low rate of natural mortality (~0.22; Morgan 1977); and the biomass of lobsters in these northern waters would have been supplemented by many previous migrations into this area. However, over the past few decades the Big Bank region has experienced high levels of fishing pressure.

The period identified during this study when the migration stopped short would have resulted in fishing being focussed entirely on the breeding stock. There was a hypothesis that the recent span of poor puerulus settlement may be partly related to this poor migration period refocusing the commercial catches onto the breeding stock. The residual stock levels during the final years of fishing would likely have been the lowest since fishing began, as was also the breeding stock year (2006/07) that would have contributed to the 2007/08 puerulus settlement year, which was the first in the current span of poor recruitment years (de Lestang *et al.* 2012). The Big Bank area of the fishery was closed to western rock lobster fishing in February 2009 as a precautionary measure and independent monitoring of the breeding stock in this area commenced during the breeding season in October 2009 (de Lestang *et al.* 2012). Although the time series for this location is quite short (four years) there has been a dramatic increase in egg production levels, increasing 3-fold over three years (de Lestang *et al.* 2012). How far below virgin biomass levels this area still remains is unknown and at current levels of breeding stock in the northern area, the magnitude of puerulus settlement has still not returned to average.

Table 7.5.1. Relationship between mean latitude of migration with log-transformed abundance (puer3.4) and mean latitude (mlat3.4) of puerulus settlement 3-4 years earlier and meridional current (cur) in January. Multiple R-squared: 0.95 (P<0.001)

```
Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)  -43.3079     7.1327  -6.072 <0.001
log(puer3.4)  -1.1125     0.2235  -4.978 <0.001
mlat3.4        2.4870     0.2569   9.680 <0.001
cur          -14.9482     2.2567  -6.624 <0.001
```

Table 7.5.2. Relationship between Big Bank catch (log transformed) with abundance (puer4) and mean latitude (mlat4) of puerulus settlement 4 years earlier and meridional current (cur) in January. Multiple R-squared: 0.82 (P<0.001)

```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  21.4249     9.8963   2.165 0.05
cur          20.4600     4.4164   4.633 <0.001
log(puer4)    1.5525     0.3116   4.982 <0.001
mlat4        -0.7083     0.3532  -2.005 0.07
```

Table 7.5.3. Relationship between Big Bank catch (log transformed) with abundance (puer4) and mean latitude (mlat4) of puerulus settlement 4 years earlier and mean latitude of migration (migr). Multiple R-squared: 0.63 (P=0.003)

```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  45.4464    11.9927   3.789  0.002
migr         -0.5451     0.1621  -3.363  0.005
log(puer4)    1.4639     0.3870   3.783  0.002
mlat4        -1.0264     0.4215  -2.435  0.029
```

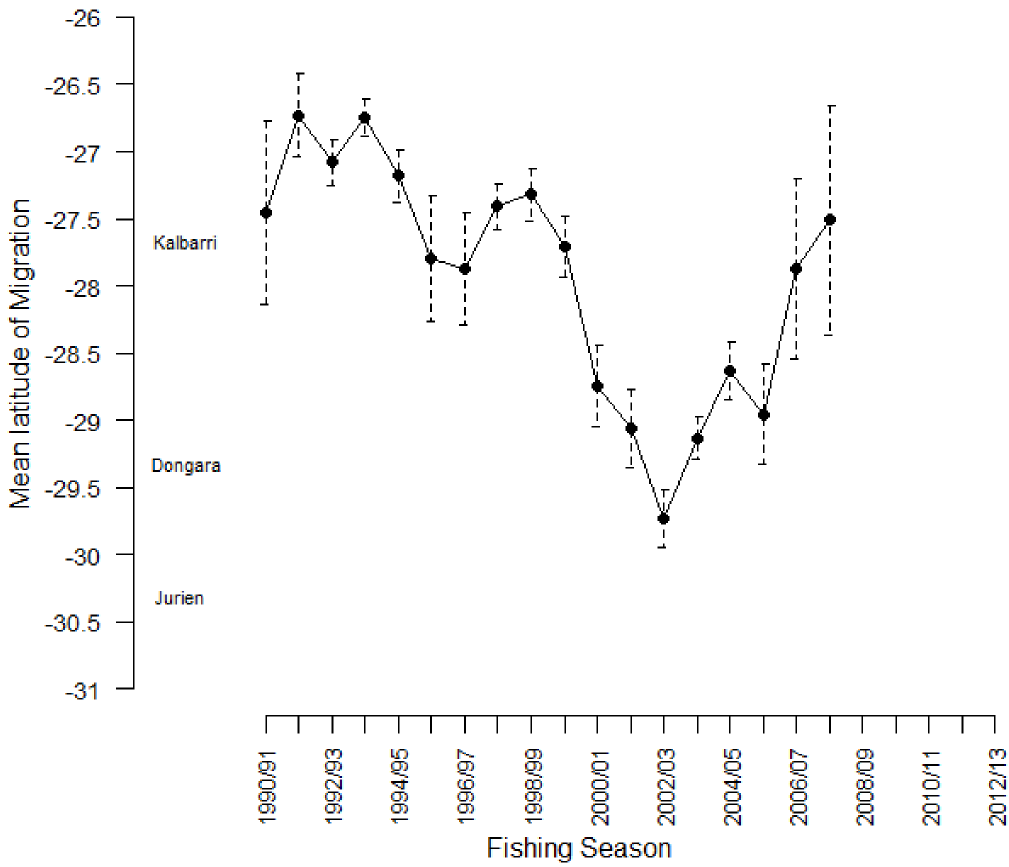


Figure 7.5.1. The mean (± se) latitude of migration between 1990/91 and 2007/08 fishing seasons. In seasons when not enough data was available to calculate the mean latitude of migration (from 2008/09) have been left blank. The latitudinal locations of three major fishing ports are depicted to the right of the y-axis.

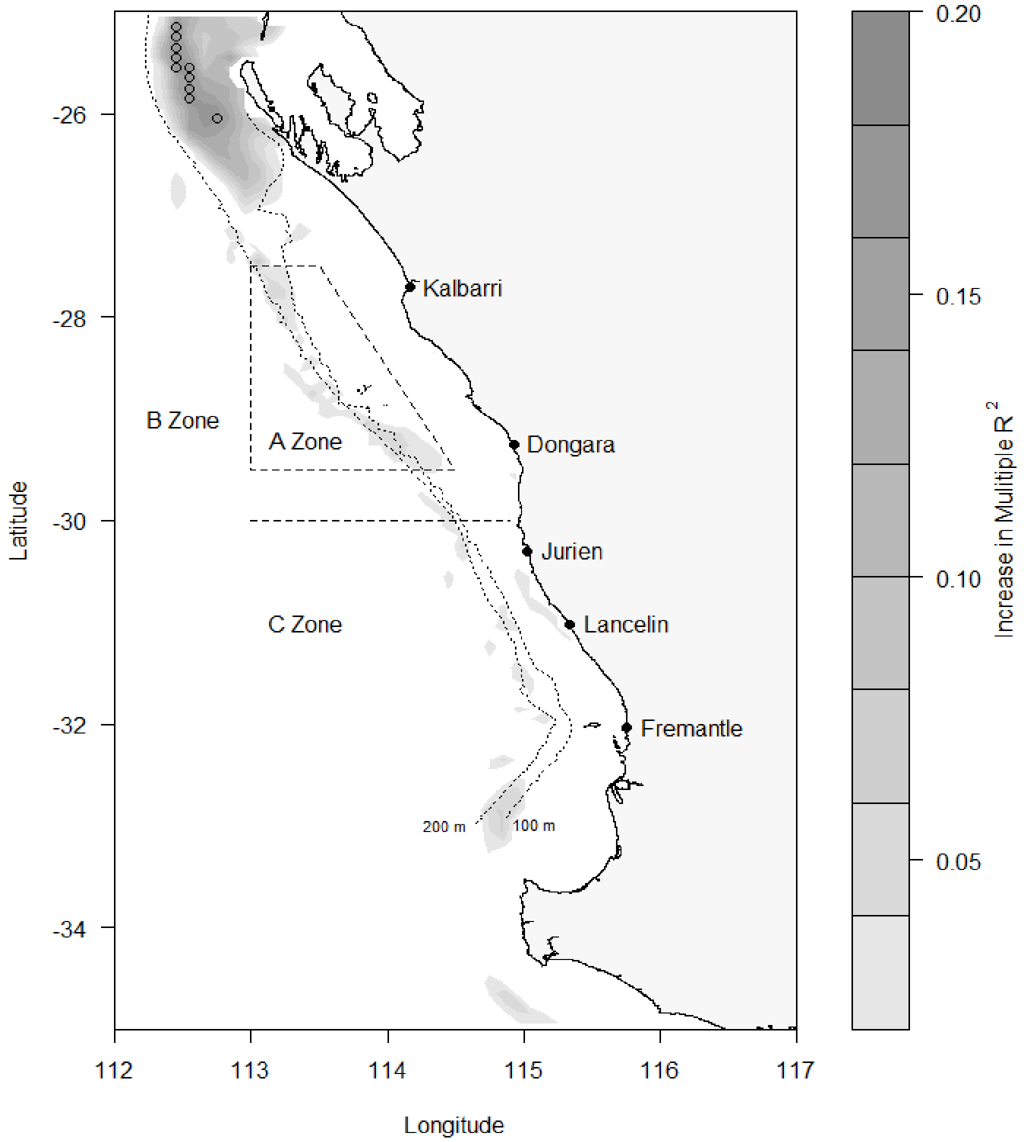


Figure 7.5.2. Bathymetric map of the western rock lobster fishery showing increase in multiple R^2 values from log-linear models between the mean latitude of migration and the magnitude of coast-wide puerulus settlement three and four years previously by adding the meridional current strength at each 0.1 latitude x 0.1 longitude point on the map. Locations of maximum increases in R^2 values used to create an average index of current velocities identified by ten open circles.

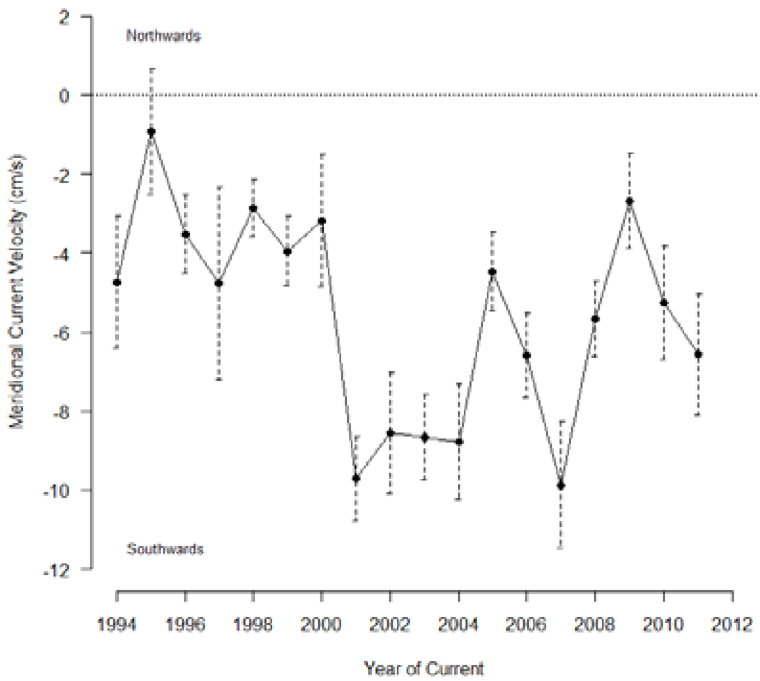


Figure 7.5.3. Mean (± s.e.) meridional current velocities in January determined from ten locations north-west of the Abrolhos Islands on the edge of the shelf break, identified by the open circles in Figure 7.5.2.

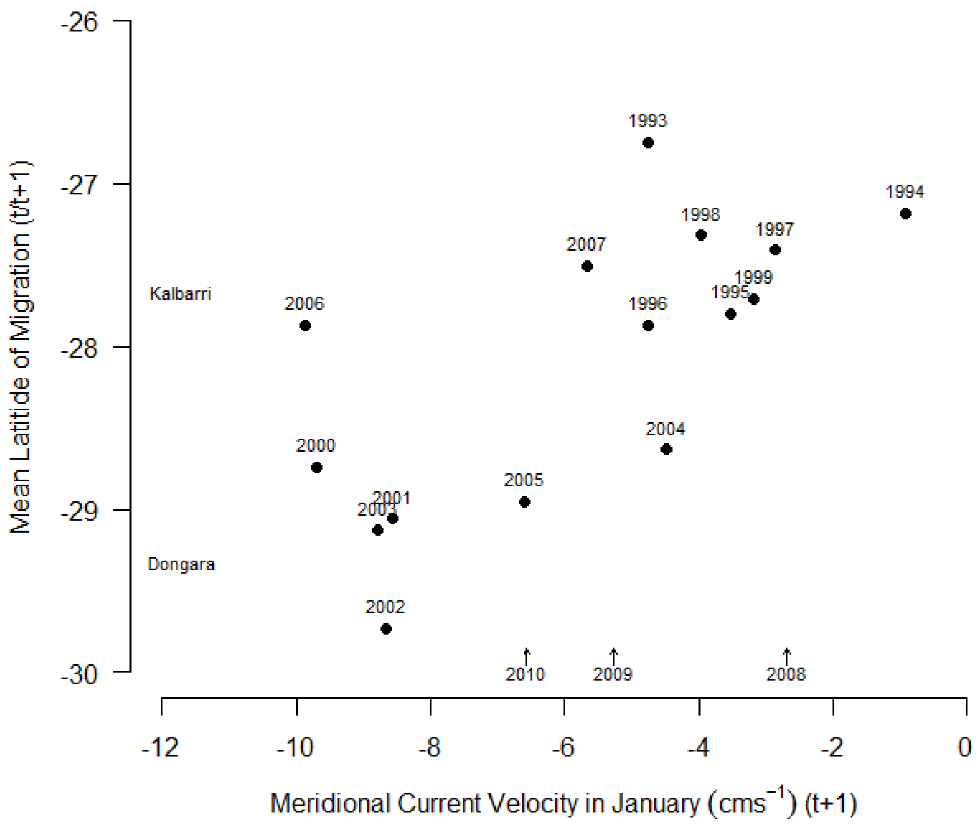


Figure 7.5.4. Relationship between the mean latitude of migration and the average meridional current velocities in January from ten locations north-west of the Abrolhos Islands on the edge of the shelf break. Current velocities in January 2008 to 2010 are shown on the plot indicating the general latitude where migration may have occurred to in those years. For referencing purposes the latitude of two fishing towns are shown just to the right of the y-axis. The year indicated represents the first year of the migration period i.e. 2007 represents the migration during 2007/08 and current velocity in January 2008.

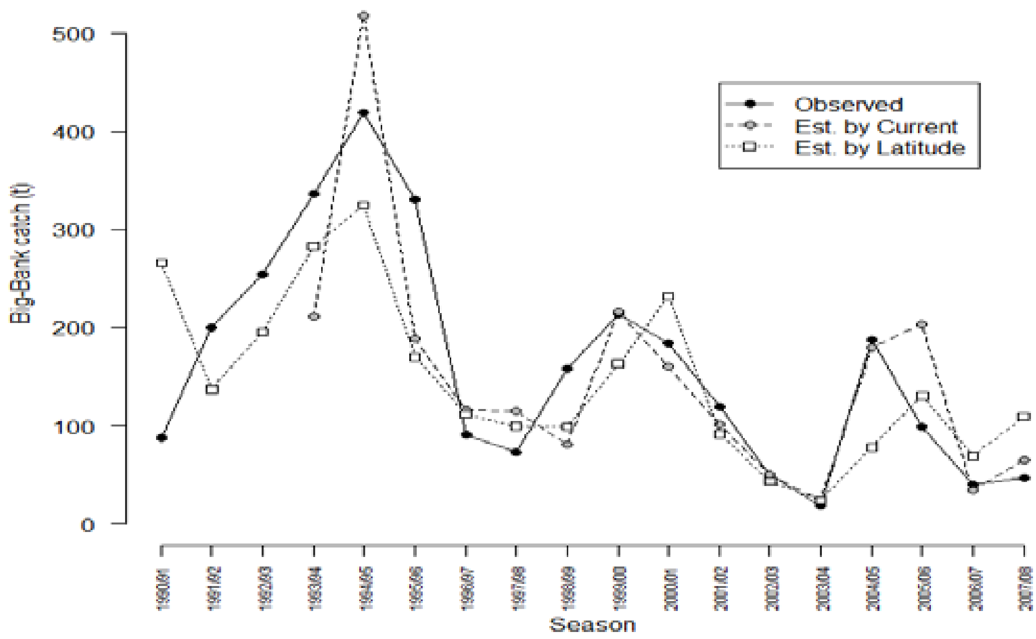


Figure 7.5.5. Relationship between observed Big Bank catch and modelled catch estimated from meridional current in January (Current) or mean latitude of migration (Latitude) combined with abundance and mean latitude of puerulus settlement 4 years earlier.

7.6 Environmental effect on timing of spawning

Prior to 2004 the timing of the onset of spawning (October) varied slightly between years, with the index ranging between 0.05 and 0.3, and 0.16 being the median value (Figure 7.6.1). After this period the index has remained at or above 0.3 with a maximum value of 1.1 occurring in 2007. This index shows that since 2004 *P. cygnus* has displayed a precocious spawning in six of the nine years (Figure 7.6.1).

The standardised proportion of mature female lobsters still carrying external eggs towards the end of the spawning season (January-March) ranged between 0.14 and 0.27 with a median value of 0.2 from 1991 to 2006 (Figure 7.6.2). After 2006 four of the time-series earliest completions to spawning (lowest points) were recorded, in 2007, 2008, 2011 and 2012 (Figure 7.6.2).

A significant ($p = 0.019$) inverse relationship exists between these two time-series with an earlier onset of spawning correlating with an earlier completion of spawning later in that spawning season (Table 7.6.1, Figure 7.6.3).

The apparent change in the above two indices in the mid-late 2000s is similar in timing to when the puerulus settlement began to be consistently below average and the relationship between puerulus settlement and the off-shore water temperatures (which is influenced by the Leeuwin Current) began to fail. There is a significant ($p = 0.003$) relationship between the timing of spawning and the magnitude of puerulus settlement, with the onset of spawning being by far the most significant factor in this relationship ($p = 0.001$) while the timing of completion adding little to the overall model (Table 7.6.2, Figure 7.6.4). The year with the lowest puerulus settlement (2008/09) is associated with the year with the earliest onset of spawning in 2007.

The variation shown in the onset of spawning between years is presumably due to variation in one or more of the environmental cues used by this species to initiate reproduction. The most likely cues for the onset of spawning are associated with water temperature; either its magnitude at a given time, the timing of reaching a threshold or the timing or rate of increase when water temperatures begin to warm after winter. These factors were examined and the magnitude of bottom water temperatures in some months prior to and during spawning (averaged across the breeding grounds; water depths 20–100 m between latitudes 29 and 33°S) showing a strong relationship with the timing of the onset of spawning (Figure 7.6.5). This relationship first started to form with August water temperatures, rapidly increased to maximum value in October before declining slightly in November and December (Figure 7.6.5).

The magnitude of water temperatures in October throughout this region were averaged to develop an index representing breeding ground water temperatures during the start of the spawning season. This index remained relatively constant from 1992 to 2003, between 17.4 and 18.8°C, before a shift occurred in 2004 with all but one of the subsequent years being greater than 19°C (Figure 7.6.7). The relationship between the bottom water temperature and timing of the onset of spawning was highly significant with water temperatures greater than about 19°C appearing to be related to a precocious onset to spawning (Table 7.6.3; Figure 7.6.7).

The oceanographic larval model identified the timing of spawning as an important factor affecting puerulus settlement. When the larval release was focused on the early months in the model it provided the best fit of the model settlement to the actual puerulus settlement.

Examination of the timing of the start of the spawning period using the fishery-independent breeding stock survey has indicated that in recent years there has been an earlier start to the spawning season compared to previous years. This appears to be associated with water temperatures during the start of the spawning period being warmer in recent years. This may be a contributing factor as to why the recent years have a consistent below-average settlement. The mean October water temperature in 2011 was again above average and the timing of the onset of spawning was the second earliest of that time series (Figure 7.6.7). The effect of this on the 2012/13 puerulus settlement is expected to be negative with settlement measured to date (December 2012) being below average (Figure 7.6.4). The timing of the onset of spawning in the 2012 survey was for a relatively late start compared to the last nine years but earlier than any of the years before 2003. The effect of this will be assessed in the 2013/14 settlement season. The effect that an earlier start to the spawning season has on the larval development and movement and subsequent effect on the puerulus settlement is being examined using the oceanographic larval model.

Table 7.6.1. Linear model between standardised annual indices of the onset (October) of spawning and completion (February) of spawning. $R^2 = 0.267$

Coefficients					
	Estimate	**Std. error**	**DF**	**T value**	**Probability**
Intercept	0.225	0.0194		11.574	< 0.001
Completion of spawning	-0.111	0.0433	18	-2.561	0.019

Table 7.6.2. Linear model between the log of a standardised index of puerulus settlement (all sites) and the standardised indices of the onset and completion of spawning. $R^2 = 0.503$

Coefficients					
	Estimate	**Std. error**	**DF**	**T value**	**Probability**
Intercept	5.571	0.956		5.771	< 0.001
Onset of Spawning	-3.423	0.859		-3.984	0.0011
Completion of Spawning	-4.909	4.117	16	-1.192	0.2505

Table 7.6.3. Linear model between the bottom water temperatures in the breeding grounds between latitudes 29 and 33°S and the standardised timing of onset of spawning. $R^2 = 0.341$.

Coefficients					
	Estimate	**Std. error**	**DF**	**T value**	**Probability**
Intercept	-4.122	1.519		-2.713	<0.015
Water temperature	0.239	0.081	17	2.966	0.008

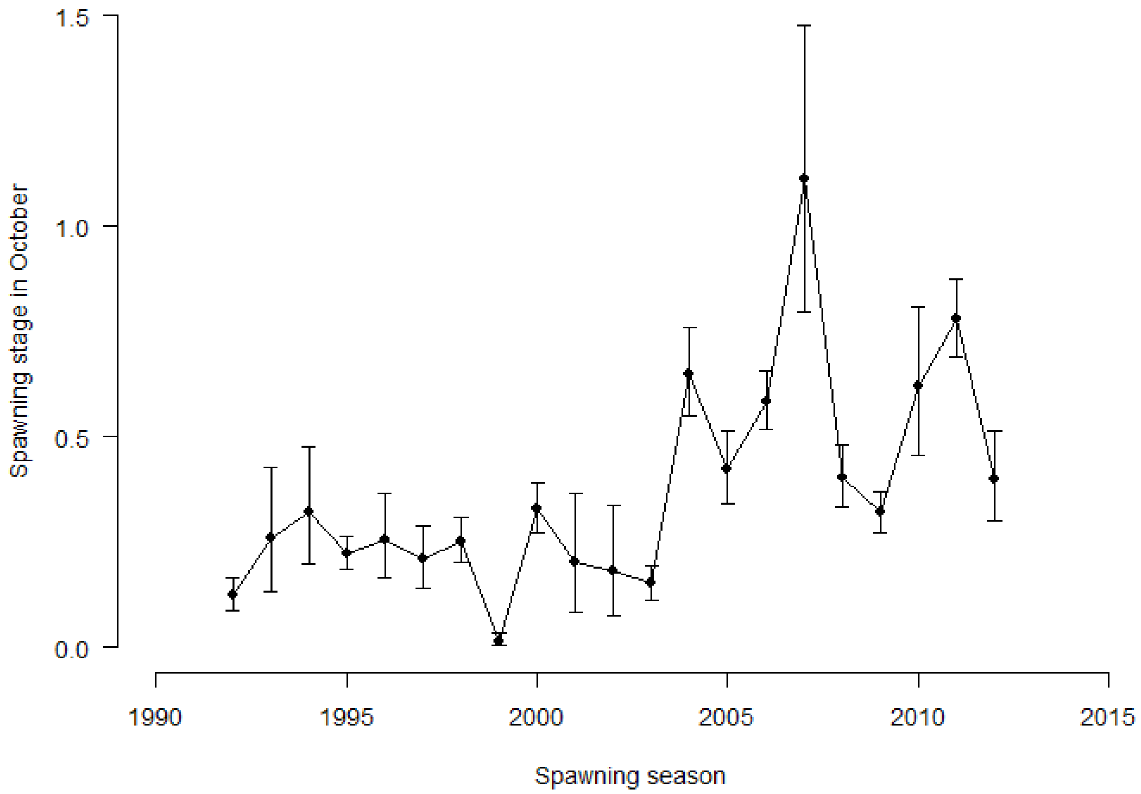


Figure 7.6.1. Standardised mean (± 1 se) breeding stage of mature females during the IBSS. A higher value indicates an earlier start to spawning.

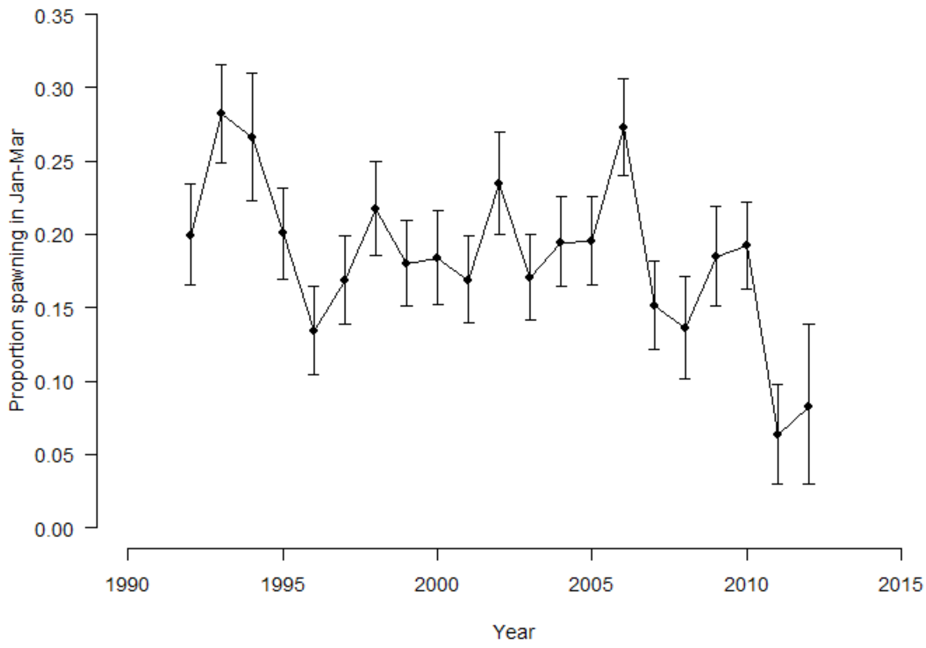


Figure 7.6.2. Standardised mean (± se) proportion of breeding females at the end (January-March) of the breeding season recorded during the monitoring of commercial fishing.

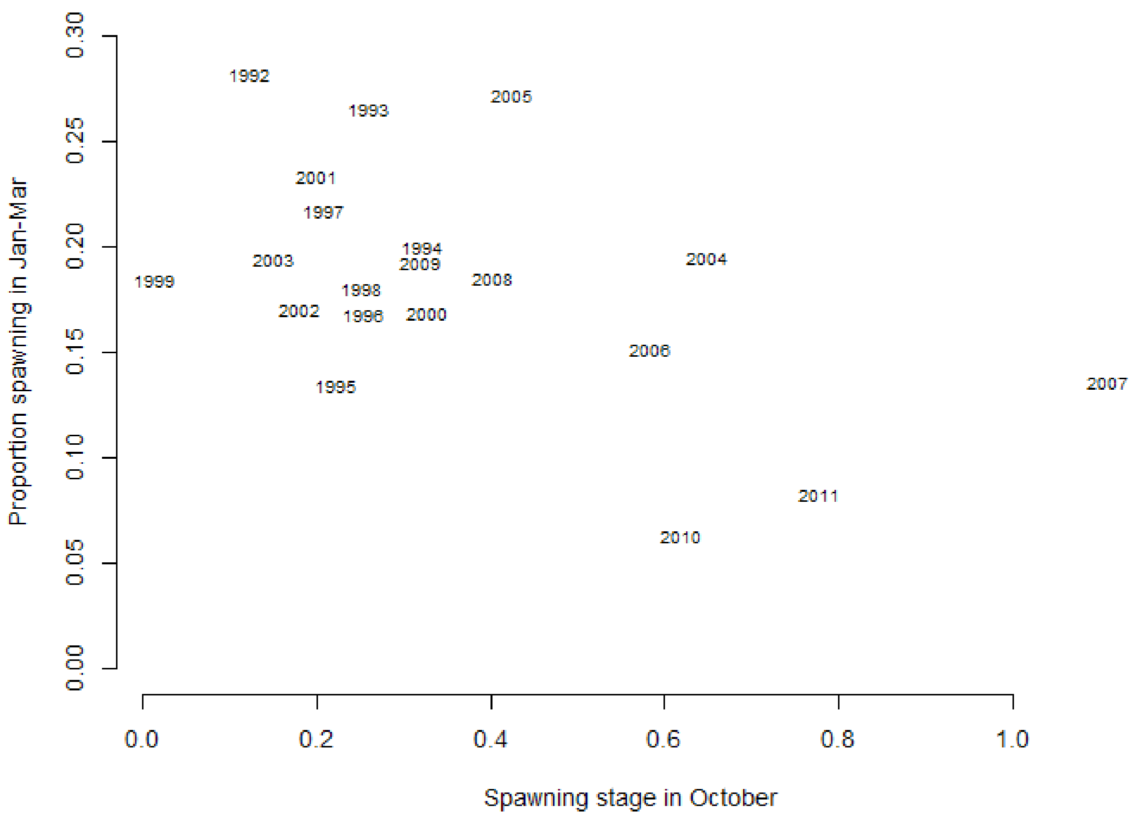


Figure 7.6.3. Standardised annual mean breeding stage of mature females at the start of the spawning season (October) and the standardised proportion of mature females spawning at the end of the spawning season (January – March).

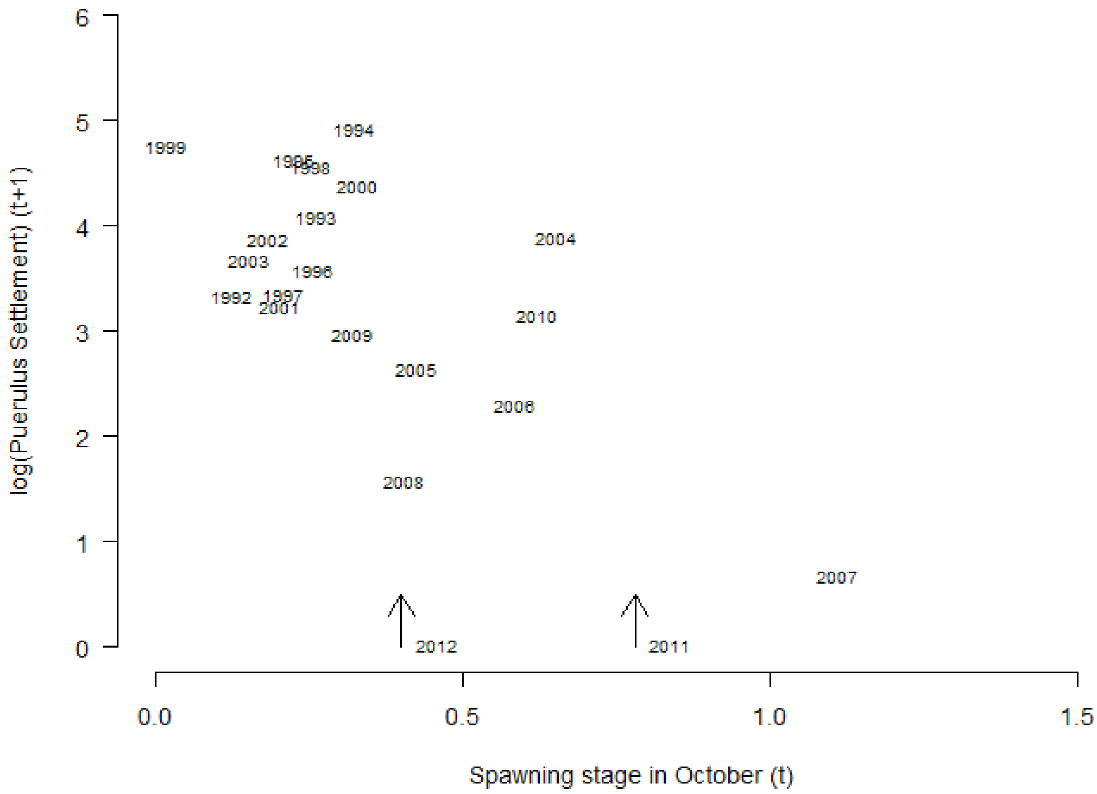


Figure 7.6.4. Standardised mean breeding stage of mature females during the IBSS and the log of a standardised index of puerulus settlement (all sites). Years represent the start of the spawning year (e.g. 2007) with the puerulus settlement occurring the following year (e.g. 2008/09). The arrows represent the observed October spawning stages in 2011 and 2012 IBSS.

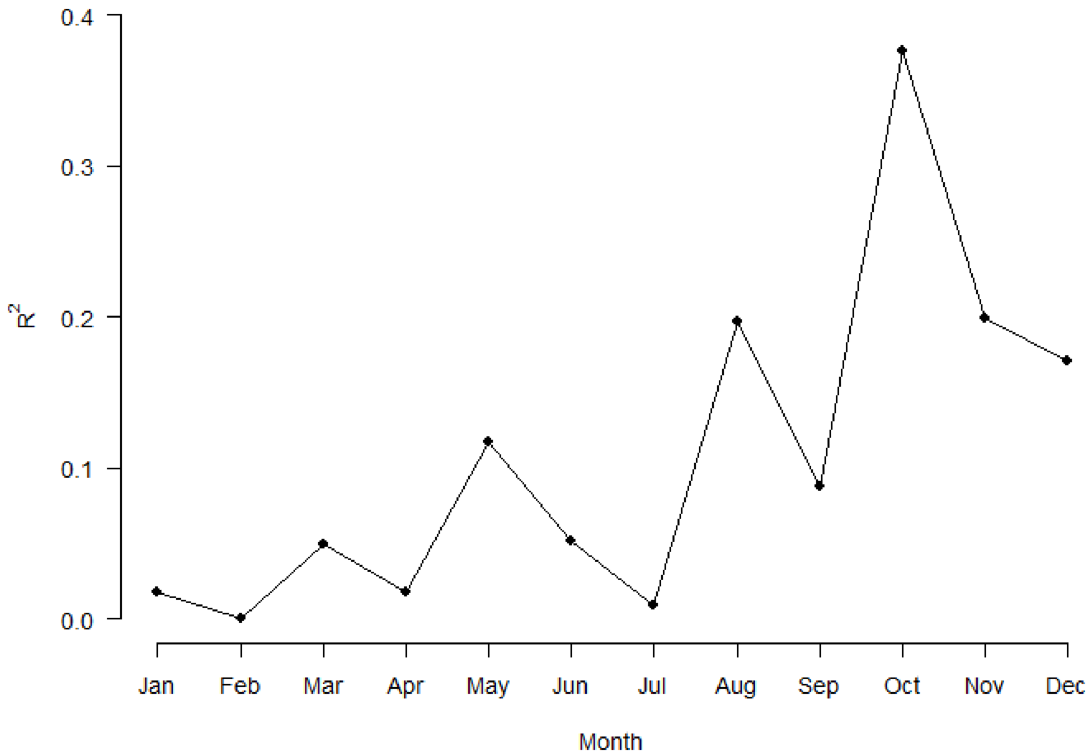


Figure 7.6.5. R-squared values from the relationship between bottom water temperatures throughout the breeding grounds (20–100 m depth and between latitudes 29 and 33°S) and the timing of the onset of spawning.

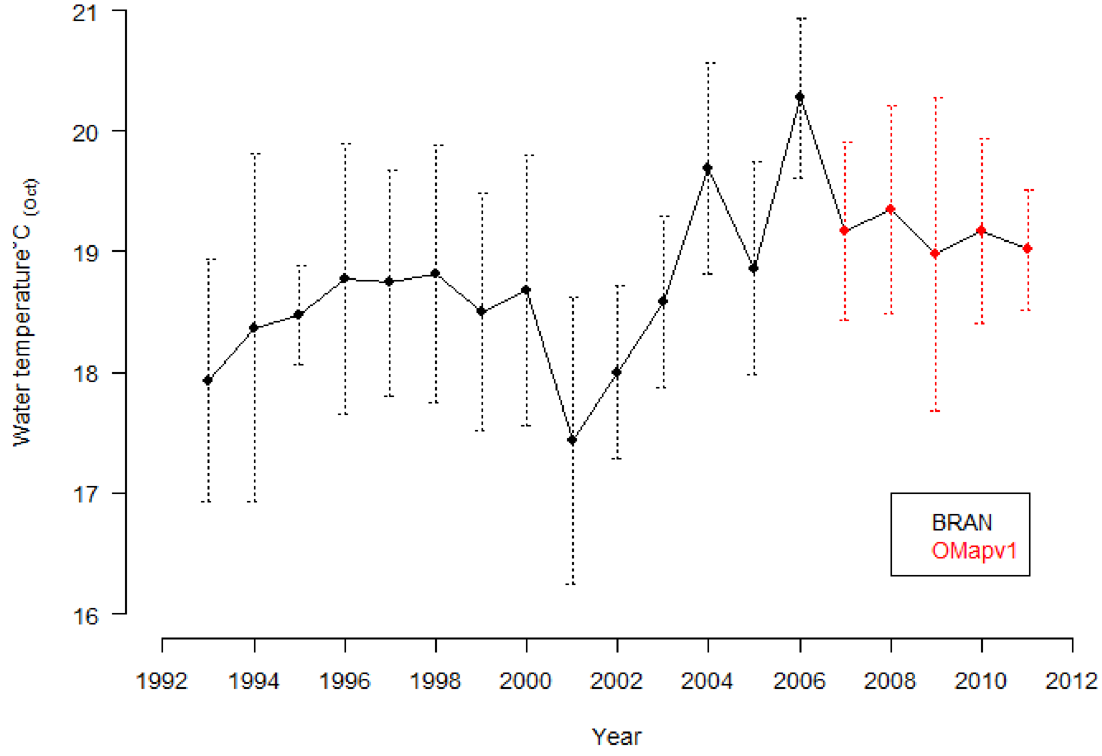


Figure 7.6.6. Mean (± 1 SE) sea floor water temperatures for October in the breeding grounds between latitudes 29 and 33°S. Water temperature data is derived from two oceanographic models, BRAN (Black) and OceanMaps.v1 (Red). The trend of 0.06°C per year since the early 1990s is significant (P = 0.015).

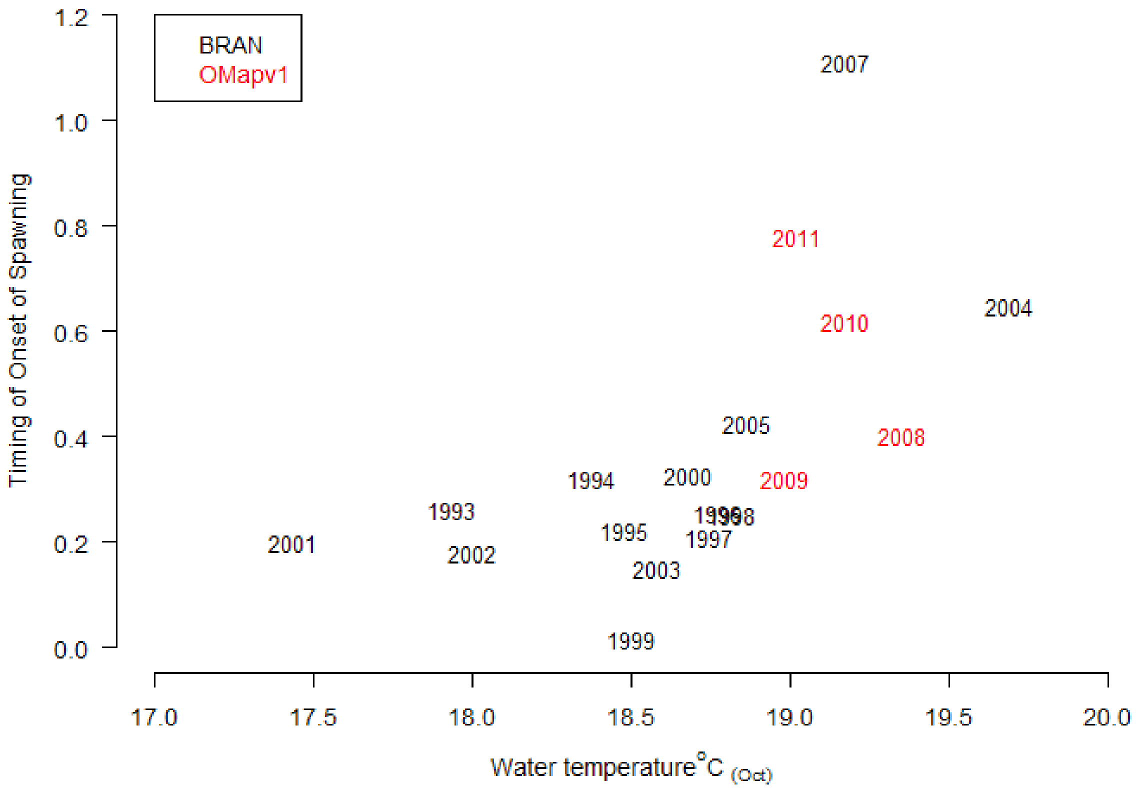


Figure 7.6.7. Relationship between the bottom water temperature in the breeding grounds during October and the timing of the onset of spawning (mean egg stage) during the IBSS. Years represent the start of spawning year (e.g. 2006 represents the 2006/07 spawning year that contributes to the 2007/08 puerulus settlement). Water temperature data is derived from two oceanographic models, BRAN (Black) and OceanMaps.v1 (Red).

7.7 Stock-recruitment-environment relationship

Egg production: fishery-independent breeding stock surveys

The overall trend in egg production estimated from the IBSS indicates an increase from the early 1990s to the mid to late 1990s which was probably as a result of the major management changes introduced in 1993/94 involving effort reductions and increased protection of mature females. Then there was a general decline in the 2000s until about 2007 followed by a sharp increase from about 2008. The second increase reflects the significant reductions in nominal fishing effort of 44-73% of the 2007/08 levels that started in 2008/09. This has resulted in the level of egg production estimated from the IBSS in October 2010 being at relatively high levels and levels in the most recent surveys (2011 or 2012) being at record high levels in all locations (Figure 7.7.1 and 7.7.2).

The Big Bank surveys in 2010, 2011 and 2012 showed a significant improvement in lobster abundance and egg production compared to the first survey undertaken in 2009. This is due to the closure of Big Bank since 2009 and a conservative harvesting strategy in the rest of the fishery since 2008/09 that allows greater numbers of lobsters to migrate into this area (Figure 7.7.2).

The very high level of breeding stock sampled in 2011 will influence the 2012/13 puerulus settlement (which started in August 2012) and may provide some insights on the effect of breeding stock during this period of low settlement. Puerulus settlement estimates to date (December 2012) indicate another year of well below-average settlement. This indicates that egg production alone is unlikely to be the cause of the recent downturn in puerulus settlement.

Egg production: stock assessment model

The egg production from the stock assessment model shows similar trends to that from the IBSS with an increase in the late 1990s, followed by a decline during the early and mid 2000s, and an increase in the late 2000s as a result of the recent management measures (Figure 7.7.3). The projected egg production after 2010, assuming that the legal proportion harvested remains at 0.5, shows that egg production should be maintained or increased from the current high levels.

Stock-recruitment-environment relationship

We examined the relationship between a coast-wide index of puerulus settlement and egg production (from stock assessment model) and factors previously shown to be related to recruitment levels; sea-surface temperatures (SST) from an offshore block in February (see Section 6.5), rainfall during the period before and during settlement (see Section 6.5) and the timing of the onset of spawning (see Section 6.6). Combinations of spawning stock and these variables are examined to determine which model provides the best fit to the puerulus settlement (Table 7.7.1).

The best single variable that explains the puerulus variation since the early 1990s was the natural logarithm of egg production ($R^2 = 0.45$; $P<0.01$) (Table 7.7.1). The relationship between puerulus settlement and egg production was however not 'biologically sensible' as it suggested that increases in egg production resulted in an exponential increase in puerulus settlement. This significant relationship between this factor on its own and puerulus was therefore considered to be spurious. The factor that explained the second greatest amount of variation in egg production was the spawning stage index in October ($R^2 = 0.43$; P<0.01). This relationship showed that a large spawning stage index during the independent survey, which represents an earlier start to spawning, results in a decline in puerulus settlement (Figure 7.6.4).

The two-factor model that described the greatest amount of the variation in puerulus settlement contained the factors of spawning stage index in October and rainfall ($R^2=0.72$; p<0.001) (Table 7.7.1). This model displayed the same exponential decay relationship with increasing spawning stage and rainfall having a positive impact on puerulus settlement (Figure 7.7.6).

The combination of breeding time with monthly rainfall was examined for each month (January to December) of the larval period prior to and during the settlement period to determine which months may be critical. The May-July period appeared to be most important followed by October (Figure 7.7.4). The rainfall time series that covers both these periods, i.e. May-October has been used in the relationship with puerulus settlement. The rainfall during this period shows a declining trend since the early 1990s with the four of the lowest values occurring in last seven years (Figure 7.7.5). This decline is part of a long-term trend of declining rainfall in the south-west of Western Australia that has intensified in the last 10 years (Indian Ocean Climate Initiative 2012). Previous studies have identified rainfall during July to November as being a significant factor affecting puerulus settlement up to the early 1990s (Caputi and Brown 1993, Caputi *et al*. 2001). However in this study the rainfall that includes an earlier period of May-June provided a better fit to the puerulus settlement since the early 1990s. The rainfall represents an index of storms affecting the lower west coast of WA. These storms influence the water conditions and are generally associated with westerly winds that may help bring the larvae back to the coast.

The three-factor model that described the greatest amount of the variation in puerulus settlement was that which contained the factors, spawning stage index in October, rainfall and offshore SST in February (R^2=0.84; $p<0.001$) (Table 7.7.1). However the SST was only significant as an interaction with rainfall. This model again displayed the same exponential decay relationship with increasing spawning stage with both rainfall and SST having positive impacts on settlement (Figure 7.7.7).

While there are other combinations of spawning stock and environmental variables that are significant they generally have a lower R^2 than the above relationship using spawning stage and rainfall, or are not as parsimonious.

The key points of this assessment of possible biological and/or environmental factors affecting the recent years of low settlement are:

- The long-standing levels of fishing when combined with a run of environmental conditions unfavourable for the northwards migration of the whites, led to a subsequent reduction in mature lobsters and therefore egg production at the northern end of the fishery (e.g. northern Abrolhos Islands and Big Bank).
- The management actions undertaken to influence future recruitment levels were (a) to increase the egg production in the northern areas and deeper waters, through a reduction in the harvest rate of animals moving into these areas (e.g. reduce exploitation on animals that are or will migrate); and (b) by increasing protection of animals that do move into this area or are already resident there (e.g. through closed areas, reducing the maximum size of females). This approach also ensured a carryover of legal lobsters into years of low recruitment.
- The early management intervention has resulted in a record level of breeding stock in 2011 (which was maintained or improved in 2012) and its effect on the 2012/13 puerulus settlement (starting in August 2012) provides some insight on the effect of breeding stock on settlement. Preliminary indications are that the puerulus settlement will again be below average in 2012/13. This would confirm that spawning stock is not the dominant factor that has affected the recent decline in puerulus settlement.
- A key factor in the decline in puerulus settlement appears to be an earlier onset of spawning that has occurred in recent years that may be related to an increase in bottom water temperature at the time of spawning (Section 7.6).
- The reasons why an earlier onset of spawning would result in a lower settlement need further examination. A likely mechanism for earlier spawning causing lower settlement is that the earlier spawning causes a mismatch with other environmental factors such peaks in ocean productivity and/or advent of westerly winds that assist the larvae return to the coast. The oceanographic larval model outputs that take these wind driven water flows into account and has simulated lower settlement in the recent years adds support to this hypothesis.
- The onset of spawning combined with rainfall (as a proxy for storms affecting water conditions and westerly winds) during May-October explains a significant proportion (0.72) of the variation in puerulus settlement since the early 1990s and provides a plausible hypothesis to explain the decline in puerulus settlement in recent years. This relationship needs to be verified with additional years of data to see whether the relationship is maintained in the long-term. The 2012/13 settlement provides the first test of this relationship and

preliminary indications are that it will be below average which is what is predicted by the two environmental variables (Figure 7.7.6).

- The spawning stage in the 2012 surveys indicates a later onset of spawning compared to recent years which will provide another useful test of the relationship with the 2013/14 settlement.

Table 7.7.1. Summary of a linear models between the logarithm of puerulus settlement and different combinations of covariates such as the logarithm of egg production, the timing of the onset of spawning and SST (February) and a factor that represents a temporal shift in the 2006/07 puerulus season as well as some interaction between the variables. The puerulus settlement seasons from 1993/94 to 2011/12 are examined. ns=not significant *=p<0.10, **=p<0.01 ***=p<0.001

Log (stock) (a)	October Spawning stage (b)	SST (Feb) (c)	Rain (May-Oct) (d)	a x b	a x c	a x d	b x c	b x d	c x d	R^2
8.95**										0.45**
	-2.98 **									0.43**
		0.12 ns								0.01
			0.0164ns							0.12
4.16	-50.26			6.68						0.62***
-74.34		-25.4			3.47					0.51*
30.66			1.92				-0.26			0.55**
	23.71	0.74					-1.10			0.48 **
	-3.38***		0.03***							0.72***
		-0.64	-0.13						0.01	0.20
		0.65 *		13.1 **			-1.2			0.73 ***
50.87	-65.47	15.78		11.96	-2.09		-0.95			0.60**
25.91	-51.49		2.00	7.07		-0.27		-0.02		0.81***
	7.28	-2.78*	-0.94**				-0.99	0.15*	0.04**	0.84***

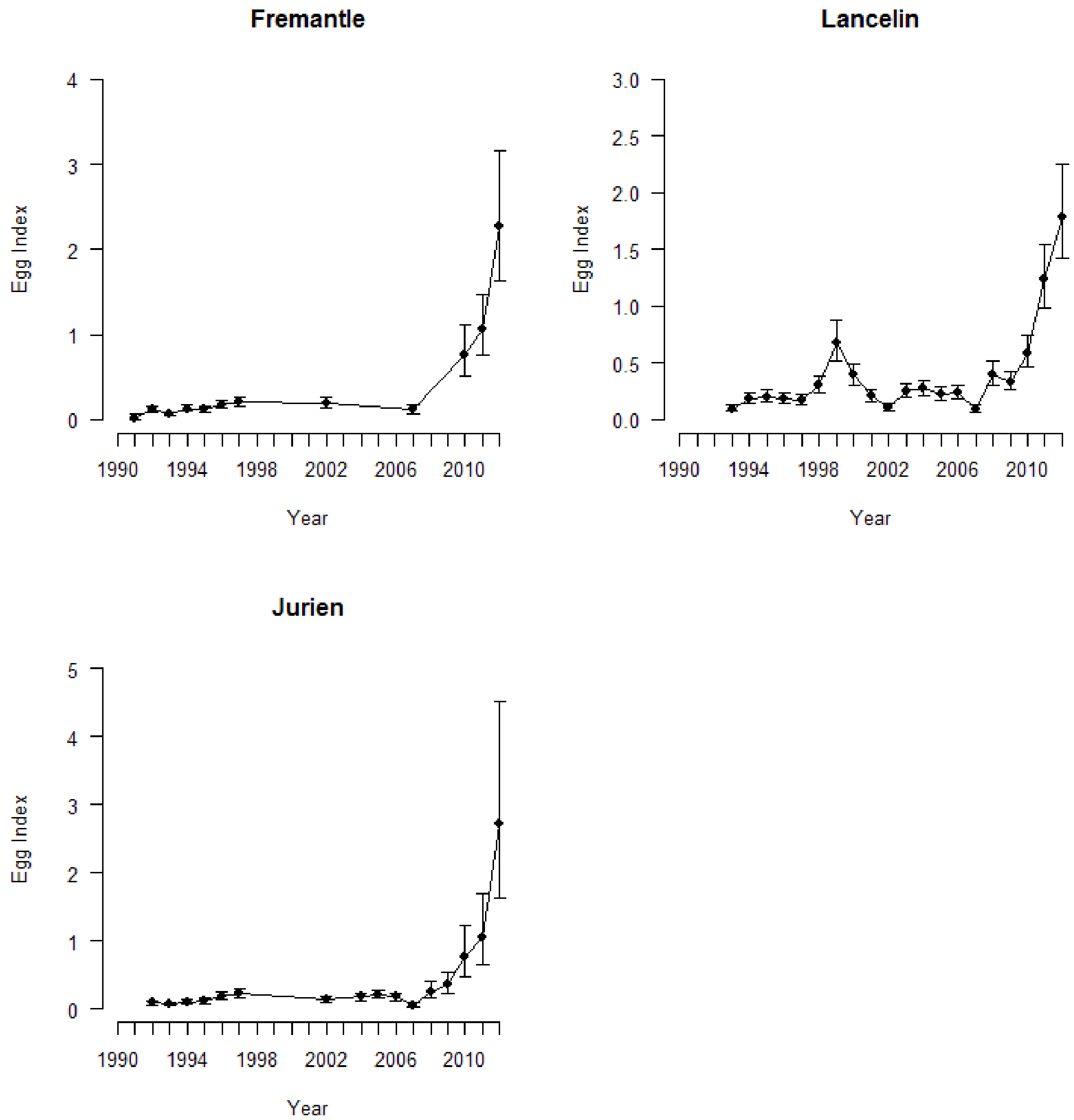


Figure 7.7.1. Fishery-independent breeding stock survey egg production indices for three sites in the southern zone of the western rock lobster fishery.

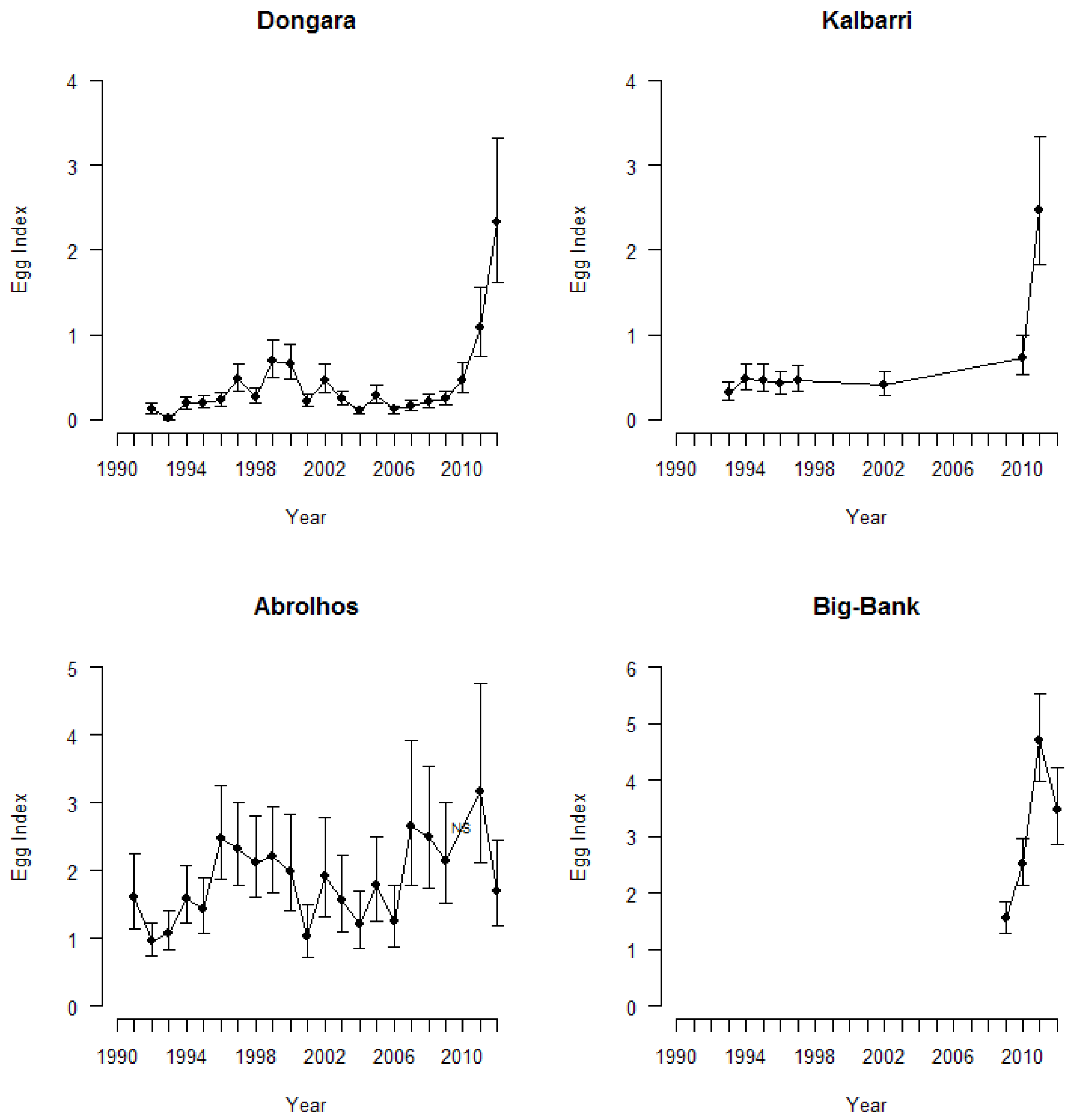


Figure 7.7.2. Fishery-independent breeding stock survey egg production indices for four sites in the northern region of the western rock lobster fishery. Note that Kalbarri was not conducted in 2012.

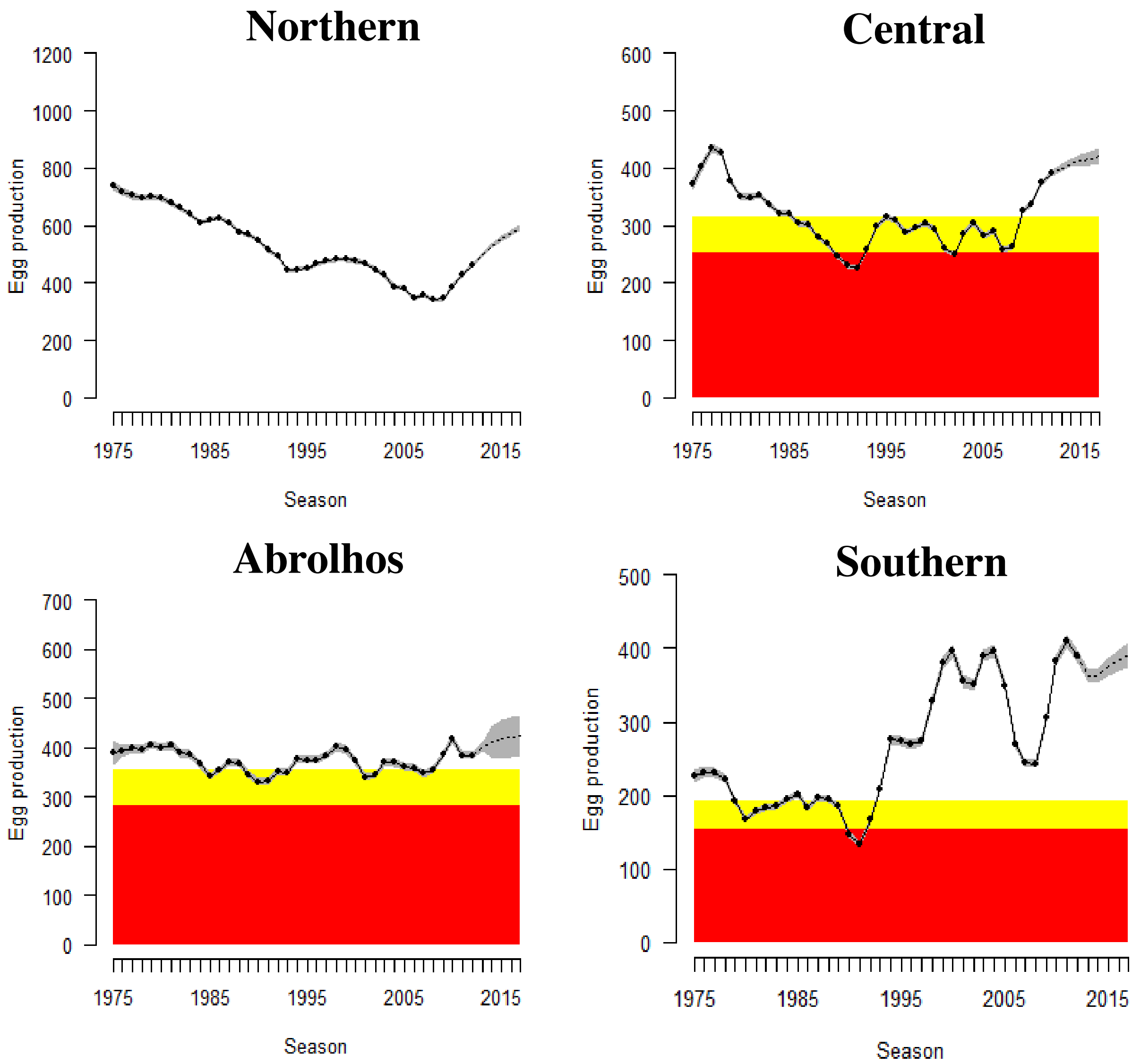


Figure 7.7.3. Stock assessment model egg production indices for four regions of the fishery (see Figure 6.8.1). The threshold (yellow) and limit (red) reference regions for the management decision rules are indicated. The projected egg production after 2011 assumes that the future Legal Proportion Harvested will remain at 0.5.

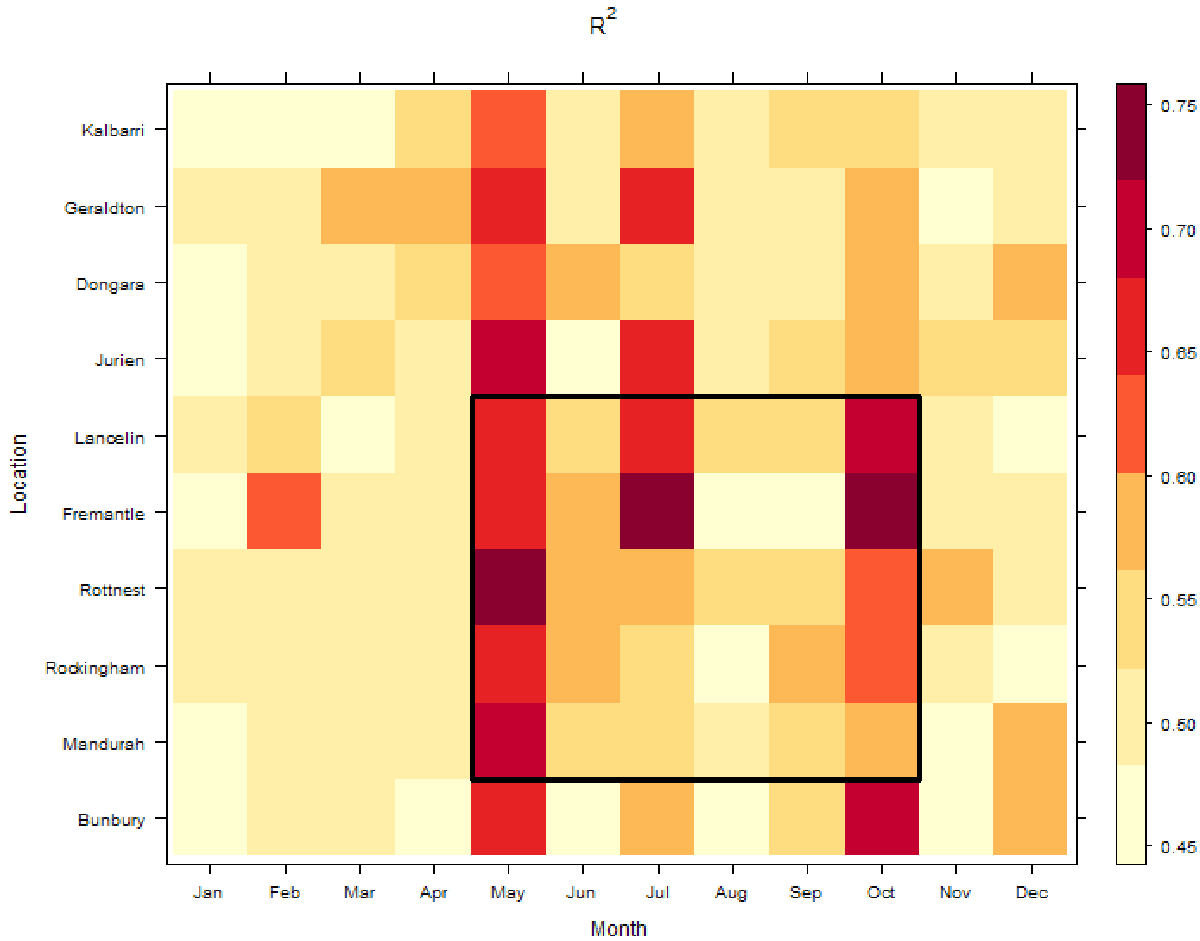


Figure 7.7.4. R-square values for the relationship between the magnitude of puerulus settlement and the factors of spawning stage in October and monthly rainfall in January to December at 10 separate coastal locations throughout the fishery. The black rectangle identifies the location and months chosen to develop an annual rainfall index.

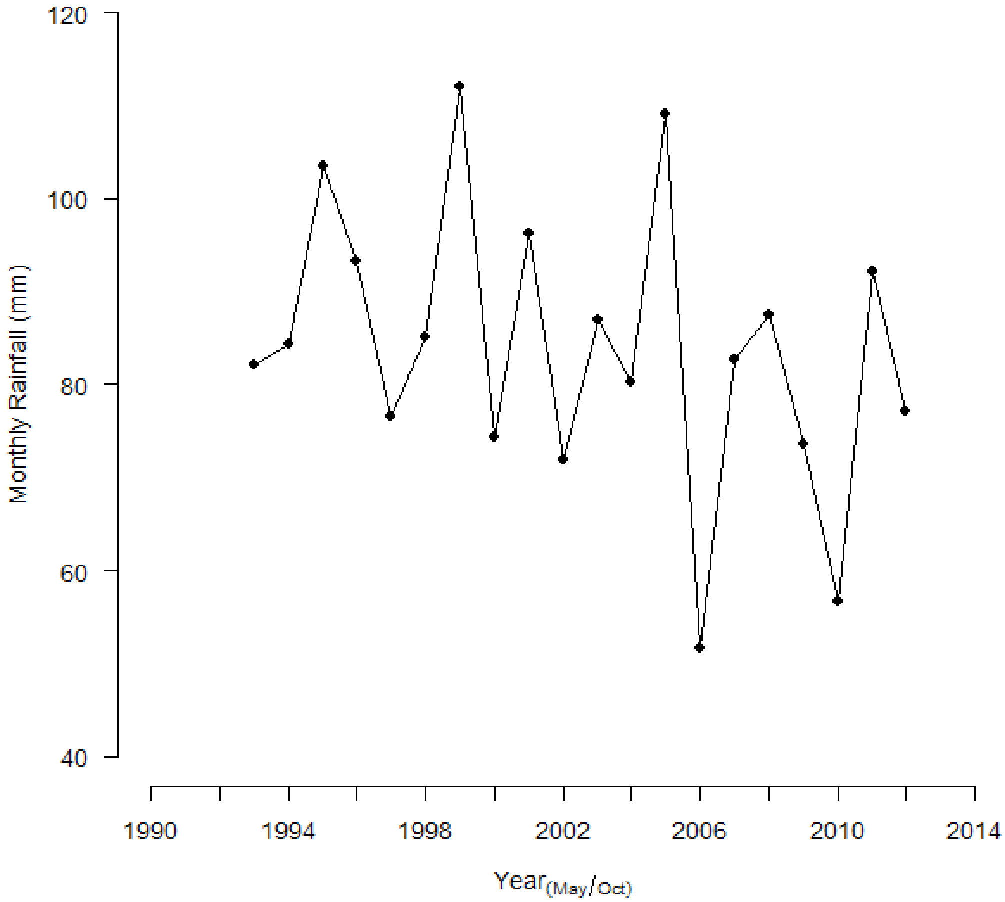


Figure 7.7.5. Average monthly rainfall for five coastal sites between Lancelin and Mandurah from May-October since 1993. The decline over this period (1.04 mm $year^{-1}$) was not significant ($P = 0.08$).

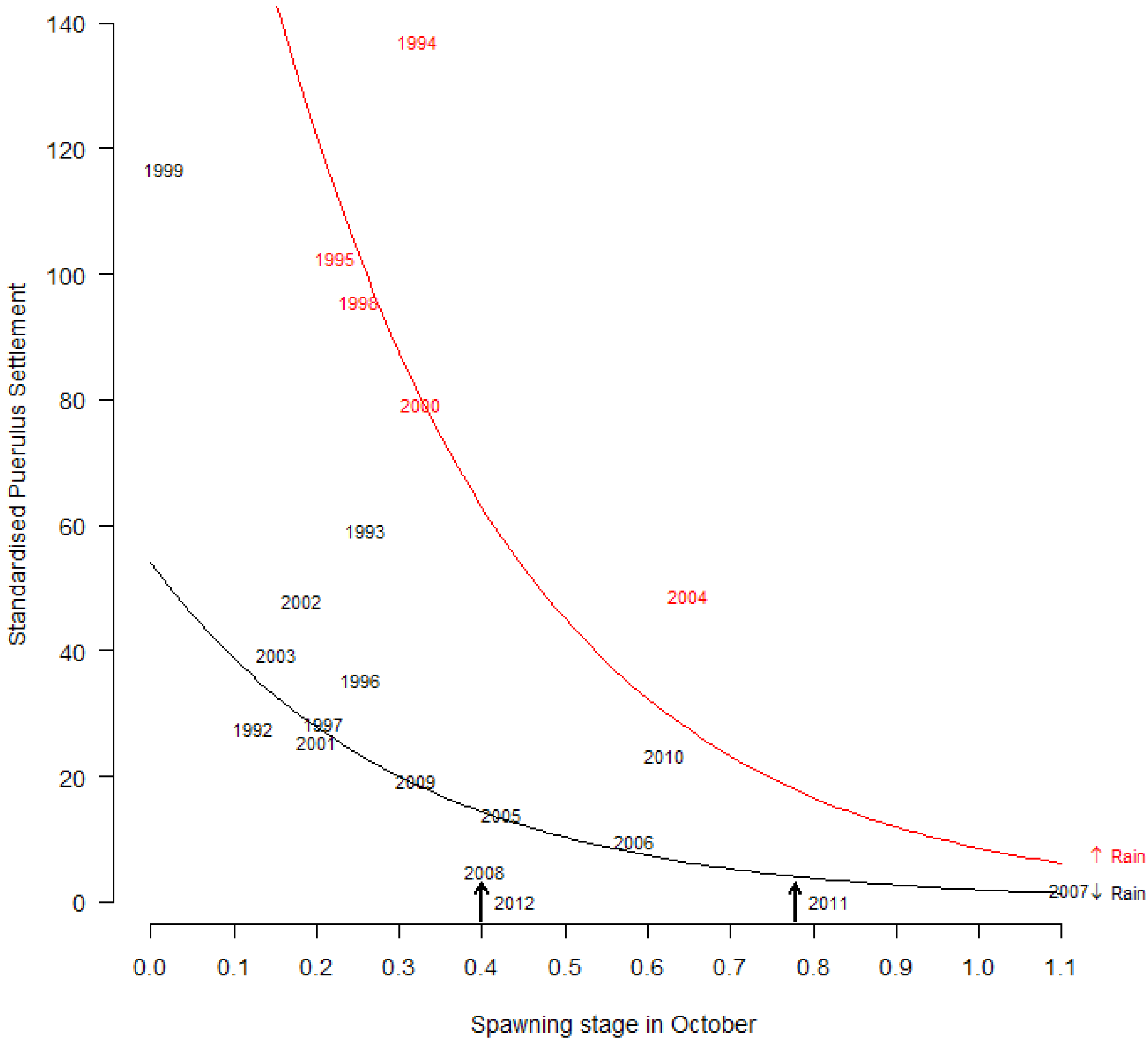


Figure 7.7.6. Standardised mean breeding stage of mature females during the independent breeding stock survey and a standardised index of puerulus settlement (all sites). The red and black values identify years classified as having high (95-120 mm) or low (50-90 mm) monthly rainfall from May-October. Years represent the start of the spawning year (e.g. 2007) with the puerulus settlement occurring the following year (e.g. 2008/09). The spawning stage for 2011 which will influence the 2012/13 settlement is shown.

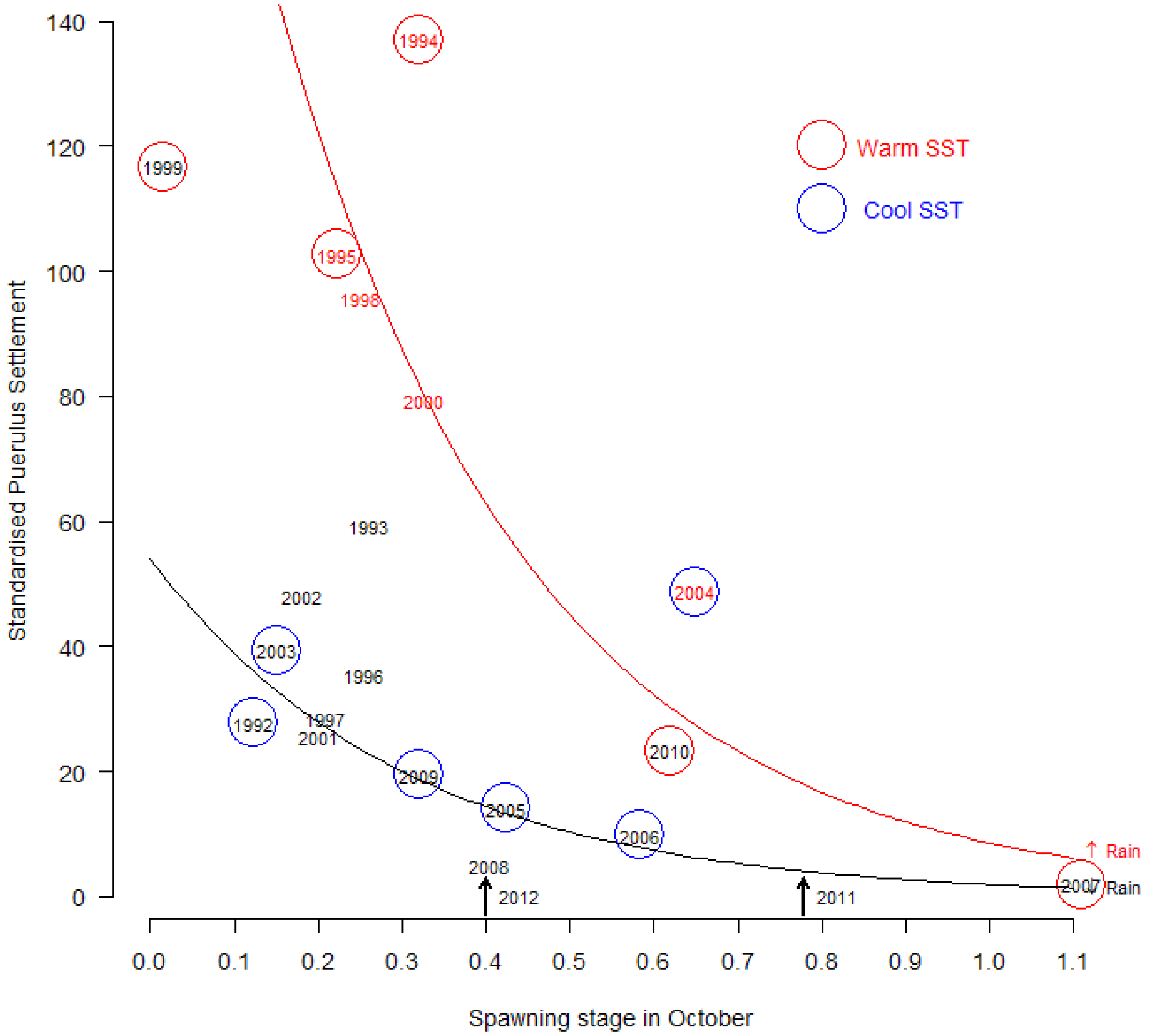


Figure 7.7.7. As for figure 7.7.6 with additional classification of years to identify when the offshore sea surface water temperatures (25-28°S, 109-112°E) were above (red circle) or below (blue circle) average.

7.8 Climate change effects

A paper summarising the climate change effects affecting the rock lobster fishery has been completed (Caputi *et al*. 2010). This section examines climate change trends for the Leeuwin Current and other environmental factors (water temperatures and rainfall) possibly affecting puerulus settlement. Environmental factors that may indirectly affect puerulus settlement via their effect on the whites migration and timing of onset of spawning are also considered.

Leeuwin Current

The Leeuwin Current has historically been identified as a key factor affecting the level of puerulus settlement and the migration of lobsters therefore understanding its long-term trend is important. The long-term trend of the Leeuwin Current is essentially driven by the variations and changes of Pacific equatorial easterly winds: the Leeuwin Current has experienced a strengthening trend during the past two decades, which has almost reversed the weakening trend during 1960s to early 1990s (Figure 7.8.1, Feng *et al*. 2010, 2011a). Currently, most climate models project a weakening trend of the Pacific trade winds and a reduction of the Leeuwin Current strength (as well as the Indonesian Throughflow) in response to greenhouse gas forcing over the next century (Figure 7.8.2). Whereas the greenhouse gas forcing induced changes may be obvious in the long-term climate projection, e.g. 2100, for assessment of short-term climate projection, e.g. 2030s, natural decadal climate variations still need to be taken into account (Feng *et al*. 2012).

From a downscaling model simulation, water temperature may increase by ~1°C in the next 50 years; in the meantime the strength of the Leeuwin Current may reduce by ~15% (Sun *et al*. 2012; Chamberlain *et al*. 2012). An examination of the eddy energetics in the downscaling model suggests that the eddies will be less energetic in the future climate, due to the reduction of the Leeuwin Current strength, which may also affect the ocean primary production in the region (Matear *et al*. in preparation).

Water temperature

Water temperature has been shown to affect a number of aspects of the life history of the western rock lobster, particularly during the spawning and larval stages. Historically there has been a positive relationship between puerulus settlement and water temperature during the early larval stages, February to April (Caputi *et al*. 2001). However this relationship has broken down in recent years (Figure 7.4.3).

In this study the bottom water temperature on the spawning grounds near the start of spawning (about October) has been identified as a factor that may be influencing the timing of the onset of spawning. Increases in water temperature in October since the mid-2000s may have resulted in an earlier onset of spawning that has coincided with the decline in puerulus settlement since 2006/07.

Studies on historic water temperature trends in Western Australia have identified the lower west coast of Australia as a hotspot for water temperature increases over the last 40-50 years (Pearce and Feng 2007). Increases were found to be particularly high in the austral autumn-winter period with little or no increases evident in the spring-summer period (Caputi *et al*. 2009). However the bottom water temperature in the spawning area during October obtained from oceanographic models shows a possible increasing trend since the early 1990s (Figure 7.6.6). This increase may reflect the increase in the strength of the Leeuwin Current since the early 1990s which has been described as a possible decadal climate change variation (Figure 7.8.1, Feng *et al*. 2010) or it may reflect an extension of the general increase in water temperature that has been described for the lower west coast of Australia (Pearce and Feng 2007, Caputi *et al*. 2009). These two possible scenarios may have important long-term implications for the rock lobster fishery since the water temperature increases under the first scenario may be expected to revert back to previous levels under periods of weaker Leeuwin Current (Feng *et al*. 2012). However under the latter scenario, long-term increases of water temperature would not be expected to be reversed in the near future.

Rainfall

Previous studies have identified rainfall during July to November as being a significant factor affecting puerulus settlement (Caputi and Brown 1993, Caputi *et al*. 2001). However in this study the rainfall during a slightly earlier period of May-October when combined with the breeding time index has provided a good fit (R^2=0.72) to the variation in puerulus settlement since the early 1990s including the recent years of low settlement. Rainfall in this context is assumed to represent an index of storm activity affecting the lower west coast of WA. These storms influence the water conditions and are generally associated with westerly winds and Stokes drift that may help bring the larvae back to the coast (Feng *et al*. 2011b)..

The rainfall time series for May-October shows a declining trend since the early 1990s with the four of the lowest values occurring in last seven years (Figure 7.7.5). This decline is part of a long-term trend of declining rainfall in the south-west of Western Australia that has intensified in the last 10 years and is expected to continue (Indian Ocean Climate Initiative IOCI 2012). The IOCI (2012) study has demonstrated that storm development has reduced in the mid-latitudes but increased in the higher latitudes (50-70°S) with the net result of fewer storms affecting south-west WA.

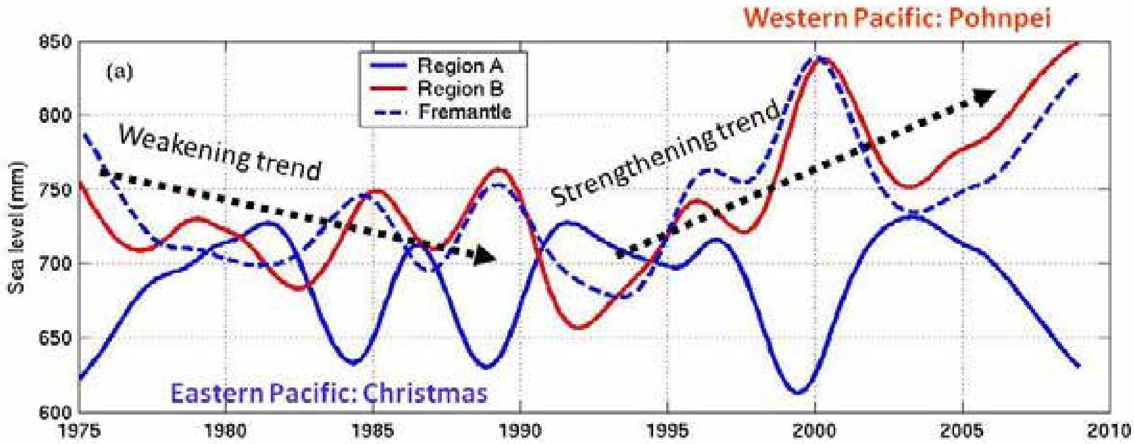


Figure 7.8.1. Low-passed filtered sea levels in the eastern (region A) and western Pacific (region B) and their relations with the Fremantle sea level (adapted from Feng *et al.* 2010). Fremantle sea level has been used as an index of the strength of the Leeuwin Current.

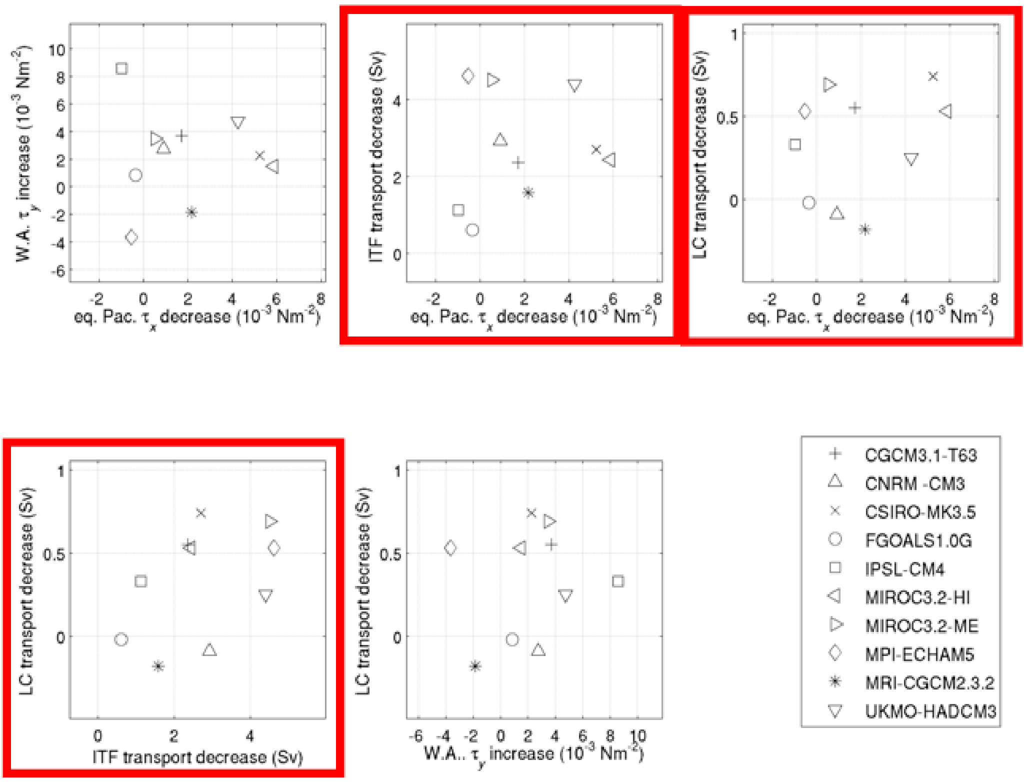


Figure 7.8.2. Relationships between future changes in climate model meridional wind off WA (WA T_y) and eq. Pacific zonal wind (eq. Pac T_x) components and Indonesian Throughflow (ITF) and Leeuwin Current (LC) transports during 2080-2099. Red boxes denote significant correlations (from Weller *et al.* unpublished result).

8.0 Benefits and adoption

The main beneficiaries of the study are the western rock lobster commercial and recreational fishers, industry, managers and scientists with the results of the project being presented to all these groups (see details below). The project has produced an improved oceanographic larval model that has provided a better understanding of the biological and environmental factors affecting the puerulus settlement. Sensitivity testing has been an important aspect of the project as it was used to improve the fit of the model puerulus settlement to the actual settlement. The project has undertaken a thorough assessment of the potential environmental factors affecting some key biological aspects such as pre-spawning migration, timing of spawning, phyllosoma stages and puerulus settlement. It has identified some changes in the environmental conditions that may explain the decline in puerulus settlement over the last six years. The interaction between the oceanographic larval modelling component of the project and the statistical component that assessed the environmental and biological effects on the puerulus settlement enabled some significant improvements in both components.

The benefits of the research to the management of the fishery include identification of the northern breeding stock as being depleted as a result of a low level of migration due to environmental conditions (Leeuwin Current) and fishing pressure. This resulted in the management closure of this area (Big Bank) in 2009 to protect the breeding stock which has resulted in a significant increase in egg production in the area. This study has also confirmed that previous short-term changes to the environmental conditions such as the strength of the Leeuwin Current that have historically been the dominant cause of the annual variation in settlement did not explain the current decline in settlement.

The assessment of the possible contribution of a long-term environmental factor(s) to the low puerulus settlement enables the stock assessment model to factor the low settlement into its assessment so that management and industry can take this into account in future planning. The fishery has been pro-active in its adaptation to the low puerulus settlement by implementing early management actions to reduce fishing effort and catch before the low puerulus year classes recruited to the fishery. This has resulted in spawning stock being protected from the effects of fishing on the low recruitment as well as achieving a carry-over of legal lobsters into the poor year-class years.

A report on a workshop reviewing the research in this project as well as related FRDC projects was undertaken in May 2011 (Brown 2011). The Marine Stewardship Council (MSC) has endorsed the certification of the western rock lobster fishery for another five years in 2012. The audit process included an examination of the research undertaken in this FRDC project to assess the cause of the low settlement as well as the management approach adopted to deal with the low settlement.

9.0 Further Development

The oceanographic larval model has improved considerably with its improved fit to the annual puerulus settlement data, however there are areas that can be examined for further development. These include:

- Improving the temperature-growth relationship to understand the effect of the record water temperatures during the heat wave event in 2011 on the spawning and larval phase and why the model settlement in 2011/12 was a significant outlier;
- Incorporating outcomes from the FRDC project 2011/018 'The biological oceanography of western rock lobster larvae' into the oceanographic larval model developed in this study to assess the effect water productivity and eddy structures may have on larval growth and survival;
- Understanding the cause of low settlement in the northern part of stock in the model compared to the good settlement observed near Shark Bay and Ningaloo;
- Improving the fit between the monthly model settlement with the actual settlement as the modelled data shows a quick drop in settlement after the peak settlement that does not properly reflect the actual distribution.
- Reducing the conflict in estimating the model parameters between early larval releases providing the best fit to overall settlement but not fitting the monthly distribution;
- Understanding the causes of the spike in model settlement at the Abrolhos that is not apparent in the actual settlement data.

The onset of spawning combined with rainfall during May-October explains a significant proportion (0.72) of the variation in puerulus settlement since the early 1990s and provides a plausible hypothesis to explain the decline in puerulus settlement in recent years. This relationship needs to be verified with additional years of data to see whether the relationship is maintained. The 2012/13 settlement provides the first test of this relationship and preliminary indications are that it will be below average which is what is predicted by the two environmental variables (Figure 7.7.6). The reasons why an earlier onset of spawning would contribute to a lower settlement need to be examined. It is possible that the earlier spawning causes a mismatch with other environmental factors such peaks in ocean productivity and/or westerly winds that assist the larvae return to the coast. The oceanographic larval model may provide some insights into the implications of an earlier onset of spawning.

The effect of the record level of egg production in 2011/12 on the puerulus settlement occurring in 2012/13 will also be assessed and may provide further evidence on the relative importance of environmental effects and spawning stock in explaining the decline in settlement.

When the onset of spawning was in the historic range until the mid-2000s, the Leeuwin Current and associated water temperatures offshore during February to April explained most of the annual variation in settlement. However since the spawning has been occurring earlier this historic relationship has not been significant. After the current settlement season, there will be 7 years of settlement data since the spawning has been occurring earlier and it would be interesting to see what factors are affecting the annual variation in this period. For example the monthly SST in offshore areas during December-January could be examined to assess if the SST in these earlier months are now significant with the spawning occurring earlier.

Some additional assessment of the potential climate change effects affecting the puerulus settlement will be undertaken as part of the FRDC project 2010/535 'Management implications of climate change effects on fisheries in Western Australia'.

10.0 Planned outcomes

The project outputs have contributed directly to planned outcomes. The progressive and final results of this project have been presented to industry, managers, scientists and community groups as follows:

- Presentations to industry and managers during the annual rock lobster tour meetings with the meetings in 2013 being held at six locations throughout the fishery, from Kalbarri to Fremantle.
- Presentations to scientists at the International Lobster Conference in Norway, University of WA, Curtin University, Notre Dame University, Murdoch University, Queensland Department of Primary Industry, Climate change conference in Melbourne, Marine Stewardship Council annual audit, ecological risk assessment workshop and Department of Fisheries (WA);
- Presentations to community groups in Busselton and Dunsborough;
- Published scientific papers (Feng *et al*. 2011, Weller *et al*. 2012) with others being prepared; and
- ABC Landline program and radio interviews;
- Popular articles in FRDC FISH magazine (June 2013) and Lobster Newsletter.

The key outcomes arising of this project include:

- An understanding of the relevant importance of breeding stock and environmental factors that have contributed to the below-average puerulus settlement for six consecutive years (2006/07 to 2011/12).
- The identification of the Big Bank breeding stock as being affected by a low level of migration due to environmental conditions and fishing pressure. This resulted in the management closure of this area in 2009 to improve the breeding stock and a fishery-independent survey has been implemented to monitor the stock trends.
- Some early management interventions to increase protection of the overall breeding stock through effort reduction, introduction of catch quotas, and reducing the maximum size of females. These management measures also ensured a carryover of legal lobsters into years of low recruitment.
- The oceanographic larval models examined indicated that breeding stock at all locations are important to the settlement so that it is important to maintain a healthy breeding stock throughout the fishery.
- The environmental factors, which could have contributed to the low puerulus settlement, may be influenced by climate change. This enables the managers and industry to take these potential longer-term effects into account in future management planning.

11.0 Discussion and Conclusions

This project achieved all three project objectives. Some of the key factors that have been identified in the previous chapters as potentially affecting the puerulus settlement, particularly the recent years of low settlement, are summarised in Table 11.1 with their relative values in recent years. Some key points arising out of this study under their relevant project objectives include:

Objective 1. To use a larval advection model and the rock lobster population dynamics model to assess the effect of the spatial distribution of the breeding stock on the puerulus settlement

- The previous oceanographic modelling suggested the northern part of the breeding stock may be important for successful larval production (Feng *et al.* 2011b). However the oceanographic larval models examined in this study indicated that breeding stock at all locations are important to the settlement and this distribution varied between models. It also identified the settlement in the northern area was underestimated and therefore the oceanographic modeling associated with the northern area needs further development.
- The oceanographic larval model identified the timing of spawning as an important factor affecting puerulus settlement. Spawning during the early period of spawning (October-November) provides a better fit to the puerulus settlement than spawning during the latter part of the spawning period. It provided a reasonable fit to variations in puerulus settlement in most years including the recent period of low settlement except for 2011/12 which was associated with the marine heat wave period which resulted in record high water temperatures during the spawning and early larval phase (November 2010 to March 2011).

Objective 2. To assess environmental factors (water temperature, current, wind, productivity, eddies) and breeding stock affecting puerulus settlement

- The puerulus settlement remained below average for the 2011/12 season, which represents the sixth season of below-average settlement. The sampling for the 2012/13 season (starting in August 2012 and up to December) also indicates another below-average season.
- The decline in settlement has been particularly strong in the early part of the settlement (August to October) with peak settlement in coastal locations in recent years occurring about two months later. The settlement peak at the Abrolhos has historically occurred later than the coastal locations and this has remained in December.
- The long-standing levels of fishing when combined with a run of environmental conditions unfavourable for the northwards migration of the whites, led to a reduction in lobsters and therefore egg production at the northern end of the fishery (e.g. northern Abrolhos Islands and Big Bank).
- The management actions undertaken to influence future recruitment levels were (a) to increase the egg production in the northern areas and deeper waters, through a reduction in the harvest rate of animals moving into these areas (e.g. reduce exploitation on animals that are or will migrate); and (b) by increasing protection of animals that do move into this area or are already resident there (e.g. through closed areas, reducing the maximum size of females). This approach also ensures a carryover of legal lobsters into years of low recruitment.
- Given the improvement in the breeding stock in coastal areas and Big Bank in recent years and the continued low level of settlement suggests that egg production is unlikely to be the main cause of the low settlement. There was a record level of breeding stock in 2011/12 and its effect on the 2012/13 puerulus settlement may provide further confirmation of the effect

of breeding stock on the current settlement decline. Assessment of the 2012/13 settlement to date (December 2012) indicates another low settlement season.

- Historic variations in puerulus settlement have been strongly associated with the strength of the Leeuwin Current (which is influenced by ENSO events) with good settlement being associated with strong Leeuwin Current and warm water temperatures during February-April. However there have been two years of strong Leeuwin Current in 2008 and 2011 (including the record water temperature in February 2011) and the settlement has remained below-average. Therefore these annual variations in the strength of the Leeuwin Current in February-April and associated water temperatures are not likely to be the main cause of the current low settlement.
- Examination of the timing of the start of the spawning period using the fishery-independent breeding stock survey has indicated that in recent years there has been an earlier start to the spawning season compared to previous years which appears to be associated with increasing bottom water temperatures in the spawning areas near the start of the spawning season in October. This may be one contributing factor as to why the recent years have a consistent below average settlement. The effect that an earlier start to the spawning season has on the larval development and movement and subsequent effect on the puerulus settlement is being examined using the oceanographic larval model.
- The onset of spawning combined with rainfall during May-October explains a significant proportion (0.72) of the variation in puerulus settlement since the early 1990s and provides a plausible hypothesis to explain the decline in puerulus settlement in recent years. This relationship needs to be verified with additional years of data to see whether the relationship is maintained. The 2012/13 settlement provides the first test of this relationship and preliminary indications are that it will be below average which is what is predicted by the two variables (Figure 7.7.6).
- Storms (measured by rainfall and associated with westerly winds) in late winter/spring have historically been shown to be positively related to puerulus settlement (Caputi and Brown 1993). They assessed the rainfall for the 22 years, 1969/70 to 1990/91 while the current study has examined the most recent 19 years, 1993/94 to 2011/12, as onset of spawning is only available for this period. The significance of winter storms in these two separate time periods covering over 40 years supports the importance of this factor on the settlement.
- Westerly wind patterns during the 2010/11 settlement season have been unusual, with the westerly component being far weaker than average. This is reflected by the second lowest winter/spring rainfall on record in 2010 with 2006 having the lowest rainfall on record. It is likely that this was adverse for the 2006/07 and 2010/11 puerulus settlement.

Objective 3. To examine climate change trends of key environmental parameters and their effect on the western rock lobster fishery:

- Taking into account the status of the breeding stock and variations in the Leeuwin Current and the fact that the settlement has remained low for an extended period, a long-term change in the environmental conditions may be the main cause of the recent levels of poor puerulus settlement. The increasing bottom water temperature that may be influencing the start of spawning and the decline in winter storms are probably both influenced by long-term climate change trends that may continue to affect the settlement into the future. These will need to be closely monitored.

The early spawning combined with the reduced storm activity (particularly during early winter) during the larval phase may have created a mismatch with the peak in food availability for metamorphosis and/or larval transport mechanism back to the coast, as per the 'match-mismatch' hypothesis (Cushing 1990). The strengthening Leeuwin Current in February-April and winter/spring storms that have historically been identified as affecting the level of settlement may both affect larval food availability and transport so that a mismatch may be occurring due to the early spawning. Schmalenbach and Franke (2010) identified that an increasing decoupling of the larval peak from optimal external conditions that affected food availability would result in a serious problem for the European lobsters in the warming North Sea. This hypothesis needs to be explored further for the western rock lobster using the oceanographic larval model and environmental data.

Table 11.1. Summary of bottom water temperature at the onset of spawning (Oct) and egg stage development (N=normal, E=early, VE=very early), spawning stock at Big Bank, SST in February during the early larval stage (C=cool, A=average, W=warm, very warm), winter rainfall (May-October) and level of puerulus settlement at Dongara and Jurien (A=average, L=low, VL=very low) and fit of puerulus settlement with the SST in February.

Spawn year	Water temp Oct	Egg stage	Spawn stock BB	Puerulus year	SST Feb	Rain	Puerulus Don/Jur	Puerulus fit with SST
04/05	W	VE	Mod	05/06	C	H	A	Good
05/06	W	E	Mod	06/07	C	VL	L	Good
06/07	VW	E	Low	07/08	C	A	L	Poor
07/08	W	VE	Low	08/09	W	A	VL	V Poor
08/09	W	E	Low	09/10	A	L	VL	V Poor
09/10	W	N	Low	10/11	C	VL	L	Good
10/11	W	VE	Mod	11/12	W	A	L	V Poor
11/12	W	VE	Good	12/13	W	L	L	V Poor
12/13		E	Good	13/14				

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13.0 Appendices

Appendix 1. Intellectual Property

Background IP: CSIRO include BLULink model output

Appendix 2. Staff List

Nick Caputi	Department of Fisheries, WA
Simon de Lestang	Department of Fisheries, WA
Ming Feng	CSIRO Marine and Atmospheric Research, Perth
Ainslie Denham	Department of Fisheries, WA
James Penn	Department of Fisheries, WA
Dirk Slawinski	CSIRO Marine and Atmospheric Research, Perth
Alan Pearce	Department of Fisheries, WA
Evan Weller	CSIRO Marine and Atmospheric Research, Perth (currently Bureau of Meteorology, Melbourne)
Jason How	Department of Fisheries, WA

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.

The data custodian of the puerulus data is the Department of Fisheries, Western Australia. The data custodian of the self-organising maps is Bureau of Meteorology, Melbourne.