



## CEBRA Report Cover Page

<b>Title, ID, &amp; Output #</b>	1501C: Ballast Water Risk Assessment. Output 4, Final Report.		
<b>Project Type</b>	Standard	<b>CEBRA Project Leader</b>	Andrew Robinson
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<b>Project Leader/s</b>	Peter Stoutjesdijk	<b>Collaborator/s</b>	ABARES
<b>Project Objectives</b>	<p>This project continued previous research on the BWRA methodology (project 1301c). Its objectives were:</p> <ol style="list-style-type: none"> <li><b>Identify an appropriate methodology for estimating sea surface temperatures.</b> The current Ballast Water Risk Assessment (BWRA) uses water temperature data from the array of SeaFRAME tide gauges, operated by the Bureau of Meteorology, located in 13 ports around Australia to directly estimate risk for those ports. For the other ports that lack SeaFRAME data, the BWRA extrapolates an estimate of risk based on the latitude of the port. This methodology does not consider the effects of factors other than latitude (e.g. currents) that would impact on sea water temperature and hence on direct estimates of risk for ports. Improvements in technologies since the development of the BWRA methodology may be able to provide data on sea water temperature for all ports. For example, data derived from satellite sea surface temperature (SST) imagery may be an appropriate method. Therefore, this project will research and identify the most appropriate method for collecting sea water temperature data for integration into the BWRA.</li> <li><b>Risk-based resource allocation advice for domestic ballast compliance enforcement and monitoring activities.</b> The overall risk of pest translocation between ports is the cumulative probability of successful establishment for all vessel journeys over a given time (i.e. the greater number of vessel journeys to a port, the higher the probability of a pest being transported to, and establishing in, that port). Project 1301c identified this issue as an area of future research. Estimates of risk that consider traffic volumes would provide a valuable tool to prioritise the activities of compliance enforcement officers to target ports that are likely to be those that have the highest cumulative risk of a pest establishing there. While estimates of cumulative risk in Australian ports could potentially be used to modify risk management approaches (i.e. not requiring ballast water management until a cumulative risk threshold is exceeded), this is not the intention, or planned outcome, of this objective.</li> <li><b>Risk-based survey targeting.</b> The risk tables provide assessment of low and high risk voyages for seven species. A high-risk voyage will require ballast water to be managed before discharge at the recipient port. The current option available to most ships is to travel beyond the 12-nautical mile limit and undertake a ballast water exchange. This activity has costs to the vessel owners. Collectively, at an industry level, these costs are likely to be significant. Many journeys in the current system are considered risky because the BWRA assumes a pest to be present at an uptake port if the port is suitable for the pest to establish, and there is no recent port monitoring data available to demonstrate that the pest has not established in that port. The department would like to be able to provide advice to industry on how to reduce the costs through targeting ports for surveillance. Using the Lloyd's vessel movement data, research under this objective could identify the ports, which if surveyed for the seven species covered by the risk tables, could result in significant reductions in high-risk voyages, and consequently reduce compliance costs for industry. This project will curate and analyse the data, assess the robustness and draw conclusions. This work may also complement other activities in the department which aim to make marine pest surveillance activities more, cost effective, and better focused on supplying surveillance data to inform the BWRA.</li> </ol>		
<b>Outputs</b>			
<b>CEBRA Workplan Budget</b>	<b>Year 2015-16</b>		
	\$70,000		
<b>Project Changes</b>	Accessing and processing satellite sea surface temperature data took substantially longer than it should have done. This was due principally to aging software and computer resources in the department. The consequence of this was that it was not possible to compare current BWRA life cycle completion simulations for non-tide gauge ports, based on interpolated water temperature, with those modelled using directly measured satellite SST data.		

Report Tracking:	SRC Reviews:	Date: 18/04/2017
	DAWR/MPI Policy / Operational Reviews:	Date: 27/04/2017
	BRSC Endorsement ( ) Yes ( ) No	Date:
	Report published to CEBRA Website ( ) Yes ( ) No	Date:



<b>Research Outcomes</b>	<p>Direct comparison of tide gauge water temperature and satellite SST data found minor differences in water temperature, which may be due to one or a combination of factors such as the actual siting of the tide gauge, the water depth around the tide gauge and the configuration of the coastline in the immediate area. Taken as a whole, it is reasonably clear that the tide gauges and satellite SST are measuring small variations in the same phenomenon and as such both are suitable data sources for lifecycle completion models for the locations where the tide gauges are operating. Variation in water temperature at the same latitude on the east and west coasts of Australia indicates that interpolation based on latitude is likely to give misleading results.</p> <p>Shipping data from Lloyds is an accurate guide to vessel traffic but it is not possible to distinguish between ships carrying cargo and ballast water. Another source of data, for example, the department's Maritime Arrivals Reporting System (MARS) may provide this information.</p>
<b>Recommendations</b>	<ul style="list-style-type: none"> <li>• That SeaFRAME tide gauge temperature data be replaced with satellite sea surface temperature data as the data source for the BWRA risk tables.</li> <li>• That research be carried out to obtain empirical evidence that provides insight into how well the life cycle models represent actual risk.</li> <li>• That the list of ports be revised to remove those ports where ballast-water carrying vessels in the Type A category do not currently visit and to remove duplicates.</li> <li>• That the temperature tolerances of the species in the BWRA system be revised and updated.</li> <li>• That systems be developed to access sub-sets of SST data on IMOS' system remotely using a protocol like OPeNDAP.</li> <li>• That systems be developed as part of the BWRA to capture data on domestic voyages carrying large amounts of ballast water requiring discharge.</li> </ul>
<b>Related Documents</b>	
<b>Report Complete</b>	

Report Tracking:	SRC Reviews:	Date: 18/04/2017
	DAWR/MPI Policy / Operational Reviews:	Date: 27/04/2017
	BRSC Endorsement ( ) Yes ( ) No	Date:
	Report published to CEBRA Website ( ) Yes ( ) No	Date:

# Report on CEBRA project 1501C

Ballast Water Risk Assessment.  
Exploring new methods for estimating risk:  
Using satellite sea surface temperature data;  
Incorporating vessel voyage data.

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October, 2016

### **Acknowledgements**

This project was funded by the Centre of Excellence for Biosecurity Risk Analysis (CEBRA), the Department of Agriculture and Water Resources and the Australian Bureau of Agricultural Resource Economics and Sciences (ABARES). We thank our colleagues Philip Tennant (ABARES), Kate Reid (IMOS), Helen Beggs (BoM), Christopher Griffin (BoM) and Lachlan Nicholls (BoM) for helpful discussions.



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## Executive Summary

The introduction of the Biosecurity Act (2015) means that as of 8 September 2017 when the act comes into force, all vessels, on both international and domestic voyages, will be required to manage their ballast water. To estimate and manage the likelihood of transferring marine pests within Australia, CSIRO and the Department of Agriculture and Water Resources (formerly the Department of Agriculture, Fisheries and Forestry) developed the Australian ballast water risk assessment (hereafter called the BWRA). The original system was endorsed by the National Introduced Marine Pests Coordination Group and updates have been endorsed by the Marine Pest Sectoral Committee (MPSC).

The BWRA is a modular, species-specific system that estimates the likelihood that a species could be taken up from one Australian port, transported to another Australian port and successfully complete its lifecycle there, for any given month in the year. The intent of the system is that when likelihood of a successful transfer is high, the vessel needs to manage its ballast water before arriving in the recipient port. Currently 129 ports and seven species (*Asterias amurensis* - northern Pacific seastar, *Carcinus maenas* - European green crab, *Varicorbula gibba* - European clam, *Musculista senhousia* - Asian date or bag mussel, *Sabella spallanzani* - European featherduster worm, *Undaria pinnatifida* - Japanese seaweed or wakame, and *Crassostrea gigas* - Pacific oyster) are the only species included in the system.

### Life cycle simulation modelling

A critical component of the BWRA is the simulation of species' life cycles based on daily sea water temperature. The data underpinning these simulations are extracted from the Bureau of Meteorology's (BoM) SeaFRAME (Sea level Fine Resolution Acoustic Measuring Equipment) tide gauge array for monitoring long period sea level changes. The array comprises 16 tide gauges, but data from only 13 are currently used in the BWRA. Statistical modelling of at least ten years of daily data is used to generate 1000 synthetic temperature time series for each SeaFRAME location and these are then used to simulate species lifecycles. One thousand synthetic temperature time series, combined with uncertainty in species temperature tolerances, lead to estimates of the proportion of simulations in which lifecycle is completed, for each of the target pest species in each of the SeaFRAME locations, given introduction to the location as larvae on each day of the year. For the risk tables these are then expressed as the proportion of simulations completed, given introduction in each month of the year. Life cycle completion for all the other ports in Australia is estimated from statistical models that relate simulated life cycle completion in tide gauge ports to latitude. In this report we investigate whether sea surface temperature data derived from satellites would be a better source of data than those from the tide gauges.

We found that the SeaFRAME tide gauge temperature data and satellite sea surface temperature (SST) data from the areas around the tide gauges were similar at most locations. Where the results differed, for example at Hilarys, a logical explanation was invariably possible, in this case that the location of the tide gauge inside an enclosed marina resulted in warmer temperatures in summer and cooler temperatures in winter due to reduced circulation and mixing with the open ocean, though this explanation has not been tested. The different data sets can produce different results for life cycle simulations when species temperature tolerances that underpin the life cycle models fall near the maximum or minimum water temperature recorded. It should be noted, though, that comparisons were only carried out for tide gauge locations. More substantial changes may be seen when

the life cycle simulations that are currently extrapolated to distant ports using latitude as the analogue for temperature are replaced with satellite sea surface temperature (SST) data from the areas around the ports.

There is currently no understanding of which (if either) data source, properly captures the full range of temperatures experienced by marine species in any given port environment. Similarly, our understanding of the temperature tolerance ranges of invasive marine species and the effect of other factors such as salinity, disturbance and propagule pressure is far from complete. Both temperature data sources can probably be considered reasonable representations of the general temperatures experienced by marine species in ports. Both data sources have their advantages and disadvantages: the tide gauge data may be more accurate at the point at which it is recorded, but SST data may capture the range of temperatures in the environment around a port better. SST has a considerable advantage in that it covers the entire coastline, including in or near every port in Australia, which obviates the need to use the statistical models to interpolate lifecycle completion to the majority of ports based on latitude. On this basis, we recommend that SeaFRAME tide gauge temperature data be replaced with SST data as the data source for the BWRA risk tables.

Regardless of whether the BWRA is to adopt satellite SST as the data source underpinning the simulation models, the list of ports in the tables should be revised and reduced from the current 129 to a number that more accurately reflects the ports likely to receive discharged ballast water, including clusters of ports. If satellite SST data is adopted for the BWRA there are a number of technical issues regarding data access that will need to be resolved with the Department's IT systems.

### **Vessel voyages and risk**

The current BWRA determines the risk of translocation for individual movements between one point and another, to determine whether ballast exchange is required. However, the overall risk of translocation is likely to incorporate the amount and type of traffic that undertakes particular voyages. We explore the use of vessel movement data for assessing the cumulative risk of establishment, and hence for identifying locations where resources would best be targeted for compliance and pest monitoring activities.

We found that Lloyds data are useful for determining how many voyages have occurred by vessels that could have been carrying bulk ballast water. However, the value of the data is limited because the data do not clearly identify whether any particular voyage was undertaken in ballast or with cargo. No data sets were identified that provide an easy and reliable way of determining this. In the future a more comprehensive data set that identifies the number of domestic voyages carrying large amounts of ballast water that requires discharge could be obtained from administration of the BWRA system. We recommend that any administrative system developed is designed to ensure comprehensive and accurate capture of these data.

### **Summary of recommendations**

- That SeaFRAME tide gauge temperature data be replaced with satellite sea surface temperature data as the data source for the BWRA risk tables.
- That research be carried out to obtain empirical evidence that provides insight into how well the life cycle models represent actual risk.

- That the list of ports be revised to remove those ports where ballast-water carrying vessels in the Type A category do not currently visit and to remove duplicates.
- That the temperature tolerances of the species in the BWRA system be revised and updated.
- That systems be developed to access sub-sets of SST data on IMOS' system remotely using a protocol like OPeNDAP.
- That systems be developed as part of the BWRA to capture data on domestic voyages carrying large amounts of ballast water requiring discharge.

# Table of Definitions

**Table 1:** Table of definitions used throughout the text.

Term	Definition
AVHRR	Advanced Very High Resolution Radiometer. A sensor carried on a number of earth-orbiting satellites that measures temperature on the Earth's surface, including the temperature of the oceans (sea surface temperature). The US National Oceanic and Atmospheric Administration (NOAA) operates at least two polar orbiting satellites with the AVHRR sensor on board.
Ballast water	Water carried in bulk carriers and other ships to replace the weight of cargo in order to provide stability and to avoid the stresses of large empty internal spaces in ships.
Bulk carrier	A generally large ship designed to carry loads such as coal and iron ore in bulk. There are several size classifications.
GAM	Generalised additive model.
GLM	Generalised linear model.
Gross tonnage	One of several measures of a ship's internal volume and used as a measure of a ship's carrying capacity. The volume of ballast water carried is proportional to the gross tonnage; for most bulk carriers it is one approximately third of the gross tonnage.
IMOS	Integrated Marine Observing System. IMOS is a national research infrastructure facility operated by the University of Tasmania and partly funded by the Australian Government. It operates in collaboration with CSIRO and the Bureau of Meteorology, among others and provides access to a wide range of marine data including satellite sea surface temperature.
netCDF	A file format commonly used for oceanographic and remotely sensed data.
SeaFRAME	Array of tide gauges operated by the Bureau of Meteorology that use acoustic sensors and include temperature sensors. (SeaFRAME = Sea level Fine Resolution Acoustic Measuring Equipment)
SST	Sea surface temperature. It is implicit that SST is derived from satellite data.
Tide gauge	A device for measuring the height of the free water surface of the ocean as it rises and falls with the tide.

# 1

## Introduction

Exotic species carried by shipping in ballast water could potentially threaten the marine environment of recipient ports by fouling infrastructure, out-competing and predating on native species and having direct and indirect impacts on fisheries and aquaculture species among other impacts [1]. To estimate and manage the risks of these species within Australia, CSIRO and the Department of Agriculture and Water Resources developed the Australian ballast water risk assessment (BWRA)[2, 3, 4, 5]. The BWRA is a modular, species-specific system that estimates the likelihood that a species taken up in one Australian port (donor port) and transported to another Australian port (recipient port) could successfully complete a simulated life cycle there, for any given month in the year. The system was designed to make an assessment of whether or not IMS are likely to be present in donor and recipient ports (based on the results of surveys carried out under the National Monitoring System), whether larvae are likely to be present at the time of ballast water uptake, and whether the species is likely to be able to complete its life cycle in a recipient port. The likelihood is expressed in binary form as either a “1” for high likelihood or a “0” for low likelihood. If the likelihood is “1”, then the vessel must manage its ballast water before arriving in the recipient port. Currently vessel journeys between 129 ports are considered in generating risk tables, but only Victoria has a regulatory requirement for vessels engaged on domestic voyages to manage their ballast water; a requirement underpinned by the risk tables. However, it is anticipated that eventually all vessels on domestic voyages will be required to manage their ballast water, as required by the Biosecurity Act (2015). The BWRA code has been re-written in the R statistical environment [6] and the methods have been updated [7, 8]. The updated methods have been used in the current project.

## Sea water temperature

Sea water temperature is the principal control on the distribution of marine organisms; most species can survive across a relatively broad temperature range but are limited by the temperature range at which reproduction is possible [9]. Sea water temperature plays a critical role in marine ectotherms’ physiology through its effect on oxygen metabolism. Thermal limitation is brought on when the water temperature approaches the pejus thresholds, the limits, at both the upper and lower limits of temperature tolerance, at which haemoglobin and hemolymph (the equivalent of blood in invertebrates) are able to supply oxygen to internal organs [10]. The role of water temperature in promoting or

limiting the range of invasive marine species has been well documented e.g. [11, 12, 13]. Predictions of an invasive marine species' potential range have been carried out using temperature only [14], temperature and salinity [15] and using genetic algorithm for rule-set prediction (GARP) environmental niche models [15, 16]. The use of satellite sea surface temperature (SST) for modelling invasive marine species maximum potential ranges, based on maximum and minimum temperature tolerances, was adopted by Summerson et al. [17]. SST has been used to map the potential range of invasive marine species, using a variety of modelling techniques, e.g. environmental niche models, around the world [18, 19, 20].

## Life cycle simulations

A critical component of the BWRA is the simulation of species' life cycles based on daily sea water temperature. The temperature tolerances of the species in the BWRA were obtained from a review of the literature by CSIRO when the BWRA was first developed. The data underpinning these simulations is extracted from the Bureau of Meteorology's (BoM) SeaFRAME (Sea level Fine Resolution Acoustic Measuring Equipment) tide gauge array. Only a small number of gauges exist (data from 13 are currently used), so life cycle completion for all other ports is estimated from statistical models that interpolate lifecycle completion based on latitude.

In Chapters 3 and 4 of this report we investigate whether sea surface temperature (SST) data derived from satellites would be a better source of data than those from the tide gauges. Both sources of data have their advantages and disadvantages. The tide gauges measure water temperature directly and at high temporal resolution (every 10 minutes), but at a restricted number of localities and may be influenced by localised effects such as insolation. Tide gauges are also vulnerable to damage and outages from various causes. In contrast, satellite sea surface temperature (SST) covers the entire coastline, but rarely penetrates into ports and estuaries. It is collected at a coarser temporal scale and it can be subject to data loss on cloudy days. Both data sets need to be processed to make them usable.

## Vessel voyages

The current BWRA determines the risk of translocation for individual movements between one point and another, to determine whether ballast water management is required. However, the overall risk of translocation is likely to incorporate the amount and type of traffic that undertakes particular voyages. In Chapter 5 we explore the use of vessel movement data for assessing the cumulative risk of establishment, and hence for identifying locations where resources would best be targeted for compliance and pest monitoring activities.



## 2

# Data sources, data access & data processing

## 2.1 Tide gauge

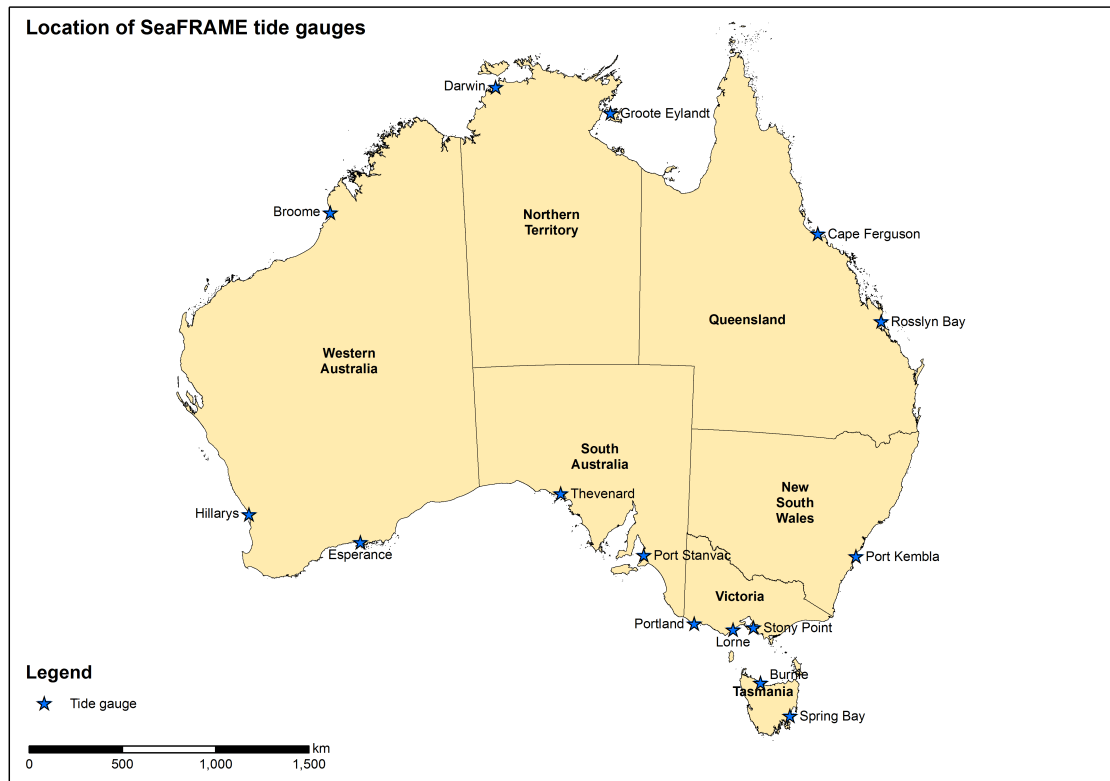
The BWRA currently uses temperature data from 13 of the Bureau of Meteorology's (BoM) SeaFRAME (Sea level Fine Resolution Acoustic Measuring Equipment) tide gauges: Broome, Burnie, Cape Ferguson, Darwin, Esperance, Hilarys, Groote Eylandt, Rosslyn Bay, Port Kembla, Portland, Port Stanvac, Spring Bay and Thevenard; a subset of the 15 shown in Figure 2.1. The tide gauge at Port Stanvac was decommissioned in 2010 but the data are still being used to populate the life cycle completion simulation models.

The BoM SeaFRAME tide gauges use acoustic sensors to measure the height of the sea surface below the acoustic sensor head. The speed of sound is critically dependent on the density of the medium through which the sound travels and therefore on air temperature. The tide gauges were therefore installed with temperature sensors, at least one of which is permanently below the water surface at the bottom of the acoustic tube (Figure 2.2).

The Bureau of Meteorology National Tidal Centre (NTC) provided information about the temperature sensors on the tide gauges. From this, it is noted that:

- The temperature sensors are high quality and are calibrated regularly - about every 18 months.
- Regular calibration should obviate any shifts in temperature when temperature sensors are changed, if there is cleaning of marine growth or other maintenance. Maintenance records are not, however, readily available.
- The water depth that the sensors are placed in varies across the network.

The tide gauges have been installed in a variety of locations including on a pier (e.g. Broome, Thevenard), inside a marina (e.g. Hilarys Boat Harbour, Rosslyn Bay) and inside a breakwater (Port Kembla). Many of the tide gauges are not close to major ports: Hilarys is over 25 km from Fremantle; the nearest tide gauge to Brisbane is Rosslyn Bay, which is over 650 km away; the nearest tide gauge to Melbourne is Portland which is over 350 km away; the nearest tide gauge to Dampier is over 650 km away. The degree of exposure to the open sea varies considerably also, from sheltered locations like Spring Bay (Figure 2.3) to more exposed locations like Burnie and Broome.

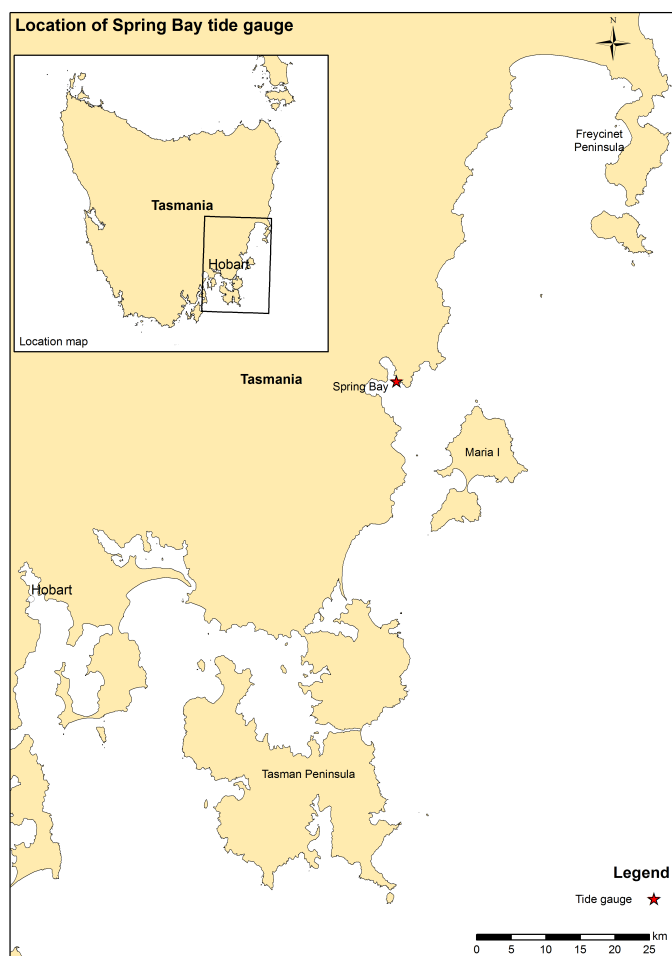


**Figure 2.1:** Location of the BoM SeaFRAME tide gauges.

In the data extracted, temperatures are recorded hourly. The maximum and minimum for each day are extracted for use in the BWRA analyses. In general this data source is reliable, but there are a number of breaks in the tide gauge temperature record, some of which are quite lengthy. For example, the Broome tide gauge was out of commission for 12 months from September 2009 to September 2010.



**Figure 2.2:** The SeaFRAME tide gauge at Spring Bay. The tube containing the acoustic sensor is visible on the left hand side of the concrete pylon.



**Figure 2.3:** Location of the Spring Bay tide gauge.

## 2.2 Satellite sea surface temperature

Satellite remotely sensed sea surface temperature (SST) datasets of the world have been available for over 30 years. These are acquired by satellites that carry instruments such as the Advanced Very High Resolution Radiometer (AVHRR), which has been flown on a succession of polar orbiting satellites operated by NOAA and is the longest continuous sea surface temperature dataset [21]. Other satellite SST instruments include MODIS on the NASA Terra and Aqua satellites and ATSR on the European Remote-Sensing Satellites ERS-1, 2 and follow-ons. NOAA operate two satellites at any one time that provide morning and afternoon coverage as well as two night time passes. Even with two satellites and two passes each day, an area the size of the Australian exclusive economic zone (EEZ) may not receive total coverage every 24 hours, especially if there is cloud coverage. The presence of cloud is a constant problem as it often prevents total daily coverage of the Australian coastline. In this project we investigated two sources of SST data: NASA monthly mean data; and daily data from IMOS.

### 2.2.1 NASA monthly means

NASA (National Aeronautics and Space Administration) use the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder to collect SST data. These data are captured at a variety of spatial resolutions: 4 km, 9 km, 18 km and 54 km resolutions and at temporal resolutions of a single pass, daily composite, eight day mean and monthly mean. There have been several eras and methods of processing the data; the most complete of which is Pathfinder version 5. These datasets are not however necessarily cloud-free. Various attempts have been made to remove or reduce the presence of cloud using image processing techniques such as erosion filtering, but they are not routinely available. The AVHRR instrument is currently operational on the NOAA-19 and METOP-B satellites, with several back-up satellites still available.

AVHRR SST data records the temperature at the ocean's surface, also known as the "skin temperature". The ocean skin is approximately 0.1 - 1.0 mm thick [22]. Skin temperature is lower than the sub-skin which may be 1 - 5°C warmer due to insolation (solar warming). The degree of insolation depends on a number of factors including latitude, the declination of the sun, cloud and wind speed. The "bulk" surface temperature of the ocean, at a depth of one metre, is usually cooler than the skin and sub-skin, depending on solar warming during the day, wave action, etc. These differences have been measured by comparison with floating buoys, on-board ship experiments and other techniques. Emery et al (2001)[23] report that the bulk-skin temperature difference is, on average, about 0.3°C with an RMS of up to 0.4°C. The thermal gradient between the ocean skin and ocean bulk that builds up during the day breaks down at night. Gentemann et al (2003)[24] and Robinson and Donlon (2003)[22] report that the skin-bulk temperature difference decays from about 3pm local time onwards until the skin temperature approaches bulk temperature at about 11pm. SST data captured during night time passes therefore represent bulk temperature better than daytime passes.

The highest spatial resolution possible for AVHRR SST datasets is a 1.1 km cell size but the NASA monthly mean datasets only have a resolution of 4.4 km. Candidate temporal resolutions possible include daily, 8-day means and monthly means. There are a number of limitations in using daily data, which include the potential presence of cloud, resolving

day versus night temperature differences and gaps in the data between satellite passes. While daily data might give a better understanding of the actual temperatures that marine species have to tolerate, the problems and time overheads of integrating data from different passes and handling data gaps from cloud and satellite passes create significant challenges.

Night time monthly mean SSTs from January 1985 to December 2009 were acquired via the NASA Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center (PO.DAAC), which maintains an archive of SST data. These data have been used in the past to model the potential maximum ranges of invasive marine species [17, 14], using a different method to the one employed in the BWRA.

Accessibility of SST data from NASA has changed since the monthly means were downloaded. December 2009 is the most recent month for which the data are available. The inception of the Integrated Marine Observing System (IMOS) and the ready availability of SST products from there has obviated the need to access data from PO.DAAC.

### 2.2.2 IMOS SST data holdings

The Integrated Marine Observing System (IMOS) is a national collaborative research infrastructure, supported by the Australian Government. It is led by the University of Tasmania in partnership with the Australian marine and climate science community (<http://www.imos.org.au/>). IMOS is also a member of the Group for High Resolution Sea Surface Temperature (GHRSSST[25]), an international group that coordinates the development of SST products. SST data available from IMOS comprise single night time passes, composite one day (one night) night time passes and three day super-composites, composed of night-time passes. These data are available from 1992–2015 (<http://help.aodn.org.au/help/?q=node/67>). Monthly mean data are also available, but a decision was made to use 3-day composite datasets as described below.

“Foundation” temperature data from 3-day composites were chosen. Foundation temperature is the temperature free of diurnal temperature variability, defined as “the temperature at the first time of the day when the heat gain from the solar radiation absorption exceeds the heat loss at the sea surface” (GHRSSST, 2013[25]). Foundation temperature is modelled from the skin temperature that the satellite senses and is the best estimate of temperature at a depth of about 2 metres, which is therefore the nearest temperature to those recorded by the tide gauge temperature sensors. Three-day composites were chosen to minimise unavailability of SST data over the tide gauge locations through the satellite swath coverage and loss of data from cloud, while at the same time retaining data as close as possible, temporally, to the tide gauge data. Three-day composites are time-stamped for the middle day of the time series, so comprise the day before and the day after the day time-stamped. Data from IMOS are accessible in two ways: the AODN Portal (<http://portal.aodn.org.au/>), which uses a data aggregator to compile data requests; and Amazon S3 data storage, which is only accessible using the Amazon S3 browser.

The satellite SST data for the years of 1999 – 2009 were downloaded from the IMOS website in netCDF 4 format. Each netCDF file includes three main  $6000 \times 4500$  (longitudes  $\times$  latitudes) matrices, namely *sea surface temperature (foundation)*, *ses bias* (which are corrections for corresponding temperatures) and *quality levels* associated with the temperatures. Data were extracted from required grid cells in R [6]: Processing the satellite SST data requires the following steps:

1. The netCDF files were loaded into the R work space and the three matrices identified above were extracted.
2. Satellite records for the combinations of longitudes and latitudes were calibrated by subtracting the bias matrices from the sea surface temperature matrices. For each SST record, a quality level, ranging from 1 (the lowest level) to 5 (the highest level) is given by an associated element in the *quality level* matrix. In this project we considered only SST records with a quality level of 3 or greater, and set the records with a quality level of 1 or 2 as NA.

## 2.3 Vessel traffic data

Data for the seven year period 2008–2014 were purchased by the Department of Agriculture and Water Resources (DAWR) Marine Pest Unit from Lloyds Maritime Intelligence Unit (“Lloyds”). Lloyds data are recognised world-wide as the authoritative data source on ships and shipping movements. The data purchased from Lloyds include all vessel movements for all vessels that visited Australia during 2008–2014, thus they form a continuous record of vessel movements during this time, not only voyages to Australia and between Australian ports, but their movements before and after visiting Australia.

The data were provided in a Microsoft Access relational database and include three key tables: Vessels, Moves and Ports. The Vessels table provides data on vessel names, types, flag and tonnage. The Moves table makes it possible to track vessels as they move from port to port. Additional, optional extra tables purchased include data on vessels’ survey histories, dimensions, capacities and speed.

There are a number of limitations in the data. The accuracy of some of the data is questionable, which may be due to information not being received by Lloyds; for example up-to-date information about dates of class surveys. It appears that some vessels have their names changed relatively frequently, which may not be updated in the Lloyds data for some time after a change has been effected. This affects tracking of individual vessel movements, but would not affect estimates of frequency of movements by vessel type. Overall the data are of sufficiently high quality for estimating the frequency of voyages by different types of commercial vessels.

### 3

# Comparison of Satellite Sea Surface Temperature and SeaFRAME tide gauge temperature data

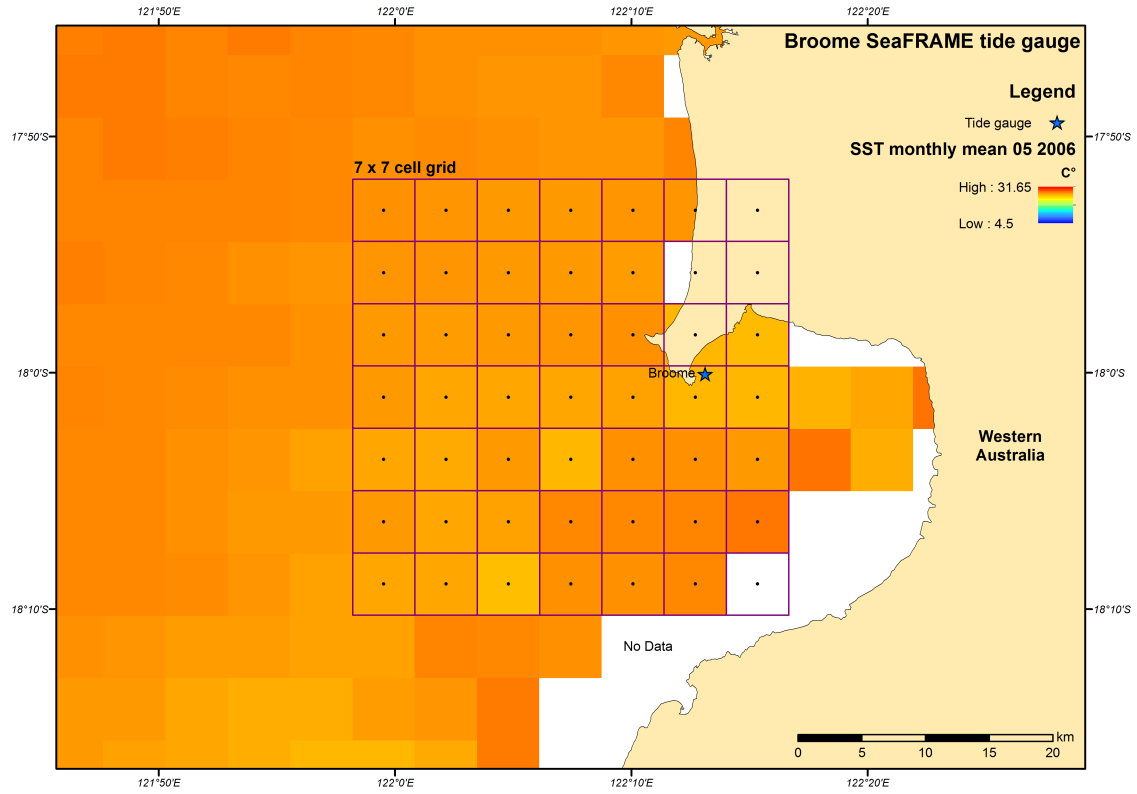
## 3.1 Introduction

In this chapter we explore how seawater temperature measured by the SeaFRAME tide gauges differs from temperatures measured by satellite. In the first section we compare the monthly mean data from NASA obtained for previous work, to determine whether there were any broad differences between data from the two sources. In the second section we do a more detailed comparison based on daily data from IMOS.

## 3.2 General methods

A potential issue with the comparison is that in many cases tide gauge and SST data do not exactly overlap spatially. This occurs because the satellite data is often not coincident with the coast due to: a land mask used to delineate land from sea; the presence of coastal cloud; and geo-locational problems. To account for this, satellite data for comparison were extracted from a 7 by 7 grid for each port, positioned over the site of the tide gauge. The choice of a 7 by 7 grid was considered a reasonable compromise between proximity to the tide gauge location and the need to acquire multiple SST data values in the event of data drop out or loss from cloud. The 7 by 7 grid is positioned differently for each tide gauge location to maximise the capture of SST data, as the configuration of the coastline is different at each location. Broome is shown as an example (Figure 3.1). NASA monthly mean values were extracted using a Python script in ArcGIS 10.2, while IMOS data were extracted using R scripts.

Once extracted, values corresponding to the tide gauge location were interpolated from the grid using Kriging. We used the R function *ksline* from the *geoR* package; the default (exponential) model for correlation was used. Kriging produced a few unusual errors due



**Figure 3.1:** Map of  $7 \times 7$  grid of monthly mean SST for Broome. White grid cells over the ocean had no data available at the time.

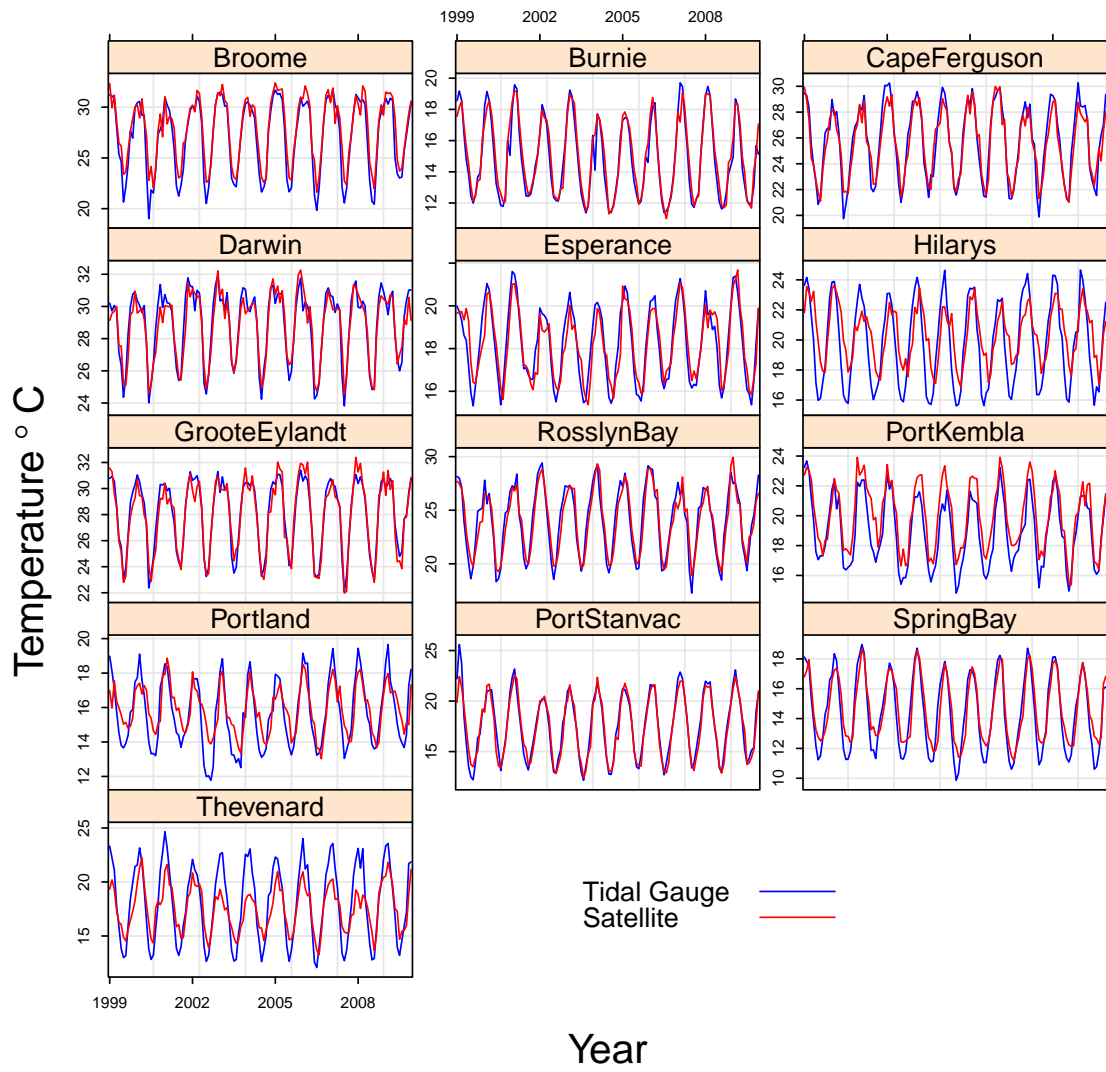
to singularities caused by temperature values on some grids being too similar. In these cases, we used the mean of the available temperature values on the grid.

### 3.3 Comparison of monthly means

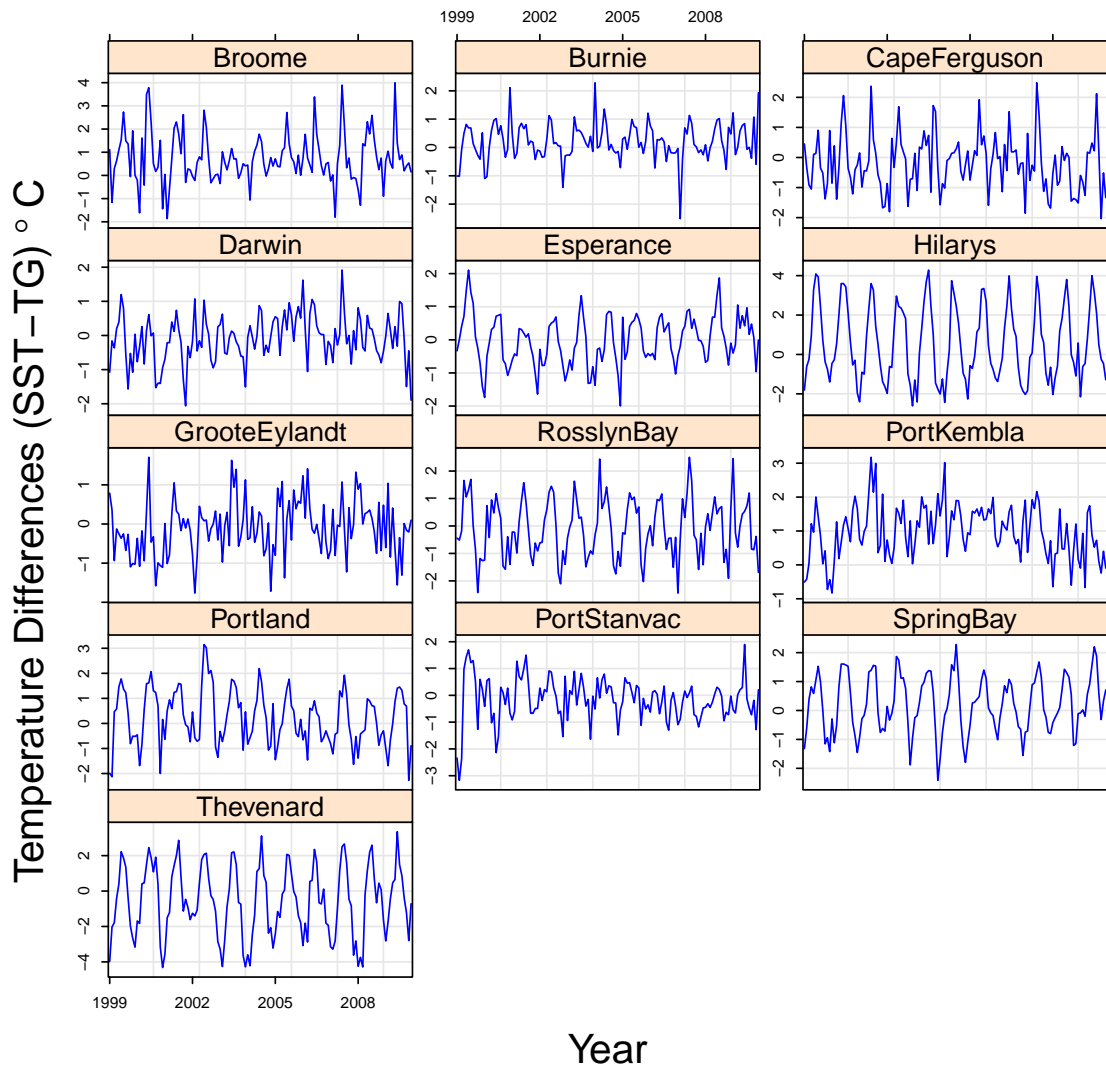
The NASA monthly mean data, covering 11 years between 1999–2009, were compared with SeaFRAME data from the thirteen ports used in the BWRA. Means for SeaFRAME data were obtained by calculating daily means from the hourly records, and then calculating monthly means from these daily means. Figure 3.2 shows a direct comparison of the data for all ports. Figure 3.3 shows the differences between the two data sources.

Generally, water temperature measurements using the different methods were similar, but there were some seasonal patterns in differences for some ports. In these cases winter temperatures measured using the satellite method tended to be higher than SeaFRAME measurements (up to 4°C higher, e.g. Hilarys), while in summer they tended to be slightly lower than or similar to SeaFRAME measurements (up to 4°C lower, e.g. Thevenard).



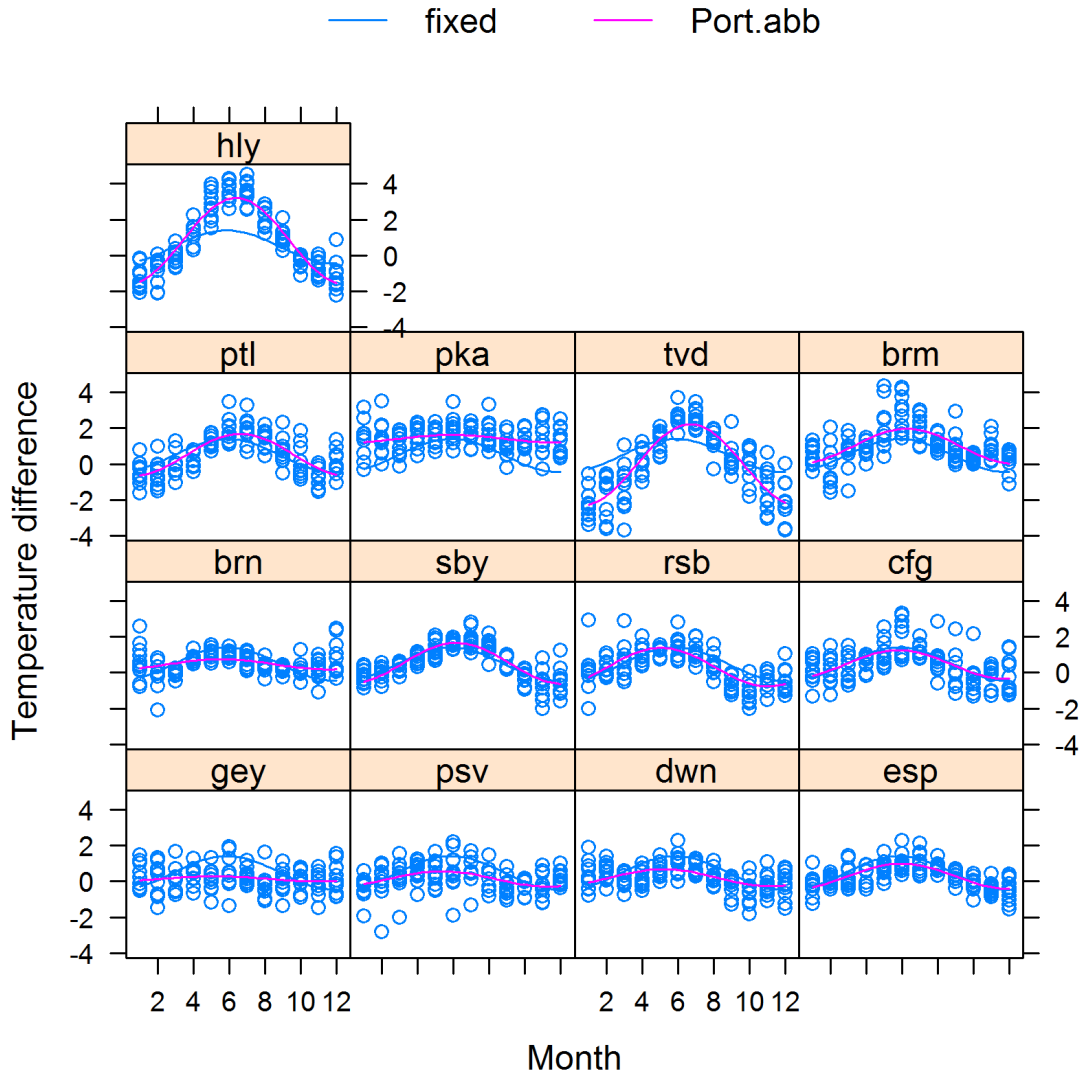


**Figure 3.2:** Monthly mean satellite (NASA) and SeaFRAME tide gauge temperatures (1999–2009).



**Figure 3.3:** Differences between water temperatures measured using satellite (NASA) and SeaFRAME tide gauges (1999–2009).

The seasonal pattern is evident from a non-linear mixed effects model of temperature difference against month, with port treated as a random effect (Figure 3.4). The fixed effects component of the model shows a minor seasonal pattern around zero, while the strong patterns of Thevenard and Hilarys in particular are evident when the random effects component is added.



**Figure 3.4:** Mixed effects model of temperature difference (SST - tide gauge) by month, with port as a random effect. The seasonal pattern is modelled with a sine function, with random effects on the amplitude, and on the x and y shift. Points are the raw data; fixed shows the fixed effects component of the model; Port.abb shows the prediction with random effects added - Hilarys (hly), Portland (ptl), Port Kembla (pka), Thevenard (tvd), Broome (brm), Burnie (brn), Spring Bay (sby), Rosslyn Bay (rsn), Cape Ferguson (cfg), Groote Eylandt (gey), Port Stanvac (psv), Darwin (dwn), and Esperance (esp).

Despite some differences, the results of the comparison between tide gauge and NASA monthly mean data were sufficiently promising to warrant investment in downloading daily IMOS data, to provide a more direct comparison between satellite and daily tide gauge data.

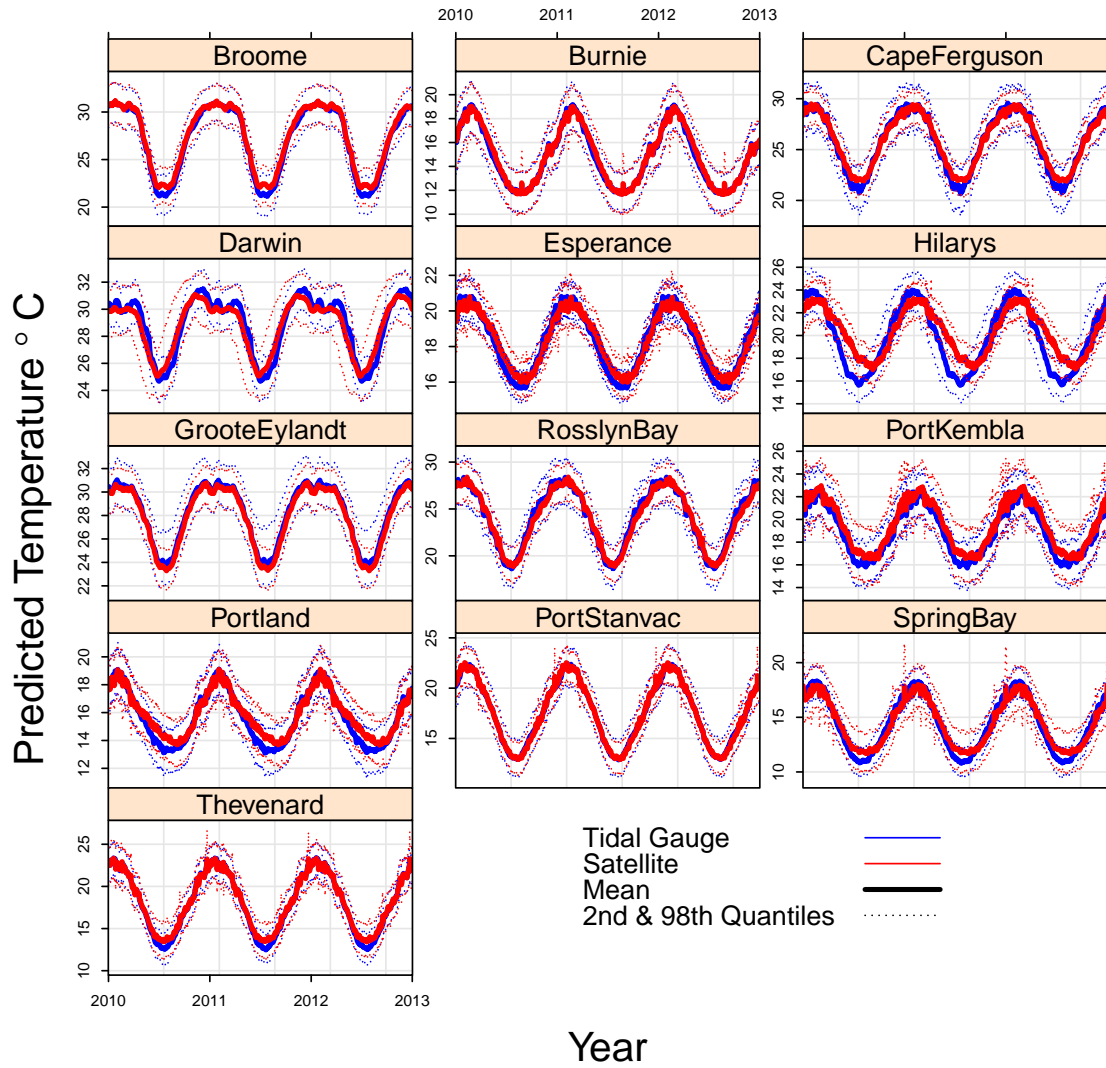
### 3.4 Comparison of daily data

Daily IMOS foundation data, covering 1999 – 2009, were compared with the daily SeaFRAME data from the thirteen ports used in the BWRA. To make these comparisons we employed the methods used in the BWRA to generate synthetic sea temperature data sets for each of the SeaFRAME ports. The BWRA generates 1000 synthetic sea temperature data sets for each port, and these are then used to model species' life cycles. The synthetic data sets are generated as follows[8]: For each port, 1000 different 10 year time series are generated by randomly selecting from yearly blocks of the observed data - this ensures yearly variation in temperatures is included in the resultant synthetic time series. Each of the 1000 time series is then decomposed into a seasonal component, a trend and the residuals, by using the *stl* (seasonal trend decomposition using Loess) function in R, and ARIMA models are applied to the residuals [3] to account for autocorrelation of daily temperatures. One three year temperature time series is generated from each decomposition, to produce a total number of 1000 synthetic temperature time series per port.

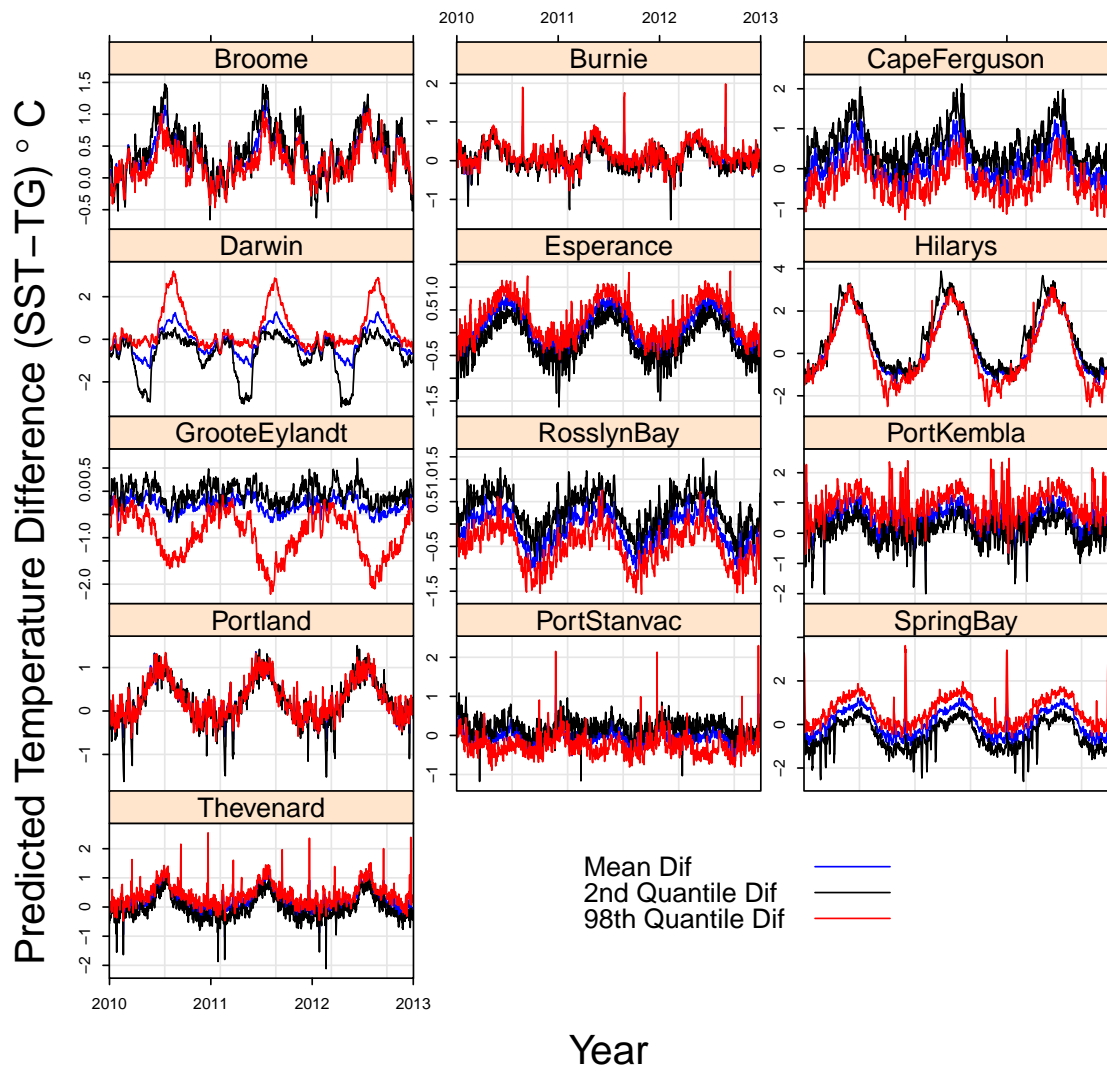
In the BWRA, this modelling is applied to the minimum daily temperature, and to the difference between minimum and maximum daily temperature, because the BWRA currently uses both daily minimum and daily maximum temperatures when the life cycle simulations are carried out. However, only one satellite temperature record is available for each day (Section 2.2.2), so to compare between SeaFRAME and IMOS SST data, we applied the above approach to mean daily SeaFRAME temperature data. We used the same bootstrapped years for both the satellite and SeaFRAME data.

For most ports, the mean and quantiles of the synthetic sea temperature data produced by the IMOS SST and SeaFRAME data were very similar (Figures 3.5 and 3.6). However, there were some systematic differences for some ports. Hilarys has a shift in when the winter minimum occurs (earlier for the tide gauge) and the magnitude of it (colder for the tide gauge, by about 2°C). The summer maximum was also offset slightly (earlier for the tide gauge) and slightly warmer for the tide gauge. A number of other ports showed slight differences in magnitude in winter (with the tide gauge generally reading lower than the SST), similar to the results seen for the monthly mean analysis (Section 3.3). For Darwin and Groote Eylandt the pattern in the quantiles was quite different, indicating greater variation in the synthetic data sets generated by one data source compared with the other at certain times of the year - for Darwin the SST showed greater variation, while for Groote Eylandt the SeaFRAME data showed greater variation.

In the next Chapter we explore how much impact these levels of difference in the synthetic time series obtained from SeaFRAME vs. SST data have on the life cycle simulations.



**Figure 3.5:** Comparison of mean daily satellite and tide gauge sea temperatures; from 1000 synthetic time series per port, derived using the methods employed in the BWRA[8]. The years indicate a prediction beyond the data (1999 – 2009) used to generate the models.



**Figure 3.6:** Differences between mean satellite and tide gauge sea temperatures.

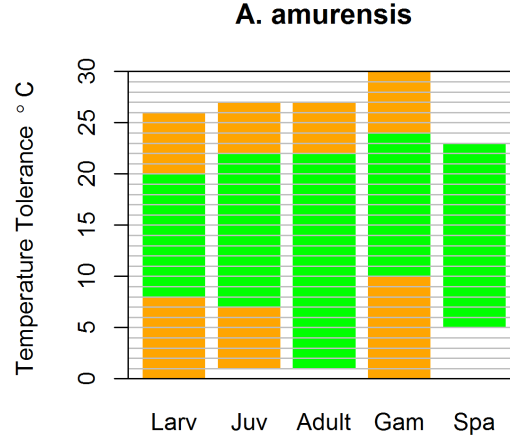
# Comparison of life cycle completion simulations with satellite and tide gauge temperatures

## 4.1 Introduction

The BWRA is based on the idea that a marine pest species that can complete its full life cycle in a recipient port, from arrival as larvae, or gametophyte in the case of a plant species, to successful production of new larvae, represents a potential risk to the port if the species is not known to be present already [2, 3, 4, 5]. The temperature simulations are used to drive life cycle models for each species to estimate the proportion of simulations in which the life cycle is completed, given introduction on a particular day of the year [8]. In the model, species are introduced as larvae and begin to progress through their life cycle. If the temperature moves outside a critical range (dependent on life cycle stage), then the species dies and hence does not progress any further. Whether the species spawns or not in the new location is also temperature dependent. Temperature tolerances used in the simulation modelling for the different life stages of *Asterias amurensis* are shown in Figure 4.1 as an example. Temperature tolerances for all species are shown in Appendix B and were derived from a review of the literature when the BWRA was first developed. Detailed descriptions of the models are provided in earlier reports [2, 3, 4, 5].

## 4.2 Methods

The synthetic time series for each port generated from both SeaFRAME and SST data (Section 3.4) were used to run the life cycle models for nine marine pest species, namely, *Asterias amurensis*, *Carcinus maenas*, *Musculista senhousia*, *Sabella spallanzani*, *Varicorbula gibba*, *Mytilopsis sallei*, *Perna viridis*, *Crassostrea gigas* and *Undaria pinnatifida*. We then produce figures showing the proportion of simulations with life cycle completed per day of introduction, and per month of introduction. The latter is the measure used to estimate risk in the BWRA. The BWRA currently considers life cycle completion ‘risky’ for a particular



**Figure 4.1:** Temperature tolerance of *Asterias amurensis* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.

month if the life cycle is completed in 5% or more of simulations. Results for all species are presented in Appendix A (Figures A.1–A.104).

### 4.3 Results and Discussion

In general the two temperature data sources produced similar outcomes in the life cycle simulations in the tide gauge locations. Where they differed they tended not to result in a change in the ‘risk’ estimate based on the 5% cutoff. Of 1404 possible combinations (13 ports  $\times$  9 species  $\times$  12 months), 40 changed their risk classification (Table 4.1). Among the nine modelled species, *C. maenas* was the only species where the use of SST data did not result in any changes from the tide gauge data.

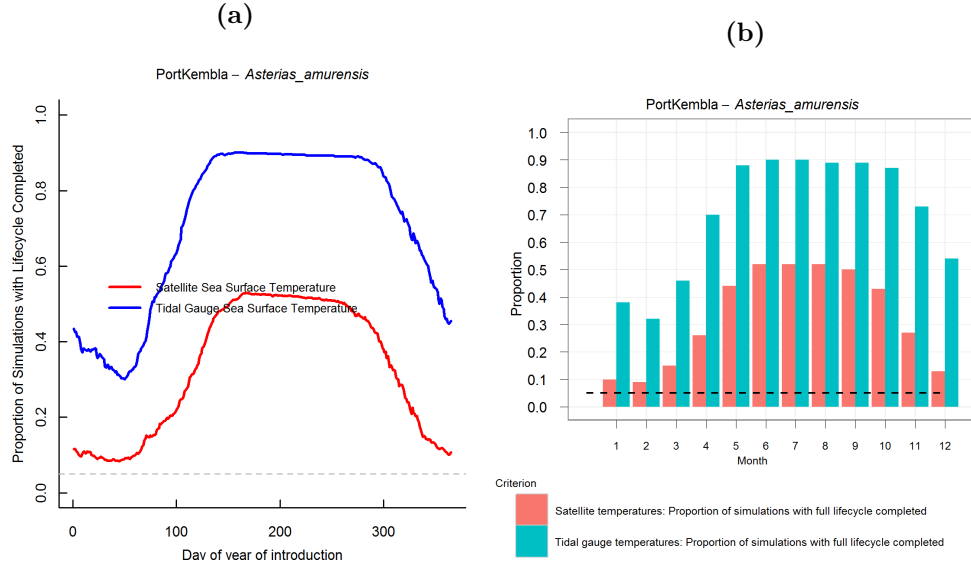
Figure A.8 shows an example (*A. amurensis* in Port Kembla) where the simulation results were reasonably different, but there was no change in the risk estimate because the differences did not result in the proportion of life cycle completed falling below the 5% cutoff. If we compare the temperature tolerances for *A. amurensis* (Figure 4.1) with the synthetic temperature time series for that port (Figure 3.5) we can see that the upper bound of tolerance is around the maximum temperature in summer at that port - the slightly higher temperatures resulting from the SST data compared with the SeaFRAME data result in a smaller proportion of simulations where life cycle is completed for the SST simulations.

In contrast, life cycle simulations generated from the two temperature sources were more similar for *Musculista senhousia* in Broome, but the risk classification was different in some months (Table 4.1) because the proportion of life cycle completed fell either side of the 5% cutoff (Figure A.40). As for *A. amurensis* in Port Kembla, the differences occurred because



**Table 4.1:** Port, species and month combinations where risk estimates produced from the different sea temperature sources (Satellite (SST) vs. SeaFRAME (Tide Gauge)) differed. Risk is based on whether a species completed its full life cycle in at least 5% of simulations.

Port	Species	Month	Sat Risk	TG risk
Broome	<i>M. senhousia</i>	Jan	0	1
Broome	<i>M. senhousia</i>	Feb	0	1
Broome	<i>M. senhousia</i>	Dec	0	1
Broome	<i>S. spallanzani</i>	Apr	0	1
Broome	<i>S. spallanzani</i>	Aug	0	1
Broome	<i>S. spallanzani</i>	Sep	0	1
Broome	<i>V. gibba</i>	May	0	1
Broome	<i>M. sallei</i>	Feb	0	1
Broome	<i>M. sallei</i>	Nov	0	1
Broome	<i>U. pinnatifida</i>	Jul	0	1
CapeFerguson	<i>S. spallanzani</i>	Jan	0	1
CapeFerguson	<i>V. gibba</i>	Jun	0	1
CapeFerguson	<i>C. gigas</i>	Mar	0	1
CapeFerguson	<i>C. gigas</i>	Apr	0	1
CapeFerguson	<i>C. gigas</i>	May	0	1
CapeFerguson	<i>U. pinnatifida</i>	May	0	1
CapeFerguson	<i>U. pinnatifida</i>	Jul	0	1
Darwin	<i>M. senhousia</i>	Oct	0	1
Darwin	<i>S. spallanzani</i>	Jul	0	1
Darwin	<i>M. sallei</i>	Mar	1	0
Darwin	<i>M. sallei</i>	Sep	0	1
Hilarys	<i>A. amurensis</i>	Jan	1	0
Hilarys	<i>P. viridis</i>	Feb	1	0
Hilarys	<i>P. viridis</i>	Nov	0	1
GrooteEylandt	<i>S. spallanzani</i>	Apr	0	1
GrooteEylandt	<i>S. spallanzani</i>	Sep	0	1
RosslynBay	<i>V. gibba</i>	Feb	0	1
RosslynBay	<i>P. viridis</i>	Aug	0	1
RosslynBay	<i>C. gigas</i>	Oct	0	1
RosslynBay	<i>C. gigas</i>	Nov	0	1
PortKembla	<i>P. viridis</i>	Jan	0	1
PortKembla	<i>P. viridis</i>	Dec	0	1
PortKembla	<i>U. pinnatifida</i>	Jan	0	1
SpringBay	<i>M. senhousia</i>	Nov	0	1
Thevenard	<i>A. amurensis</i>	Jan	0	1
Thevenard	<i>P. viridis</i>	Nov	0	1
Thevenard	<i>P. viridis</i>	Dec	0	1
Thevenard	<i>U. pinnatifida</i>	Jan	0	1
Thevenard	<i>U. pinnatifida</i>	Nov	0	1
Thevenard	<i>U. pinnatifida</i>	Dec	0	1

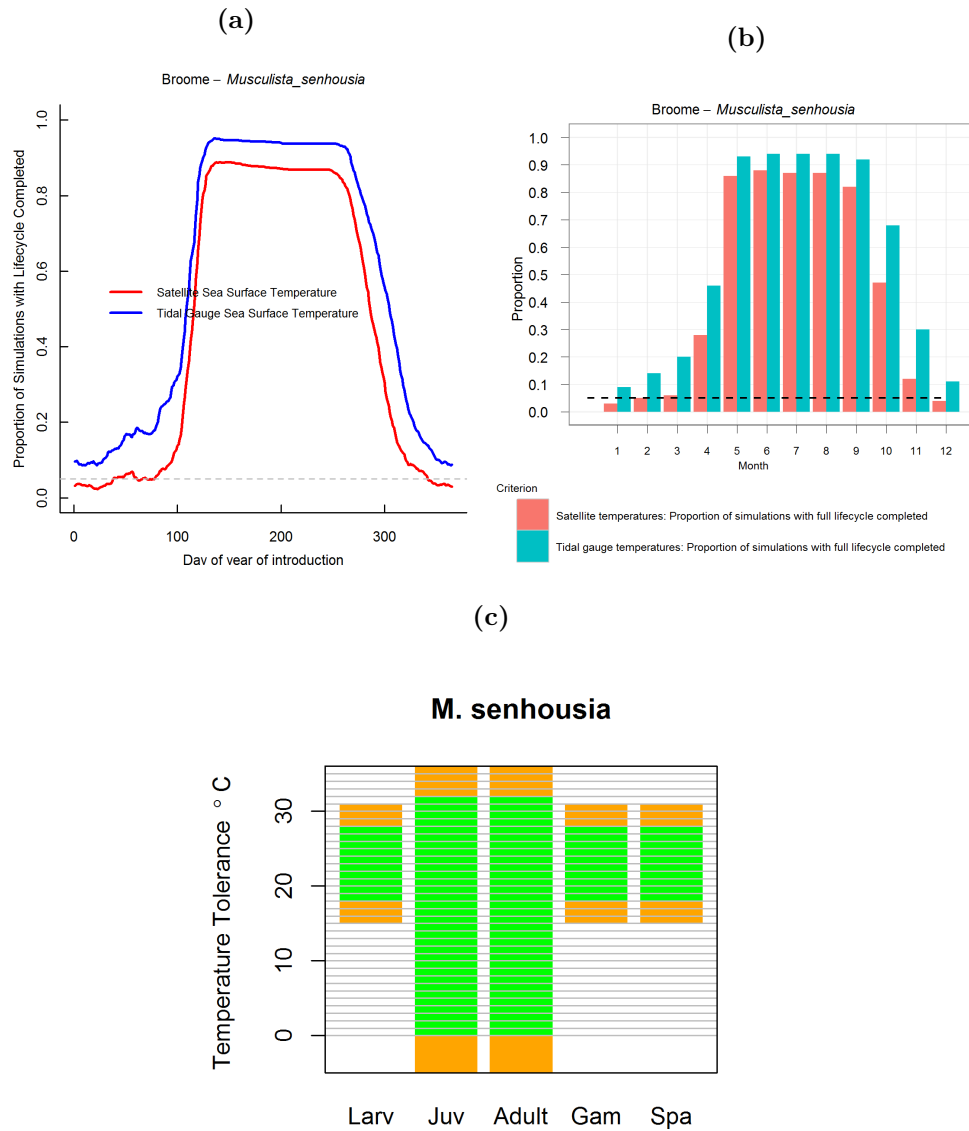


**Figure 4.2:** Simulation results for life cycle completion of *Asterias amurensis* in Port Kembla. The horizontal line shows a 0.05 cut-off. (a) daily; (b) monthly.

the upper bound of tolerance is around the maximum temperature in summer in Broome.

The results show that when temperature tolerances of invasive marine species are not near the maximum summer or minimum winter temperatures experienced in a port, then the life cycle simulations will produce very similar results. On the boundaries the two temperature sources can produce different results and these can result in changes in the estimate of ‘risk’ if the simulations are around the 5% cutoff. While this could be considered a problem, it is not known which source of data best reflects the temperatures likely to be experienced by marine pests.

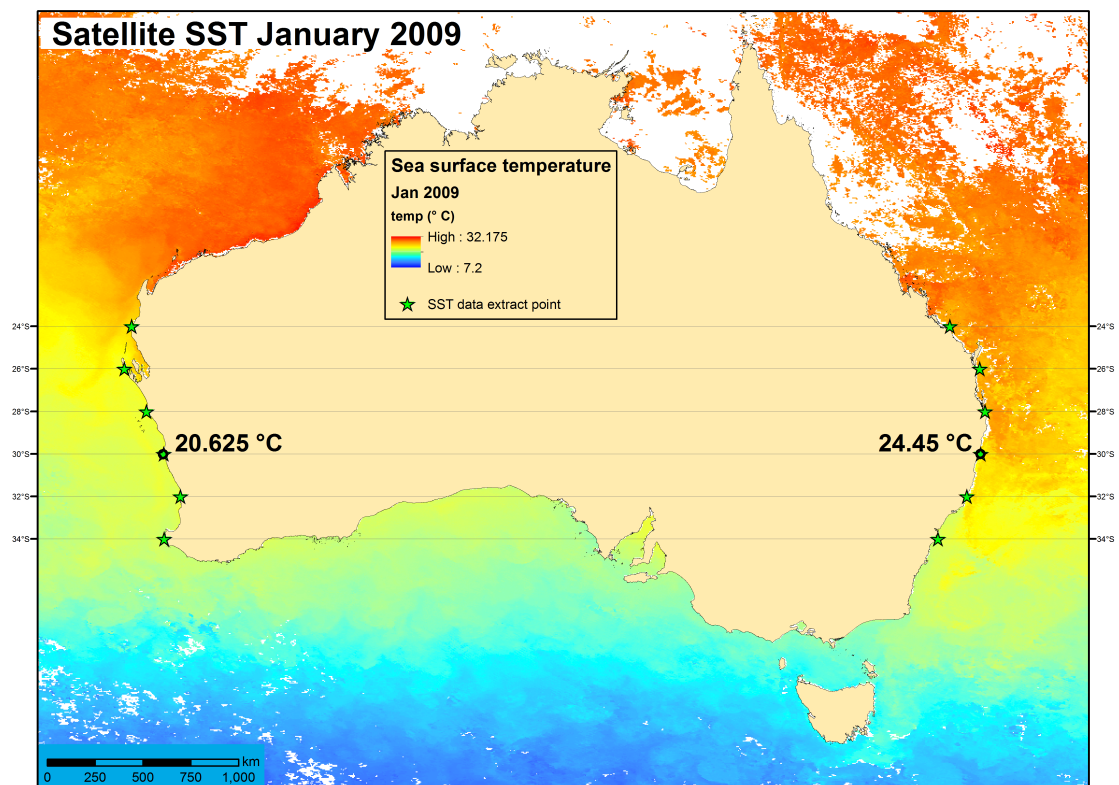
As discussed in Chapter 1, the SeaFRAME data are likely to provide a closer indication of temperature in the environment of the eight ports where the data are available than SST data. They are, however, only a measure of temperature at one point in space and hence are unlikely to reflect the full range of temperatures marine species may experience in those ports. In contrast, the satellite data measure temperatures across a broader spatial resolution, but rarely penetrate into ports and estuaries. Satellite data have the advantage that they cover the entire Australian coastline, close to every port in Australia, while the results of life cycle completion simulations based on SeaFRAME data are extrapolated to most ports using a statistical model that relates life cycle completion to latitude [8]. Differences between the effects of the East Australian Current on the east coast and the Leeuwin Current on the west coast are well known [30] and can be clearly seen in (Figure 4.4). Figure 4.5 compares SST temperature values immediately adjacent to the coast at six identical latitudes on the first day of the month in January (summer), April (autumn), July (winter) and October (spring) over three years (2009-2011). Strong seasonal and inter-annual variation results in temperatures differing by up to 5 °C in some seasons and some years at the same latitude. Latitude alone therefore provides a poor approximation of water temperature and by extension a statistical model that relates life cycle completion to latitude will introduce errors in estimates of lifecycle completion. It is possible that more substantial changes will be seen when the life cycle simulations that are currently extrapolated to distant ports using latitude as the analogue for temperature are replaced



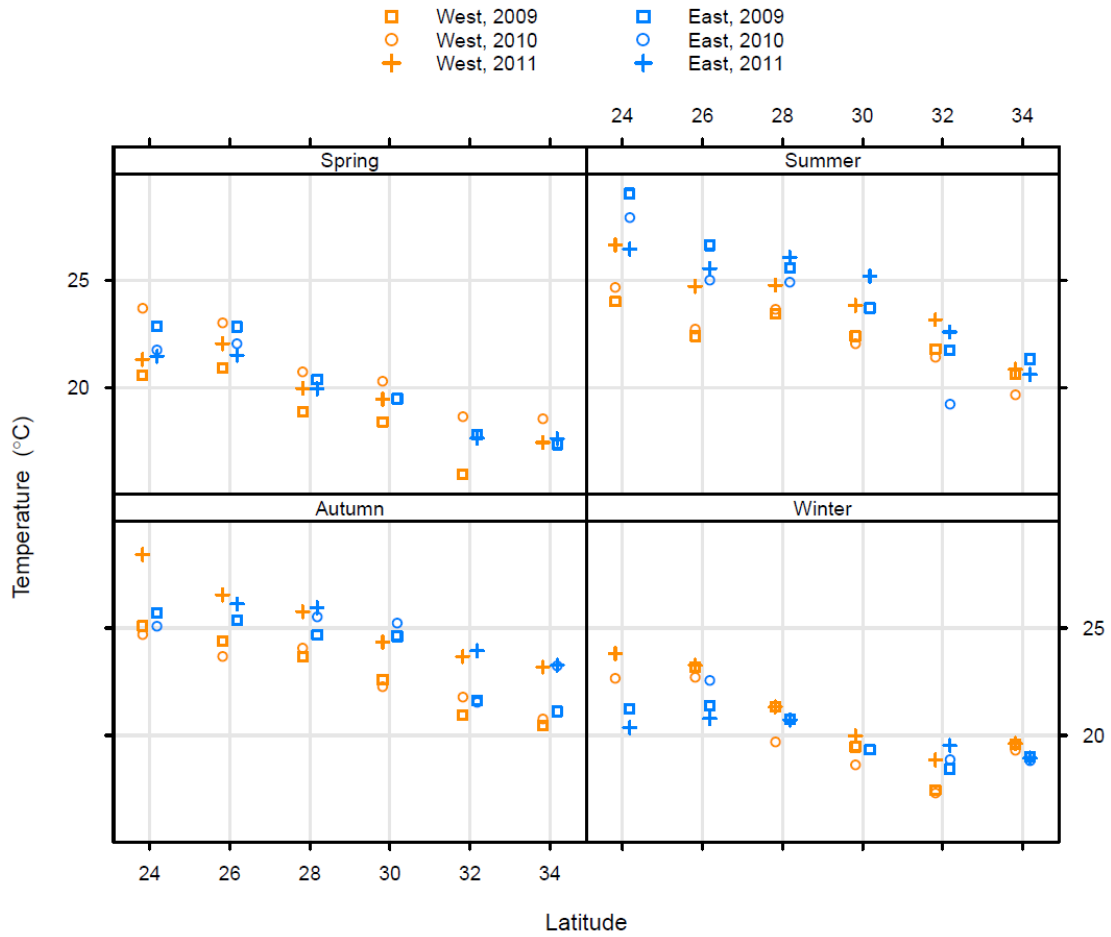
**Figure 4.3:** Simulation results for life cycle completion of *Musculista senhousia* in Broome. The horizontal line shows a 0.05 cutoff: (a) daily; (b) monthly. (c) Temperature tolerances.

with SST data from the areas around the ports.

As noted above, both extrapolation and direct modelling using satellite data will produce similar results when not close to the limits of temperature tolerance. When differences in temperature occur between these data sources that are close to a species' temperature tolerances and therefore probability of life cycle completion, this will likely result in a change in the level of risk.



**Figure 4.4:** Sea surface temperature map for January 2009 showing the temperature at two points immediately adjacent to the coast exactly on the 30° S line of latitude on the east and west coasts of Australia. SST data extracted from points on the west and east coasts on six lines of equal latitude are also shown. The temperature values extracted are plotted in Figure 4.5.



**Figure 4.5:** SST data extracted from daily SST at points on the west and east coasts on six lines of equal latitude (24–34 °C.) The data are from the first day of the month in January (summer), April (autumn), July (winter) and October (spring) over three years (2009–2011). Considerable variability (up to 5 °C) is apparent in summer and winter at 24° and 26° S in 2009 and 2010 with less variability in spring and autumn. Note that some data are missing from both east and west coasts.

## 5

# Shipping traffic

## 5.1 Introduction

In the BWRA the risk of translocation is currently based on individual voyages, ignoring the amount of traffic between ports (based on shipping movement data), the quantity of ballast water transported, and whether ballast exchange is likely (i.e. whether or not the vessel is in ballast). In this chapter we explore the use of vessel movement data for assessing the cumulative risk of establishment, and hence for identifying locations where resources would best be targeted for compliance and pest monitoring activities. We consider data from the Australian Maritime Safety Authority (AMSA), Lloyds, and the Bureau of Infrastructure, Transport and Regional Economics (BITRE) in the Department of Infrastructure and Regional Development (DIRD).

## 5.2 Methods

### 5.2.1 Source and destination locations of voyages by vessel type

Data for the seven year period 2008–2014<sup>1</sup> were purchased by the Department’s Marine Pest Unit from Lloyds Maritime Intelligence Unit. The Lloyds data identifies 100 individual vessel types. Many of these vessel types have similar characteristics, for example bulk aggregates carrier, bulk carrier with container capacity, bulk cement carrier, bulk ore carrier and wood-chip carrier are all types of bulk carrier. These vessel types have therefore been categorised into 18 categories (Table 5.1). Virtually all working vessels carry ballast water, from the largest tanker and bulk carrier to racing yachts. Three types of ballast water management can be identified:

- A Large vessels carrying bulk ballast water when not carrying cargo that must be discharged when taking on cargo. Ballast water discharge is usually predictable. Typical examples are bulk carriers.
- B Large vessels carrying ballast water for trim and stability purposes that may not need to discharge much or any of it. Typical examples are container ships that are rarely, if ever, not carrying cargo. Ballast water discharge is usually not predictable.

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<sup>1</sup>This has recently been augmented to include data for 2015.

- C Small to medium-sized vessels carrying ballast water for trim and stability purposes but rarely discharge it. The ballast water may be moved from tank to tank within the vessel.

**Table 5.1:** Vessel categories and ballast water management type categorisation.

TYPE	BW Management Type
Barge	C
Bulker	A
Cargo	B
Container ship	B
Cruise ship	C
Dredge	B
Drilling	B
Fishing	B
Harbour management	C
Livestock	B
Naval	B
Offshore support	B
Other	C
Passenger	C
Research	C
RoRo	C
Tanker	A
Yacht	C

From this list, vessels that carry bulk ballast water are likely to present a high risk for translocating invasive marine species from one Australian port to another. In this report we focus on the bulk carrier subset of vessels of Type A.

Bulk carriers are defined here to mean all dry bulk carriers, including bulk carriers with container capacity, combined ore and oil carriers and wood-chip carriers. Tankers, which are included in Category A vessels, have been excluded from these analyses because of uncertainty about their operations and, in particular, given the pervasive use of petroleum products, the extent to which vessels travel without cargo and therefore with ballast water. Most routes taken by bulk carriers are to and from the same ports, but often with quite different levels of traffic in opposite directions, which implies that vessels often take routes that are not exactly reciprocal. Not all these voyages were likely to have been cargo-carrying, for example 323 voyages from Fremantle to Kwinana and 80 voyages from Kwinana to Fremantle were likely to have been vessels in transit from one port to the other, or possibly incorrect reporting as Kwinana and Fremantle are 25 km apart. Given the close proximity of these ports, these voyages have been excluded. Similarly vessels travelling between Melbourne and Geelong, a distance of 60 km, are unlikely to manage ballast water between these two locations. They are also in the same bioregion. In 2014 there were 3654 domestic voyages by bulk carriers on 515 routes.

### 5.2.2 Voyages in ballast

A major limitation with the Lloyds data is that it is not possible to determine whether a voyage from one port to another was a cargo-carrying voyage, or a voyage to collect cargo, or a transit or port call for another reason. As noted above, many cargo carrying routes are operated between a pair of ports, for example between Weipa and Gladstone. Weipa is the site of a large bauxite mine operated by Rio Tinto. Bauxite is shipped from Weipa to Gladstone for smelting (<http://sales.riotintoaluminium.com/freedom.aspx?pid=224>). Ships returning from Gladstone to Weipa are presumably in ballast (not carrying cargo), but from the Lloyds data alone it is not possible to determine whether a vessel is carrying cargo or not. It is also not practical to manually assign likelihood of ballast transfer based on some knowledge of the purpose of particular routes.

A promising source of data on cargo-carrying voyages that could help assign whether transfer of ballast water was likely or not, was found on the website of the Department of Infrastructure and Regional Development (DIRD). DIRD maintains a list of all Temporary Licence Voyage Reports from 1 January 2012 to the present, as required under Section 62 of the Coastal Trading (Revitalising Australian Shipping) Act 2012 ([https://infrastructure.gov.au/maritime/business/coastal\\_trading/index.aspx](https://infrastructure.gov.au/maritime/business/coastal_trading/index.aspx)). Temporary Licences are required for most domestic trading voyages where they are being carried out by foreign-flagged vessels. (Not all coastal voyages by foreign-flagged vessels are required to have a licence; vessels on intra-state voyages need not have a TL). Temporary Licence Voyage Reports list those voyages and the type of cargo being transported. Comparing the temporary licences issued to a vessel with the vessel's movements in the Lloyds data provides some insights into which voyages were likely to have been carrying cargo and those where the vessel was likely to have been carrying ballast water. For example, on 03/01/2014 Vessel X, flagged in the Bahamas, departed Gladstone bound for Brisbane carrying clinker, for which a temporary licence (TL) was issued. Lloyds records that the vessel returned to Gladstone on 10/01/2014, but no TL was issued; hence, presumably this voyage was in ballast. The vessel repeated this voyage twice. The next TL was issued for a voyage from Adelaide to Melbourne carrying cement, so presumably the voyage from Brisbane to Adelaide (arriving on 22/01/2014 according to Lloyds) was in ballast. On 26/01/2014 Vessel X departed Melbourne bound for Thevenard, but without a TL, so presumably again in ballast. On 04/02/2014 the vessel departed Thevenard bound for Melbourne with a load of gypsum under a TL.

While promising, there were a number of problems encountered when trying to match these datasets. The main problem was matching vessel names, the field in common between the two datasets. Many names do not match, or match partially, implying that some vessel names are changed relatively frequently and the Lloyds database is not kept up to date. Due to the uncertainties about the reliability of the information, together with gaps in the data and the time-consuming analyses required to make it usable, we decided to classify all voyages of bulkers that are capable of carrying ballast water as high risk.

### 5.2.3 Voyage routes

Voyage routes were determined by plotting the locations of daily position reports from traffic in 2011 (<https://www.operations.amsa.gov.au/Spatial/CraftTrackingRequest>). The clustering of position report locations indicated quite clearly the routes ships take. It was



assumed that the routes vessels take is identical in both directions. Distances corresponding to these routes were calculated in ArcGIS.

### 5.3 Results and Discussion

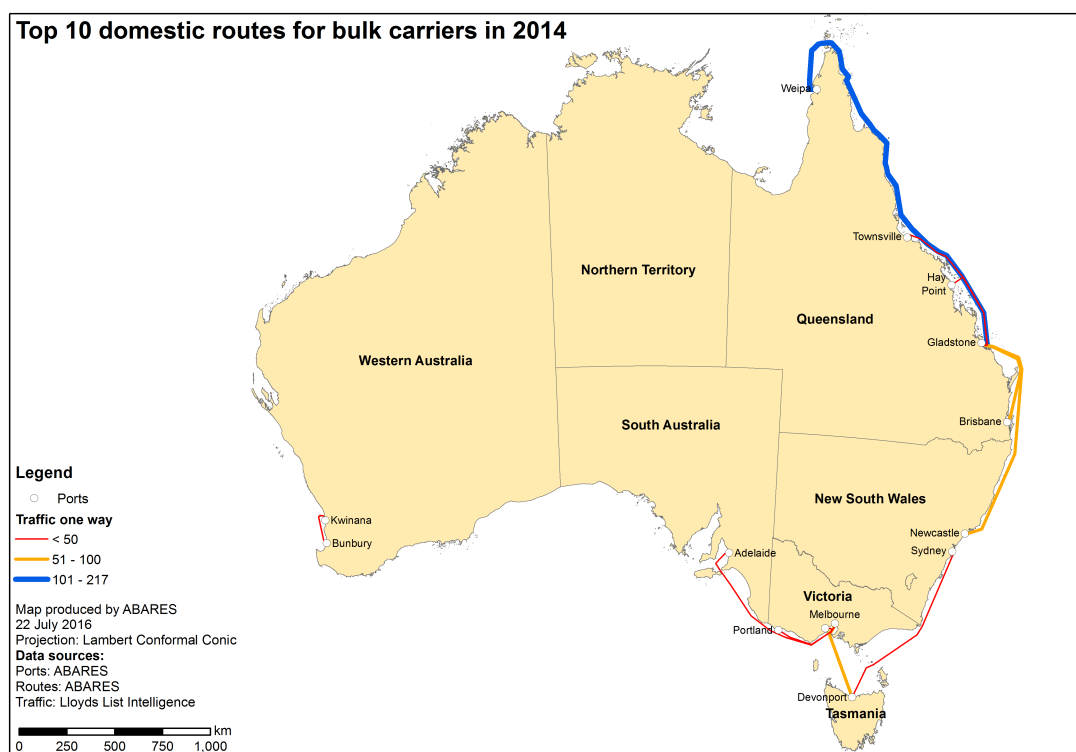
Table 5.2 lists the 16 bulk carrier shipping routes in 2014 with the highest levels of traffic, the quantity of ballast water that could potentially be discharged, and the distance of each route. Ballast water tonnage was calculated from vessel gross tonnage, which is available in Lloyds vessel data. It is straightforward to generate a table for all routes. The top 10 routes are also shown cartographically in Figure 5.1.

**Table 5.2:** Bulk carrier shipping routes with the most traffic in 2014. Note that in this table it is assumed the vessel is in full ballast for all voyages.

Departure port	Arrival port	Voyages	Ballast water (T)	Distance (km)
Weipa	Gladstone	217	6170162	2255
Gladstone	Weipa	206	5912096	2255
Brisbane	Gladstone	74	1211428	552
Devonport	Melbourne	62	339211	420
Melbourne	Devonport	62	325640	420
Gladstone	Newcastle	62	1274108	1240
Gladstone	Brisbane	58	968196	552
Newcastle	Gladstone	50	1524488	1240
Melbourne	Adelaide	45	462229	960
Adelaide	Melbourne	41	444210	960
Geelong	Portland	39	618291	362
Gladstone	Hay Point	39	1794892	493
Hay Point	Gladstone	35	1583096	493
Kwinana	Bunbury	28	421180	202
Gladstone	Townsville	28	287581	800
Devonport	Sydney	28	149520	975

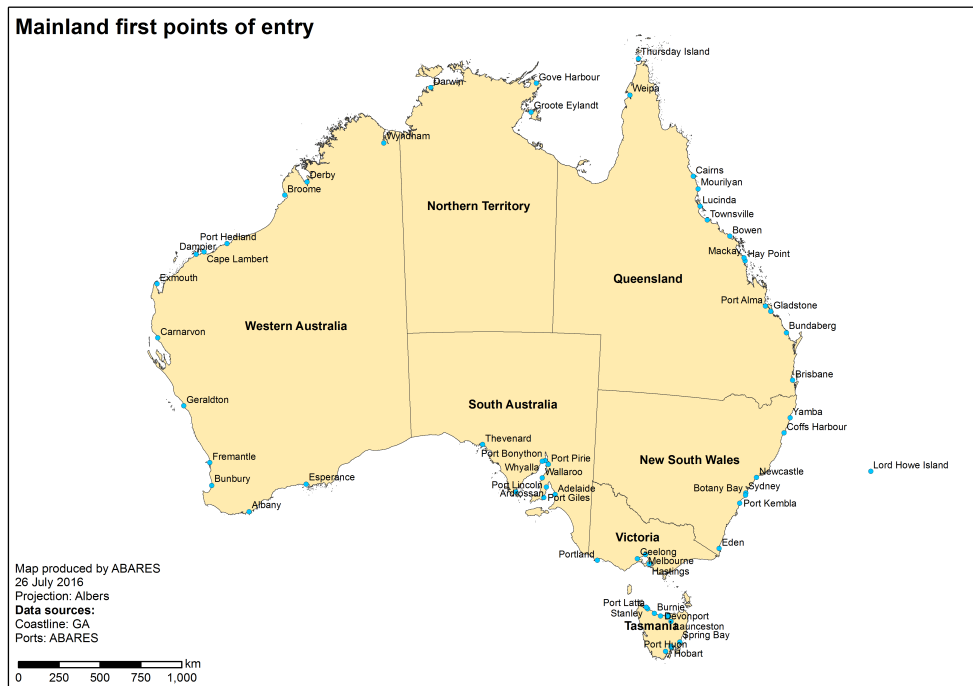
Many of the ports involved with high domestic traffic were identified as first points of entry (Figure 5.2); ports that have been declared under the Biosecurity Act (2015) as places where vessels that are subject to biosecurity control must enter Australia (<http://www.agriculture.gov.au/biosecurity/avm/vessels/ports/first-point-entry>). These ports are more likely to be first points of incursion for invasive marine species should incursions occur, from which there is a substantial network of domestic ballast water transport around Australia with the potential to spread them further.

Here we consider Gladstone as a particular example as it is a node in five of the top 10 routes for domestic bulk carrier traffic (Table 5.2 and Figure 5.3). In the current BWRA Gladstone is classified as a low risk donor port, based on a port survey for introduced marine species carried out in 2000, during which none of the invasive marine species included in the BWRA were found [28]. The initial intention with the BWRA was that port surveys should be undertaken every 2 years, but this has not occurred and the classification has

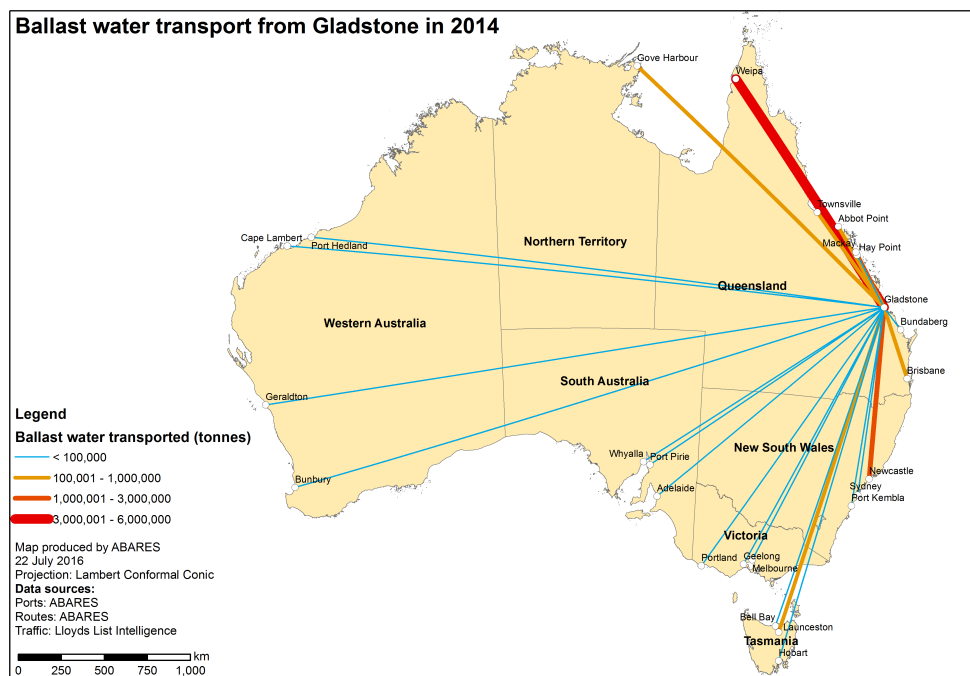


**Figure 5.1:** The 10 routes with the highest traffic by bulk carriers during 2014.

therefore not been updated. For ports where surveys have not been carried out or have become outdated, risk classifications in the BWRA consider whether any of the target species could complete their life cycle from the date of arrival in the destination port, which could be at any time of the year. If the temperature tolerance data for each species suggests that the species would be able to complete its life cycle, then this becomes a ‘risky’ donor port. If the system is to be implemented in its current form, where overall risk includes the results of port surveys/monitoring to identify whether target species are likely to be present or not, then the type of analysis applied to Gladstone will help determine where port monitoring will be most valuable. The same type of analysis will also identify where compliance activities could be targeted. However, these analyses would be strengthened if there was some way to identify the number of voyages where actual ballast exchange was likely. In the short term this is not tractable, but once a domestic ballast water management system is implemented data could be collected directly on voyages where ballast water was carried.



**Figure 5.2:** First points of entry. First points of entry in the offshore territories are not shown.



**Figure 5.3:** The quantity of ballast water transported from Gladstone in 2014 and the 24 ports it was transported to.

## 6

# Conclusions

## Sea temperature and life cycle simulations

We recommend that SeaFRAME tide gauge temperature data be replaced with satellite sea surface temperature (SST) data as the data source for the BWRA risk tables. Both data sources have their advantages and disadvantages: the tide gauge data may be more accurate at the point at which it is recorded, but SST data may capture the range of temperature in the environment around a port better. SST has the considerable advantage in that it covers the entire coastline, including in or near every port in Australia, which obviates the need to use the statistical models to interpolate lifecycle completion to the majority of ports based on latitude. The results from both sources are broadly similar, but they can produce different results for life cycle simulations when species temperature tolerances that underpin the life cycle models fall near the maximum or minimum temperature recorded. There is currently no understanding of which (if either) data source properly captures the full range of temperatures experienced by marine species in any given port environment. In reality, marine environments probably provide a much broader range of different temperatures than those measured by either data source due to things like different water depths, tides and currents, insolation effects, and variation in freshwater inputs. If that is the case, then both could be considered reasonable representations of the general temperatures experienced by marine species at the locations at which they are measured.

In the BWRA the temperature data are combined with temperature tolerances to model whether life cycle can be completed. There have been many attempts to determine the temperature tolerances of invasive marine species [26, 27]. Thermal tolerances have been found to be elastic, with some invasive marine species exhibiting much wider thermal tolerances in new environments than in their original environments [11]. The BWRA attempts to incorporate some of this uncertainty in temperature tolerance at the margins (Appendix B), but these values have not been updated since the early development of the models. We recommend that this be undertaken.

Uncertainty in tolerance parameters combines with uncertainty from the temperature data to produce the overall uncertainty in the life cycle simulations represented by ‘the proportion of simulations where life cycle was completed’. The BWRA now uses a reasonably conservative interpretation of risk based on this statistic, considering 5% of simulations in which life cycles are completed to represent unacceptable risk. However, it would be useful to have some empirical evidence that provides insight into how well these models represent

actual risk and we recommend that this be undertaken.

Regardless of whether or not the BWRA is to adopt SST as the data source underpinning the simulation models some revisions to the list of ports should be undertaken. The BWRA currently provides risk classifications for 129 ports, with the majority extrapolated from statistical models. If all these are to be modelled directly with simulation modelling underpinned by SST data, this represents a large computational overhead, both in extracting the data and in performing the modelling. Further, many of these ports are not used by vessels carrying ballast water that will be discharged, for example, Margate, Stenhouse Bay and Macquarie Island. There are also a number of duplicates such as Port Jackson and Sydney; Port Phillip Bay, Melbourne and Geelong; Botany Bay and Port Botany; Hastings and Westernport. Hence, it is recommended that the list be reviewed and only those ports that are visited by bulk ballast water carrying vessels (Type A, Chapter 5) be included in the simulation models. Even if it is decided to continue with the SeaFRAME data and statistical extrapolation, it would be useful to consolidate the number of ports considered in the BWRA. The list of ports should be reviewed periodically to ensure that it is kept up to date.

Access to SST data has proved to be unnecessarily difficult and time-consuming, due to the constraints on the use of the Department's IT systems. It does not make sense to download whole daily SST datasets, especially when they extend from the Bay of Bengal to the Ross Sea in Antarctica. It will be much more efficient to extract the data required for each port from the data on the IMOS server using a protocol like the Open-source Project for a Network Data Access Protocol (OPeNDAP), which will reduce the bandwidth required to access SST data by an estimated 95%. If satellite SST data is adopted in the BWRA it will be necessary to develop the systems to allow this to happen. We recommend that these issues be resolved in plenty of time before the system goes live.

## Using vessel voyage data

Lloyds data are useful for determining how many voyages have occurred in the past, by vessels that could have been carrying bulk ballast water. This will give an indication of the ports where compliance activities could be targeted, where monitoring to determining the likely presence of marine pests would be useful (but see Arthur *et al.* 2015b[29] for a discussion of marine pest monitoring and the BWRA), and for combining with the results of the life completion simulations to provide a more comprehensive estimate of the risk of translocation using the methods described in Arthur *et al.* 2015a[8]. However, they are limited because they do not clearly identify whether any particular voyage was undertaken in ballast or with cargo.

The list of all Temporary Licence Voyage Reports maintained by the Department of Infrastructure and Regional Development (DIRD) was identified as a possible way to determine whether voyages were likely to be in ballast or not, but it proved too difficult to easily match these data with the Lloyds data. In the future a more comprehensive data set that identifies the number of domestic voyages carrying large amounts of ballast water requiring discharge could be obtained from administration of the BWRA system. We recommend that any administrative system developed is designed to ensure comprehensive and accurate capture of these data.

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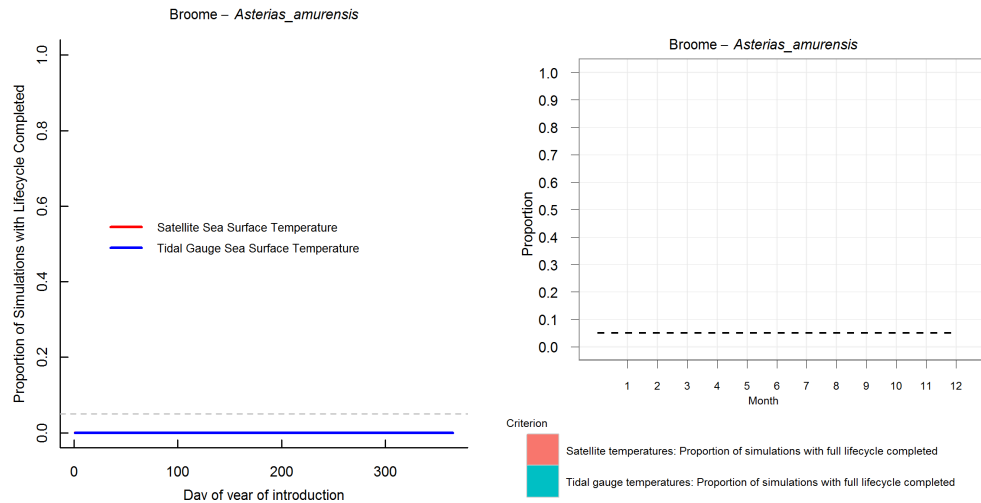
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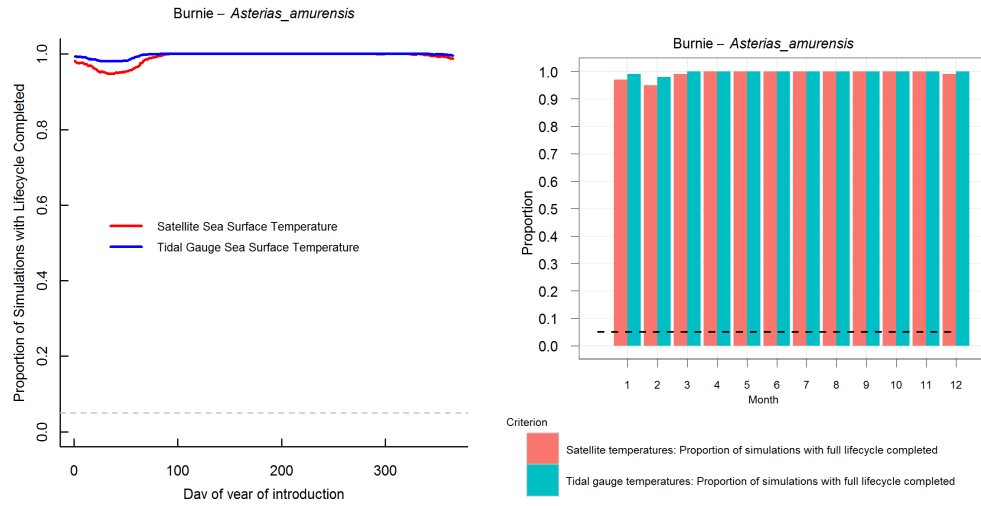
## Appendix A

# Comparison of the proportion of simulations with life cycle completed based on SeaFRAME versus satellite SST data.

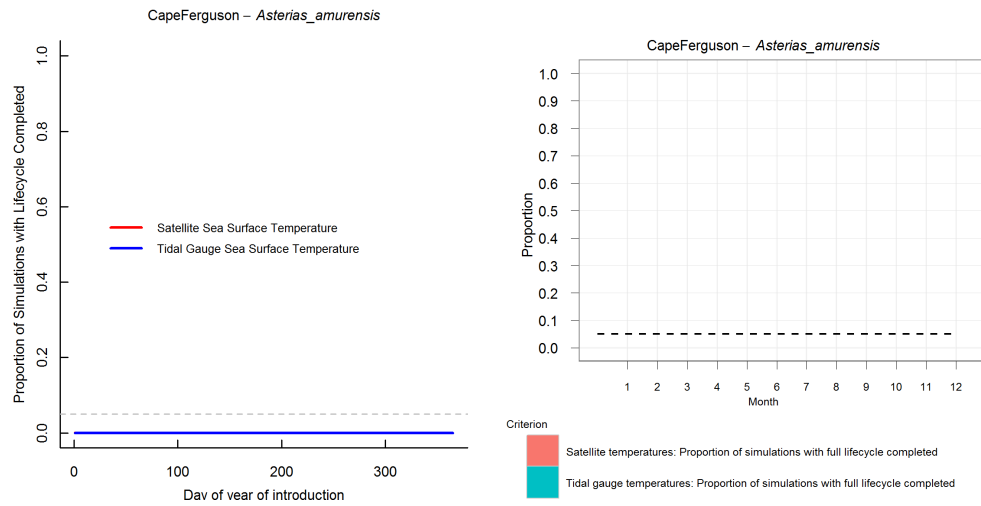
### A.1 *Asterias amurensis*



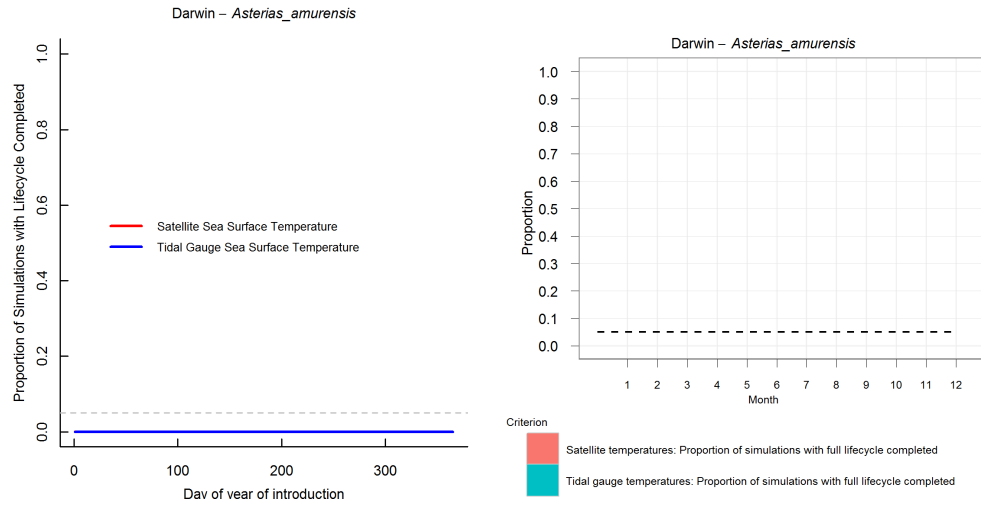
**Figure A.1:** Simulation results for life cycle completion of *A. amurensis* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



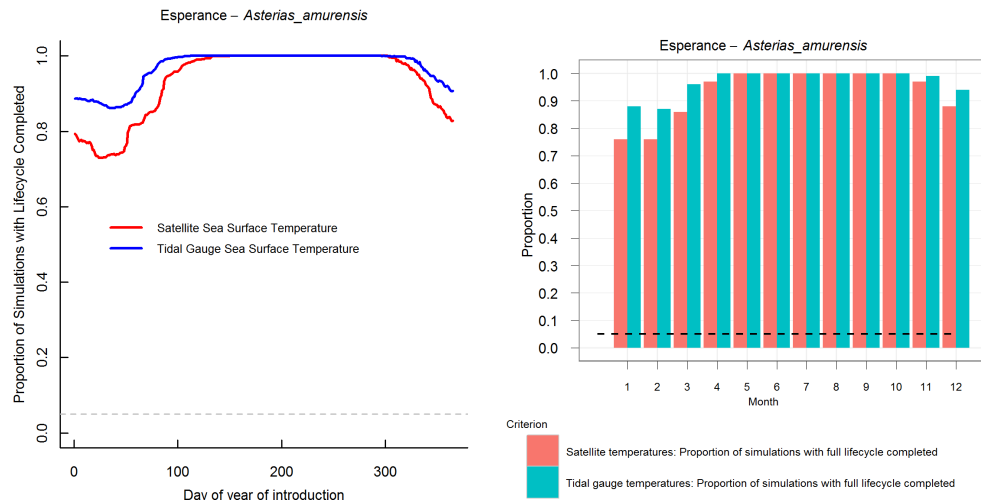
**Figure A.2:** Simulation results for life cycle completion of *A. amurensis* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



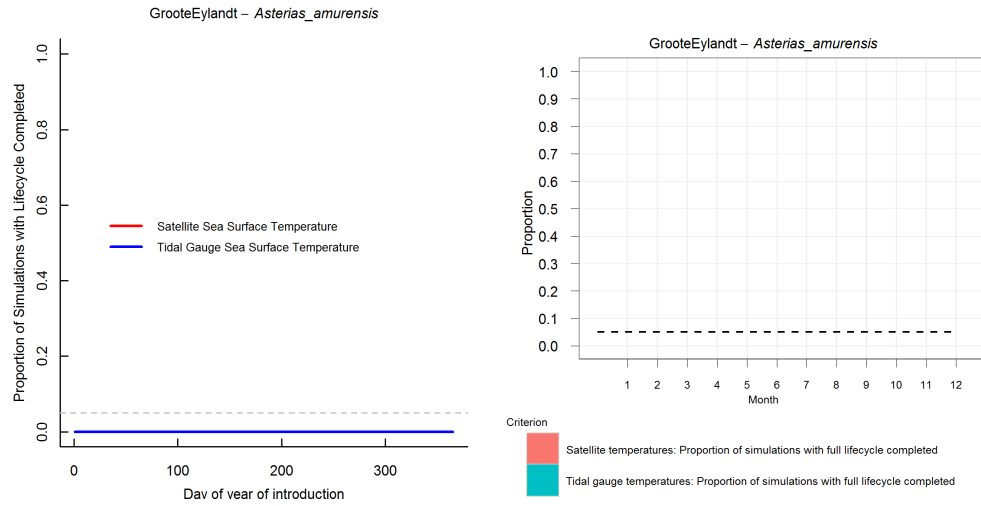
**Figure A.3:** Simulation results for life cycle completion of *A. amurensis* in Cape Ferguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



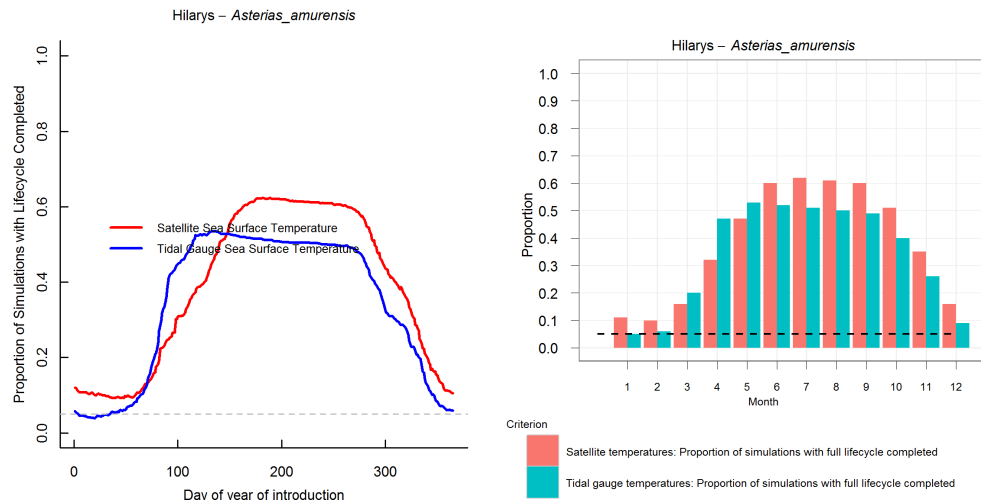
**Figure A.4:** Simulation results for life cycle completion of *A. amurensis* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



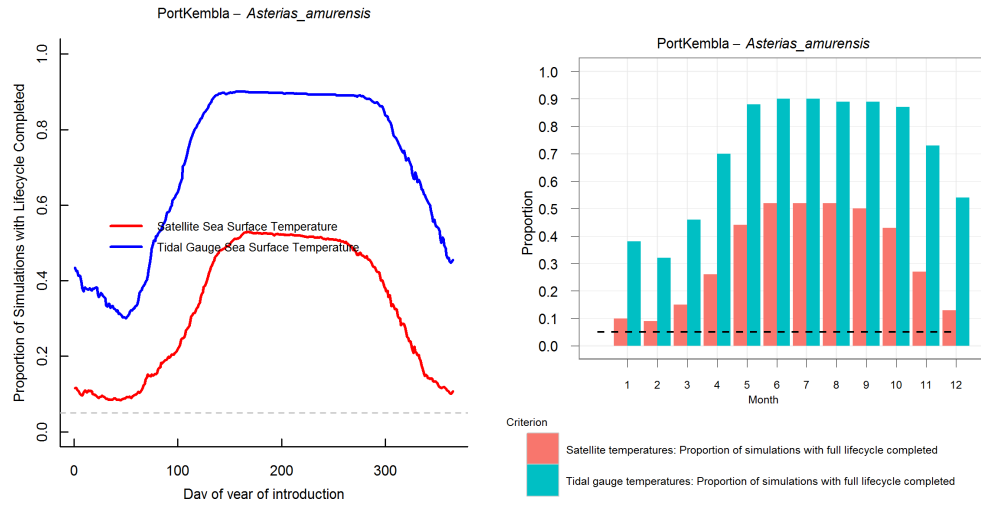
**Figure A.5:** Simulation results for life cycle completion of *A. amurensis* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



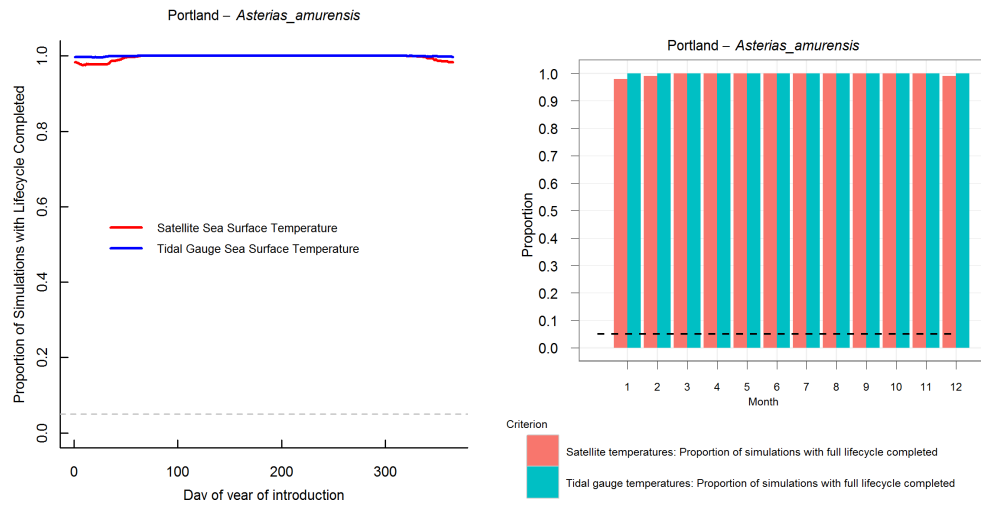
**Figure A.6:** Simulation results for life cycle completion of *A. amurensis* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



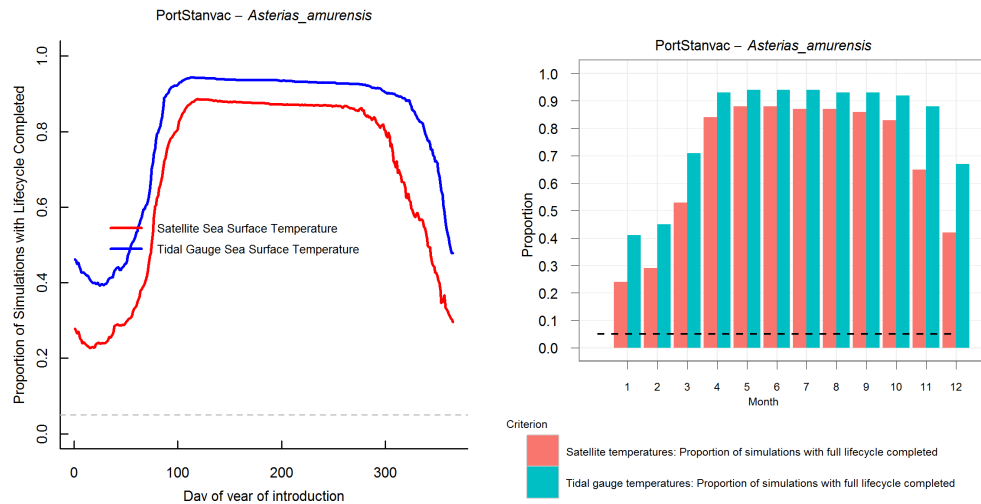
**Figure A.7:** Simulation results for life cycle completion of *A. amurensis* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



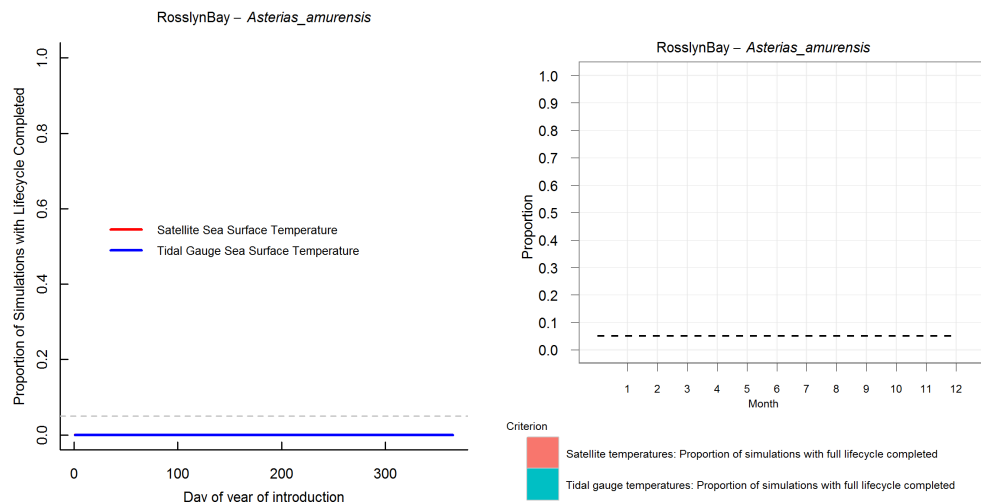
**Figure A.8:** Simulation results for life cycle completion of *A. amurensis* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



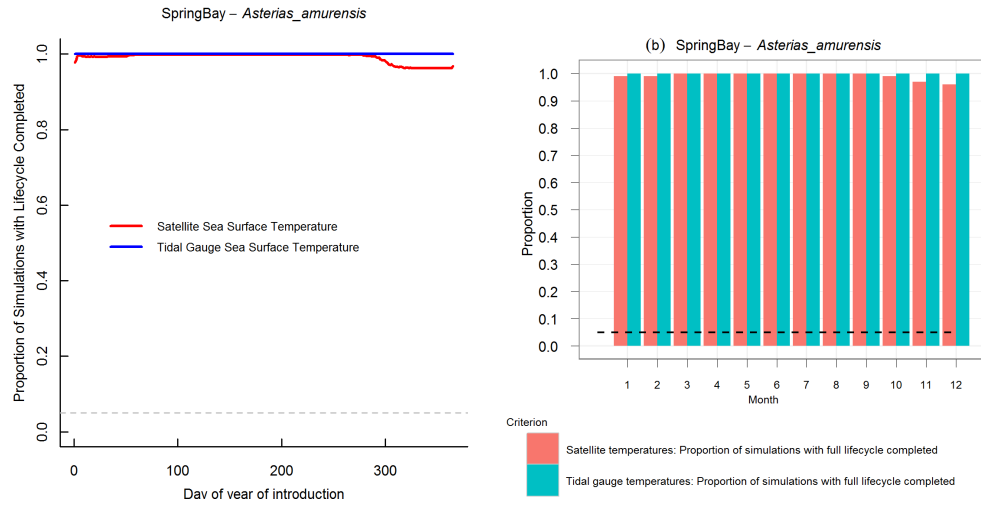
**Figure A.9:** Simulation results for life cycle completion of *A. amurensis* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



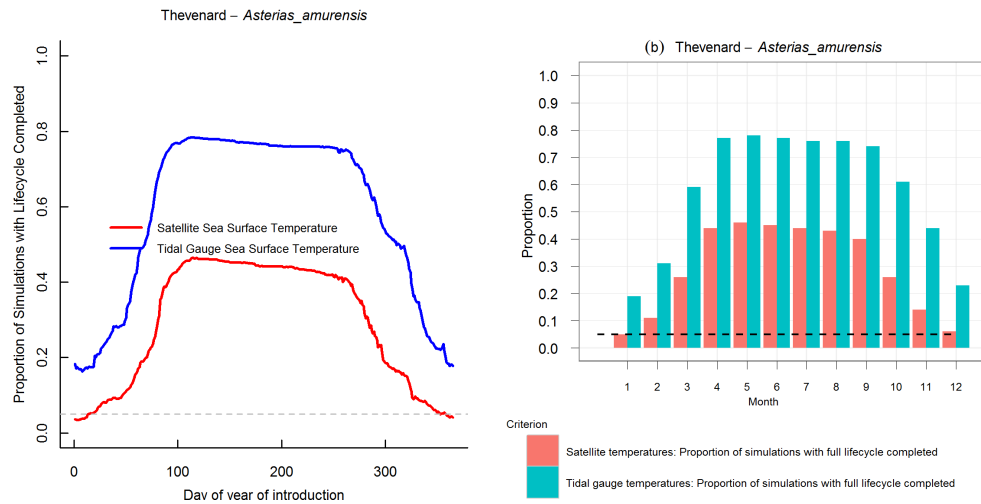
**Figure A.10:** Simulation results for life cycle completion of *A. amurensis* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.11:** Simulation results for life cycle completion of *A. amurensis* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

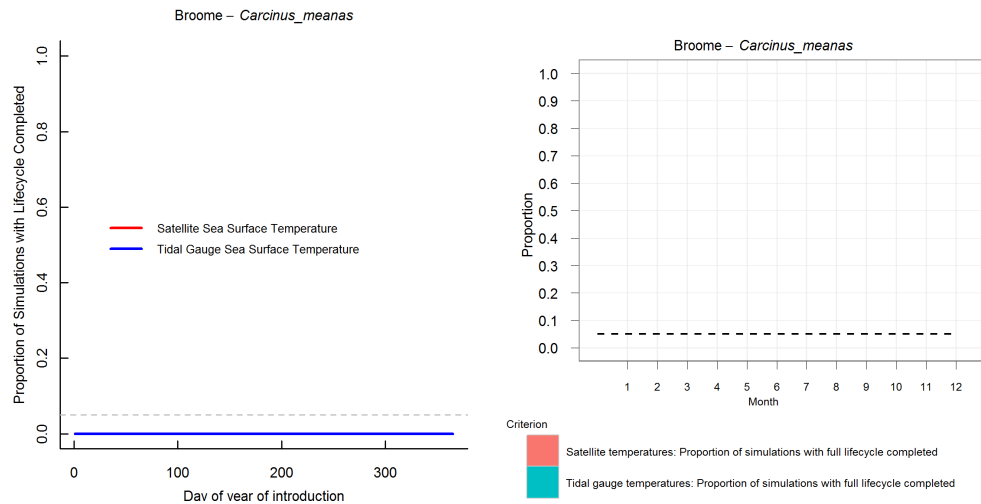


**Figure A.12:** Simulation results for life cycle completion of *A. amurensis* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

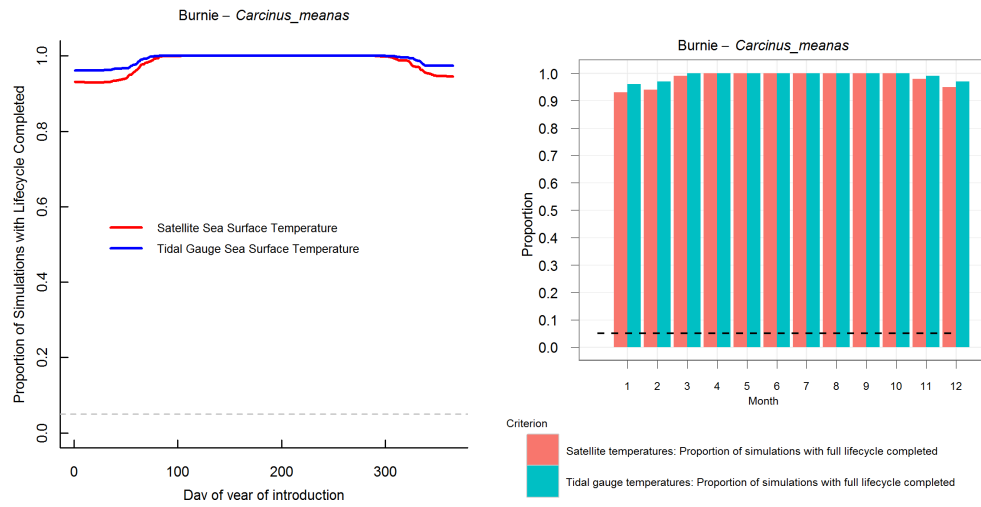


**Figure A.13:** Simulation results for life cycle completion of *A. amurensis* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

## A.2 *Carcinus maenas*

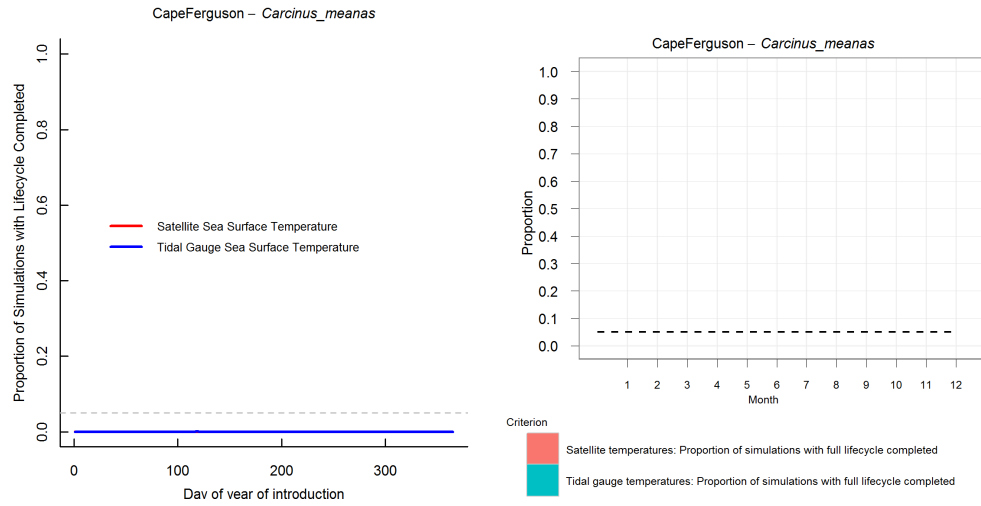


**Figure A.14:** Simulation results for life cycle completion of *C. maenas* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

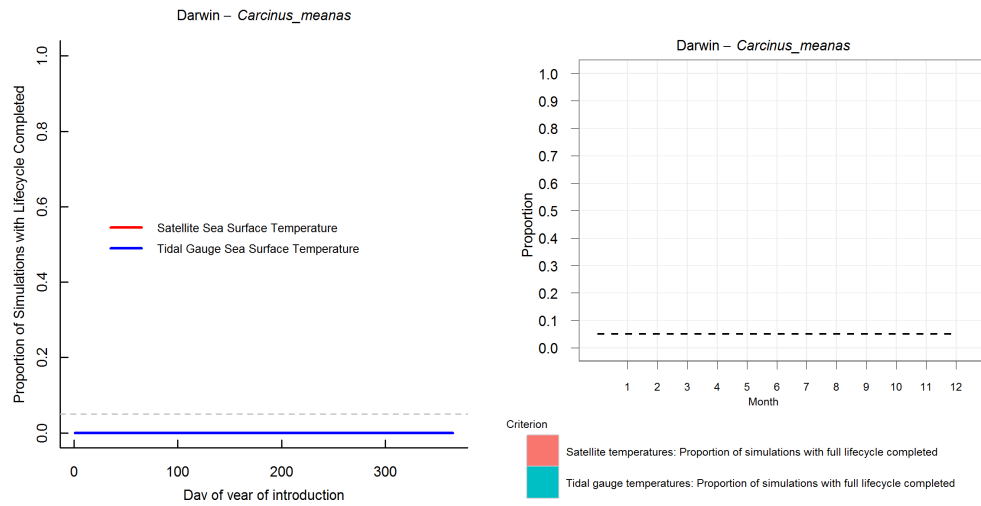


**Figure A.15:** Simulation results for life cycle completion of *C. maenas* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

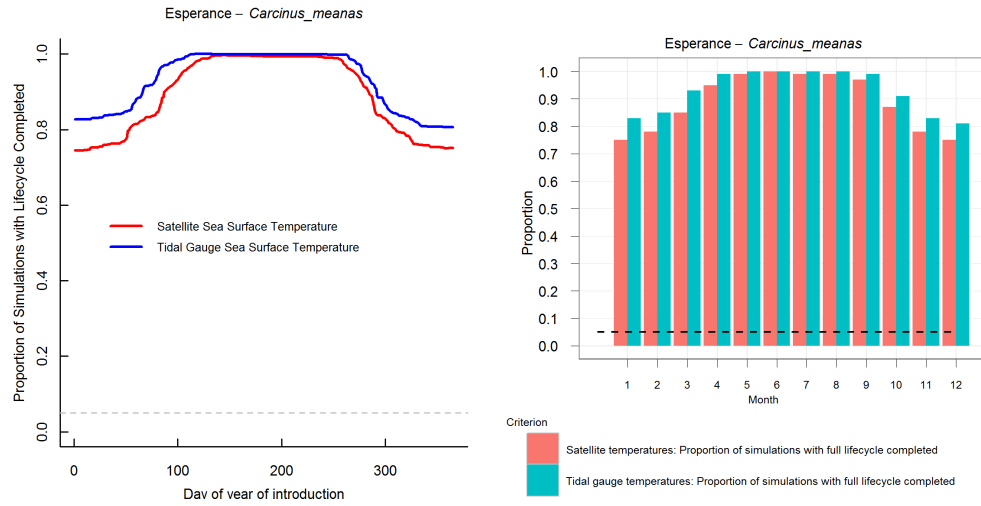




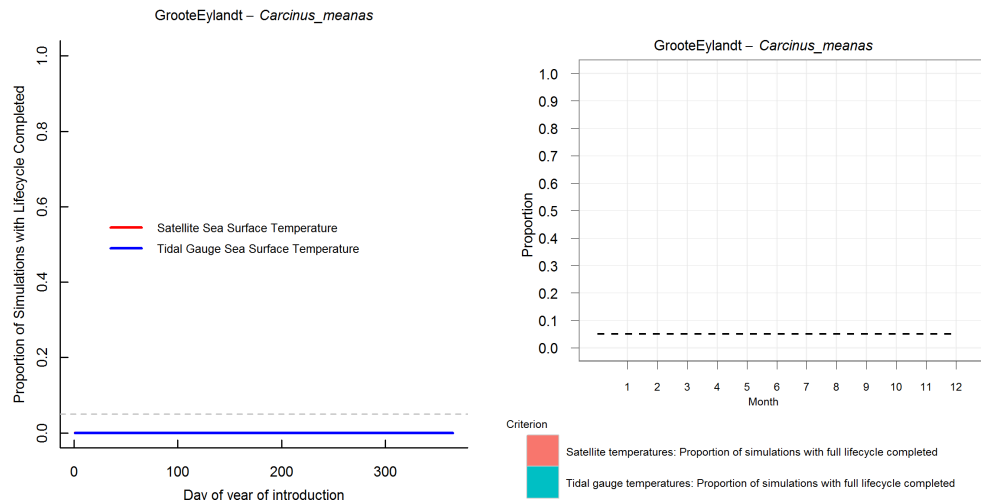
**Figure A.16:** Simulation results for life cycle completion of *C. maenas* in CapeFerguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



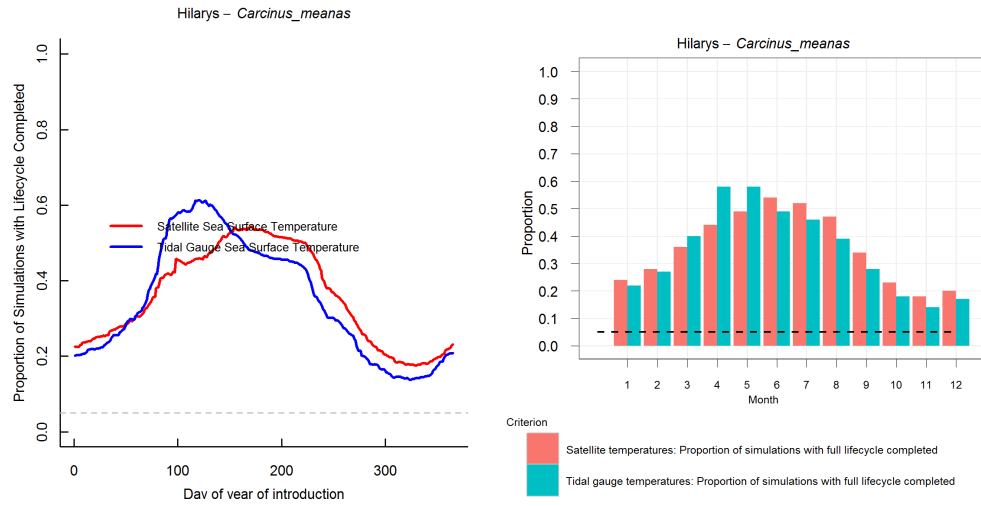
**Figure A.17:** Simulation results for life cycle completion of *C. maenas* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



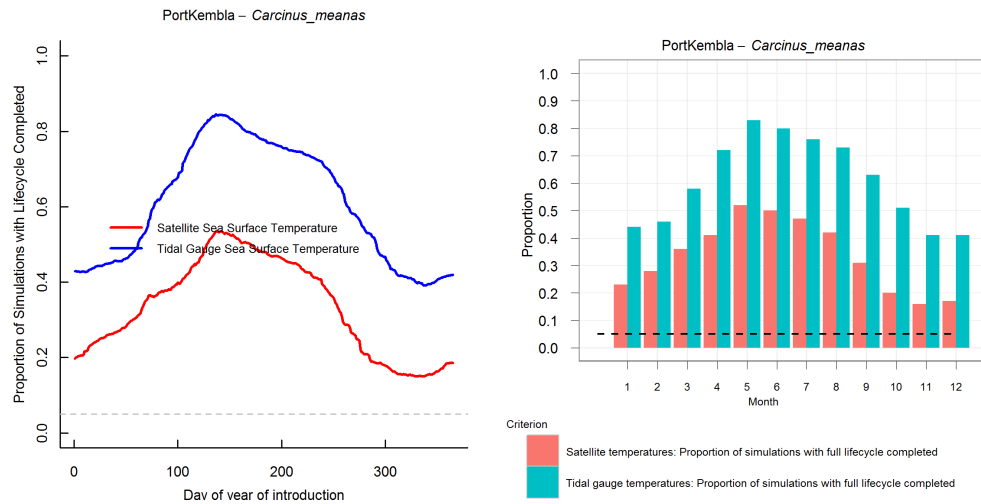
**Figure A.18:** Simulation results for life cycle completion of *C. maenas* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



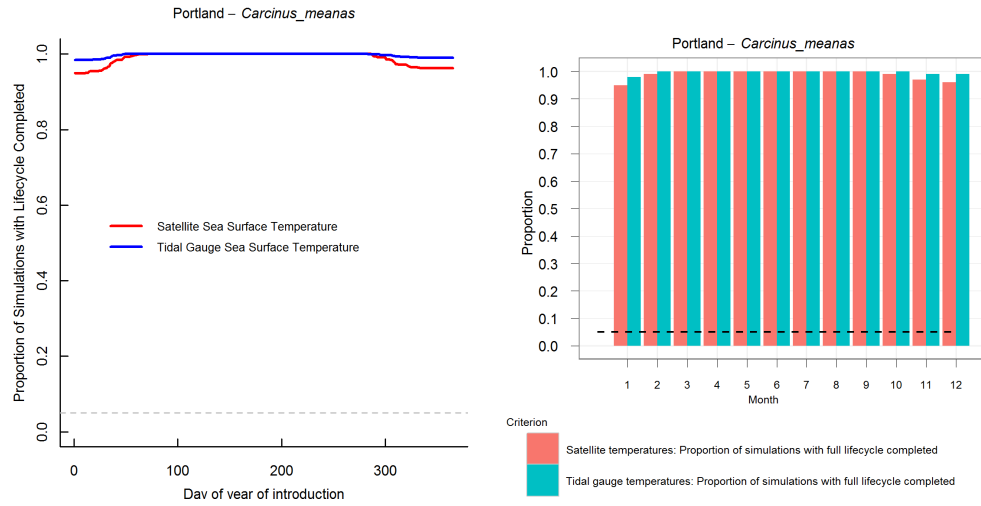
**Figure A.19:** Simulation results for life cycle completion of *C. maenas* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



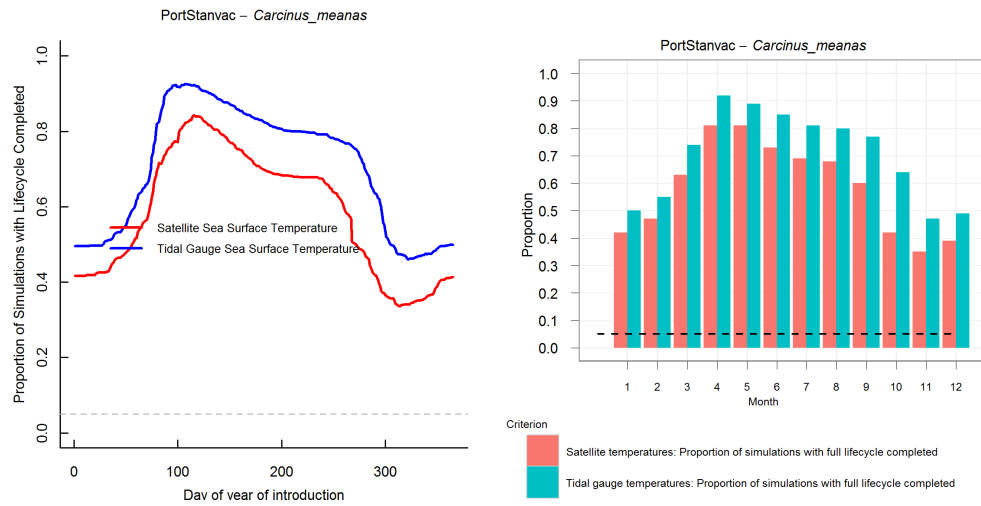
**Figure A.20:** Simulation results for life cycle completion of *C. maenas* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



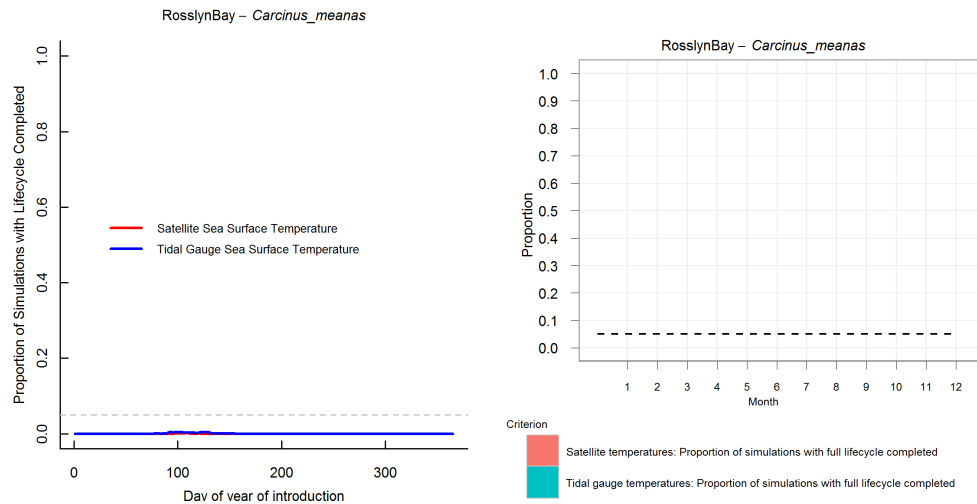
**Figure A.21:** Simulation results for life cycle completion of *C. maenas* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



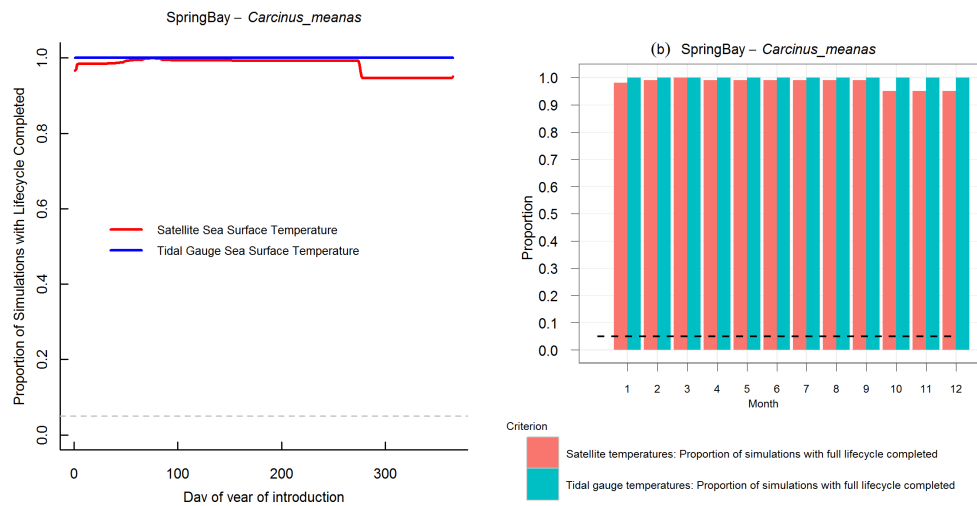
**Figure A.22:** Simulation results for life cycle completion of *C. maenas* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



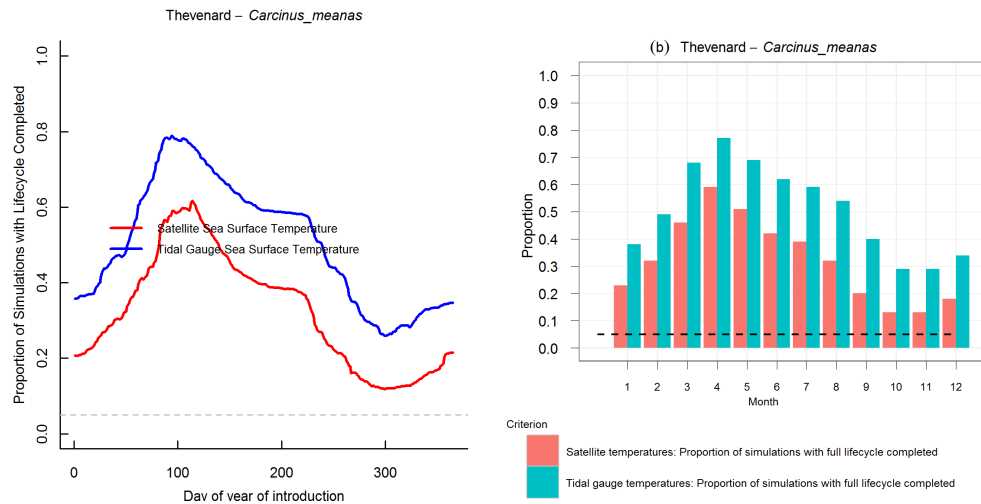
**Figure A.23:** Simulation results for life cycle completion of *C. maenas* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.24:** Simulation results for life cycle completion of *C. maenas* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

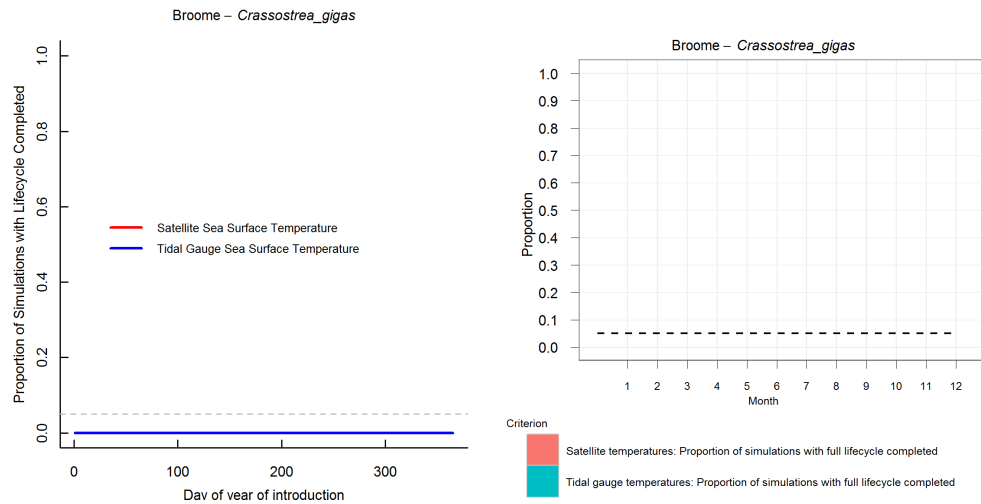


**Figure A.25:** Simulation results for life cycle completion of *C. maenas* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

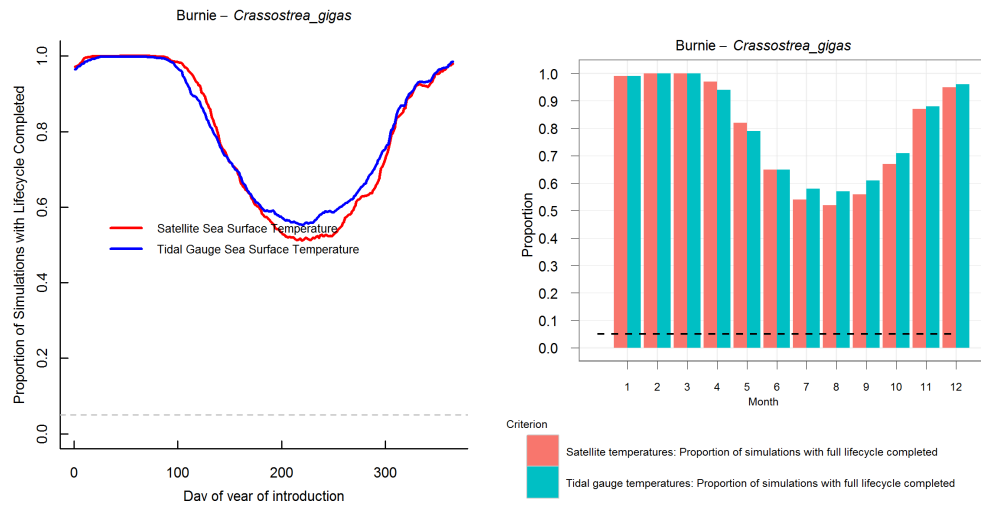


**Figure A.26:** Simulation results for life cycle completion of *C. maenas* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

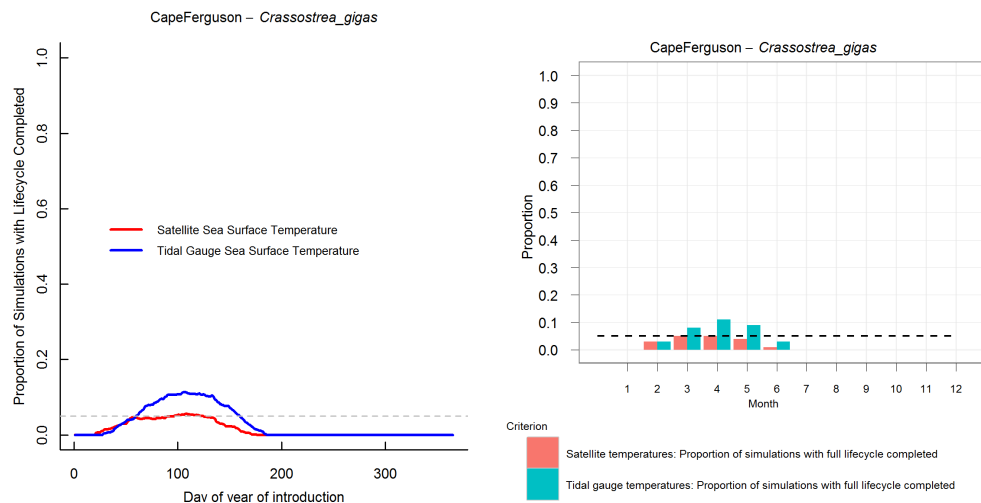
### A.3 *Crassostrea gigas*



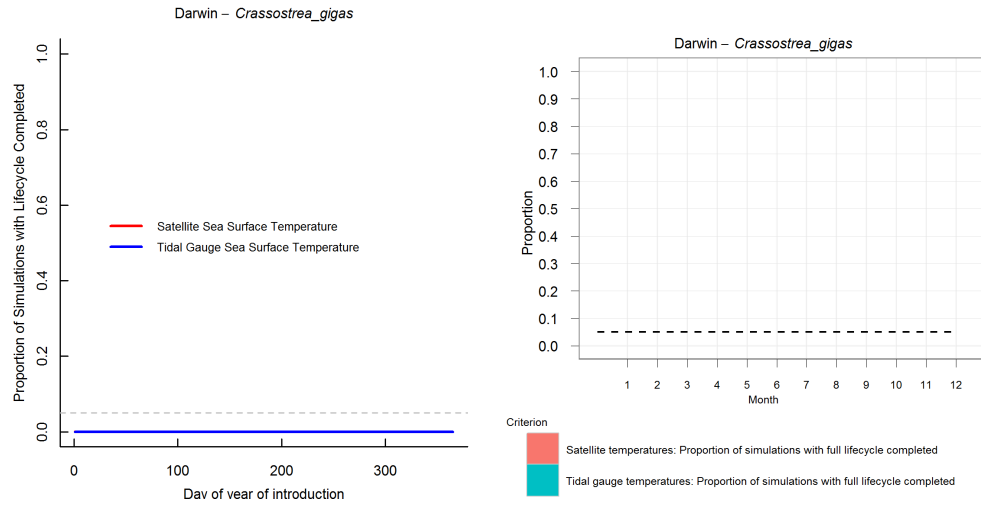
**Figure A.27:** Simulation results for life cycle completion of *C. gigas* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



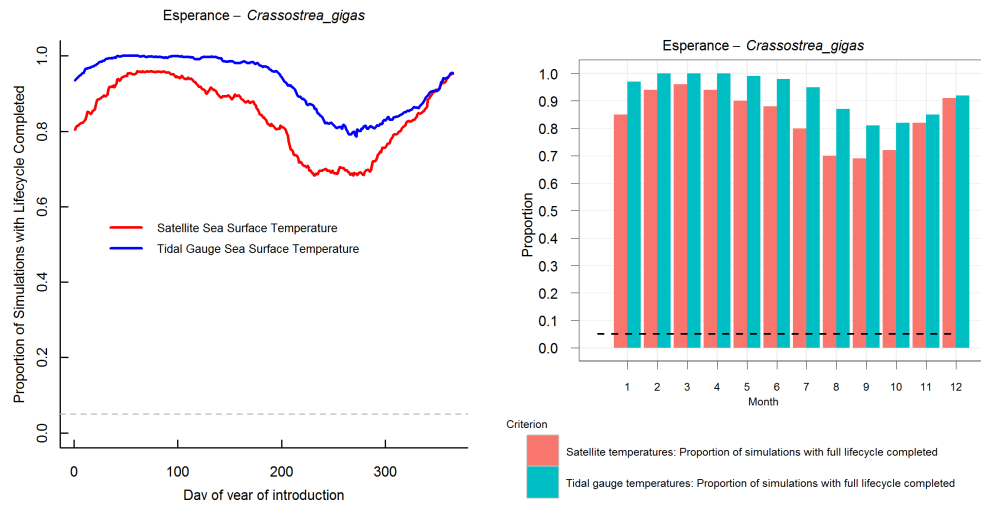
**Figure A.28:** Simulation results for life cycle completion of *C. gigas* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.29:** Simulation results for life cycle completion of *C. gigas* in Cape Ferguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

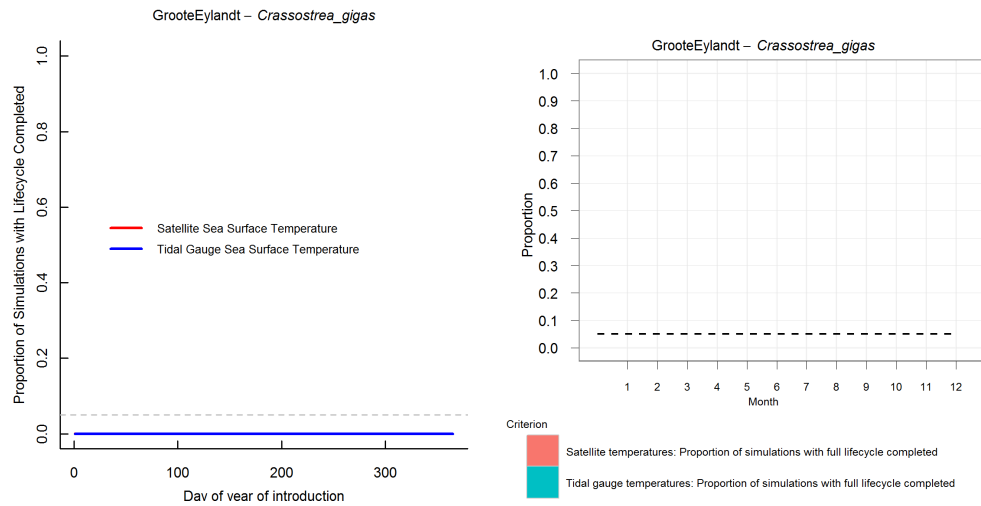


**Figure A.30:** Simulation results for life cycle completion of *C. gigas* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

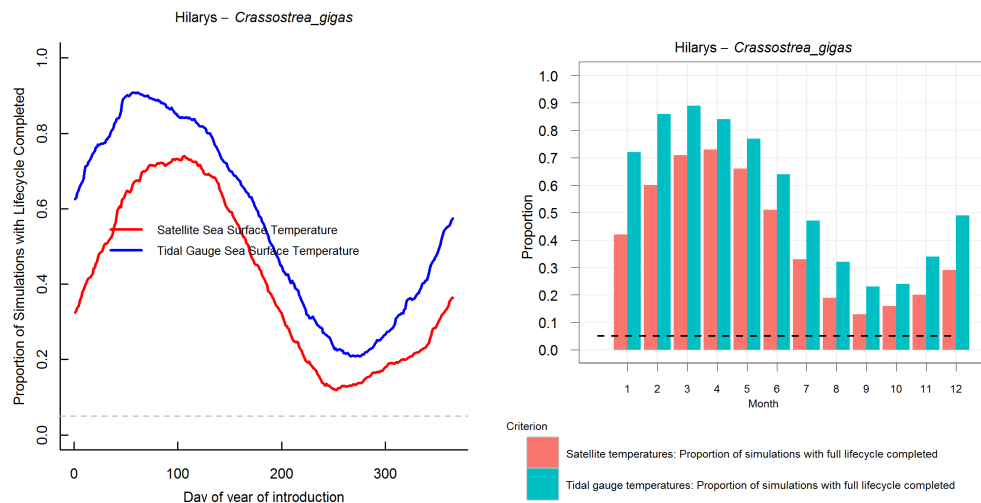


**Figure A.31:** Simulation results for life cycle completion of *C. gigas* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

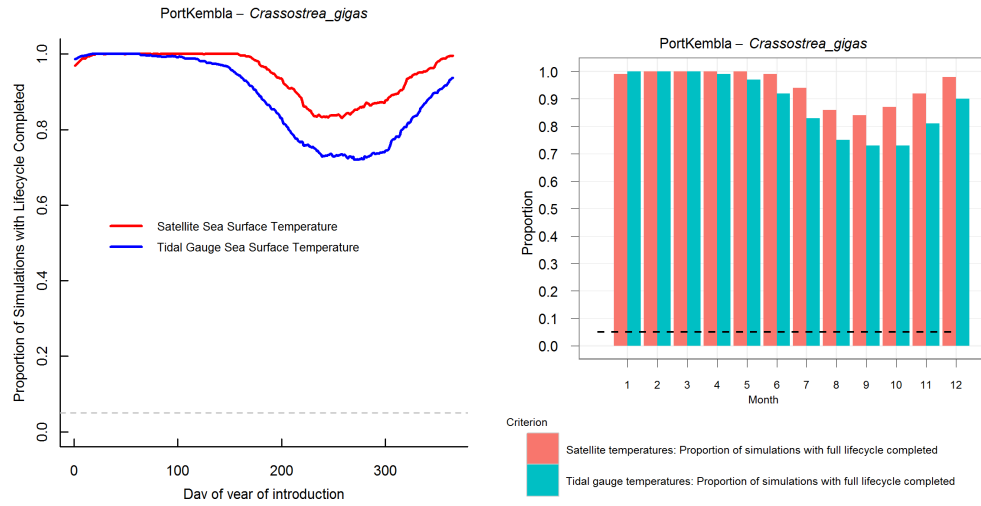




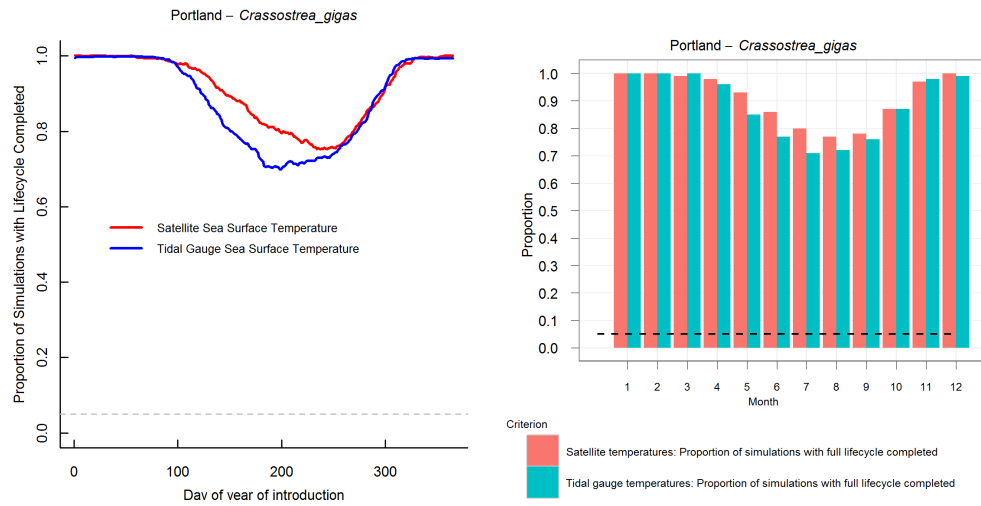
**Figure A.32:** Simulation results for life cycle completion of *C. gigas* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



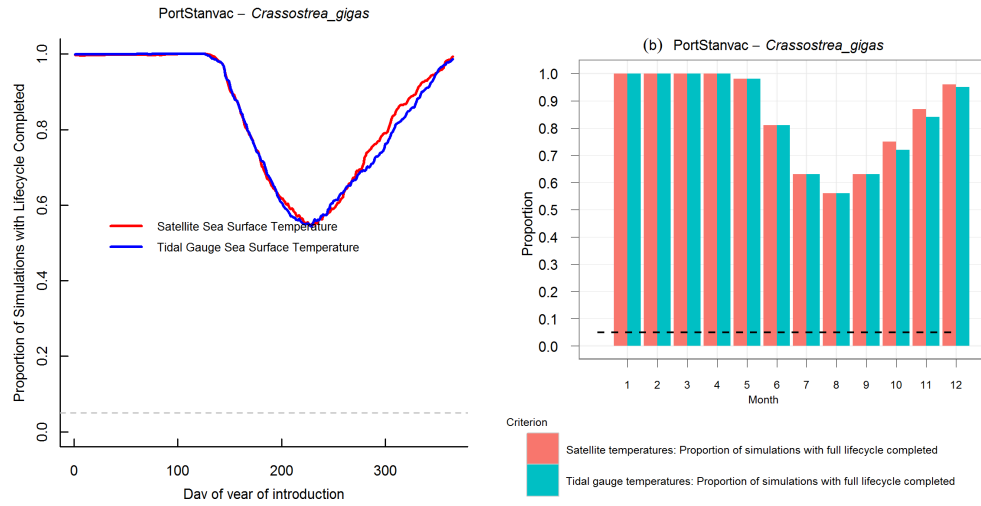
**Figure A.33:** Simulation results for life cycle completion of *C. gigas* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



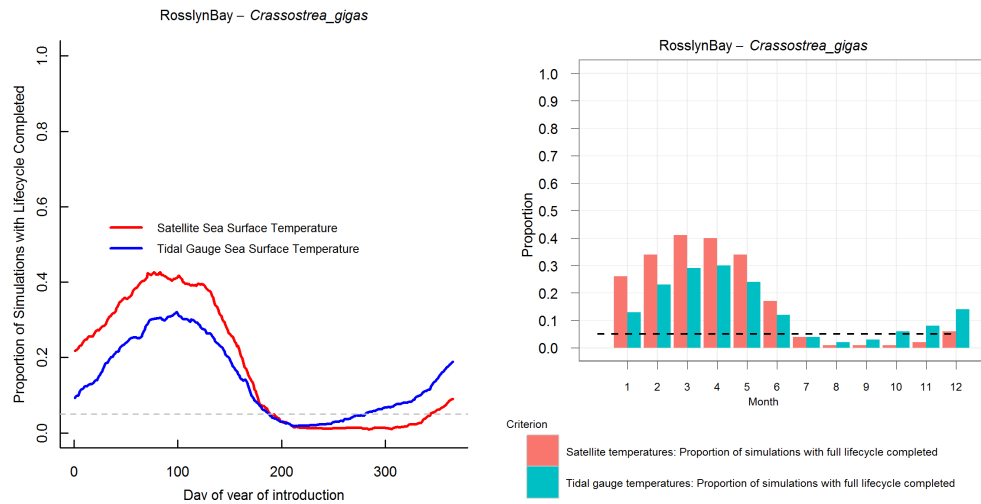
**Figure A.34:** Simulation results for life cycle completion of *C. gigas* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



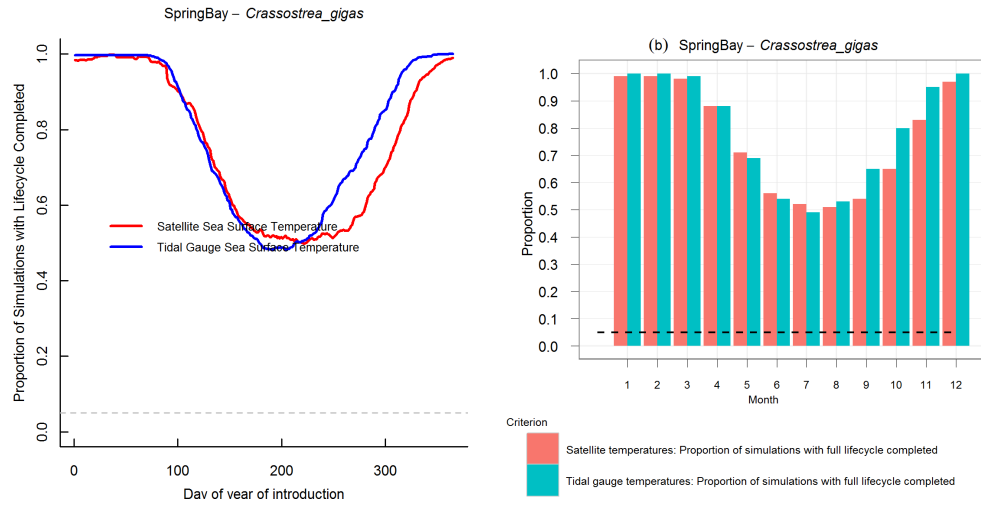
**Figure A.35:** Simulation results for life cycle completion of *C. gigas* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



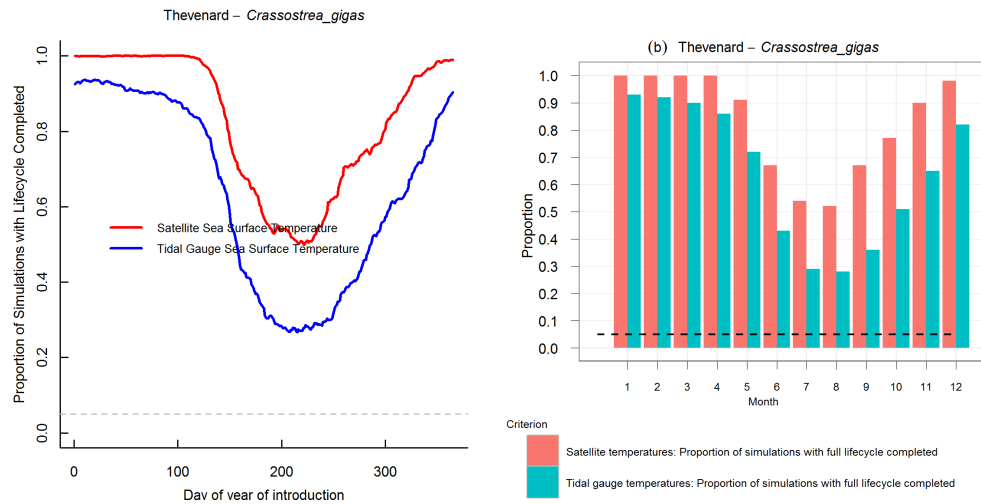
**Figure A.36:** Simulation results for life cycle completion of *C. gigas* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.37:** Simulation results for life cycle completion of *C. gigas* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

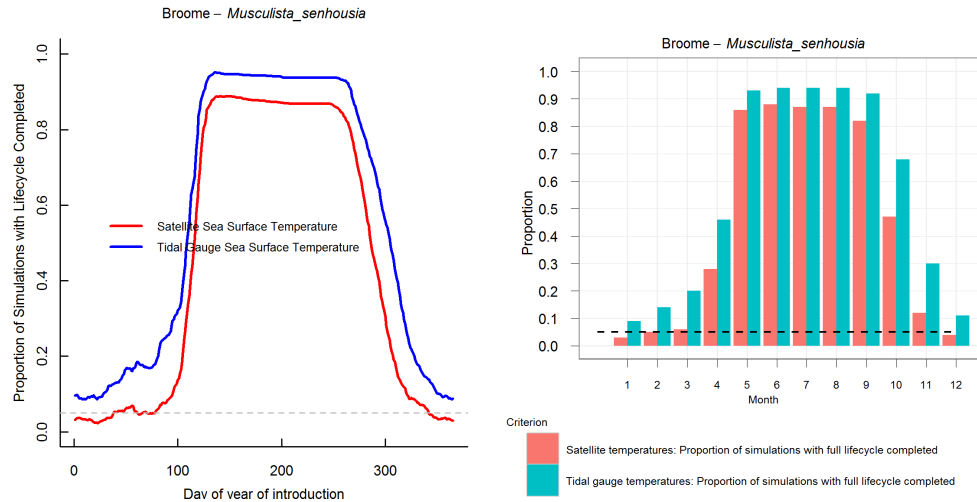


**Figure A.38:** Simulation results for life cycle completion of *C. gigas* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

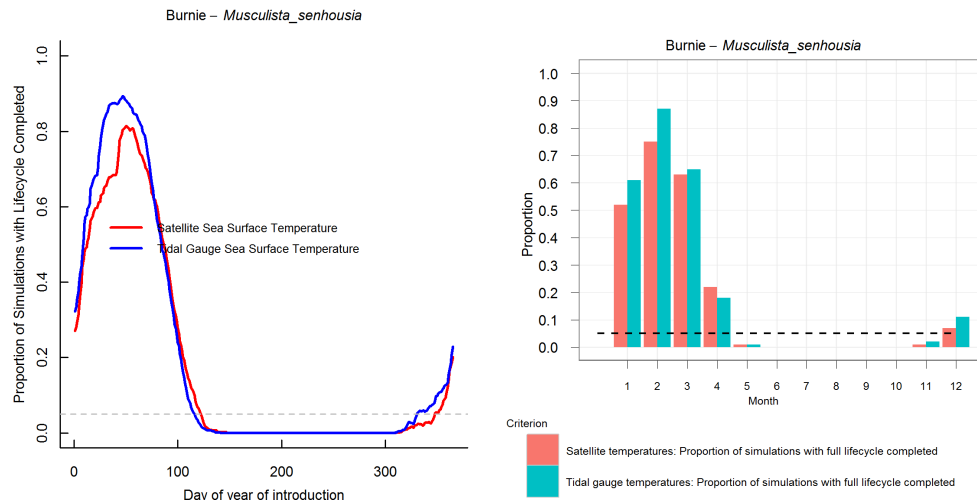


**Figure A.39:** Simulation results for life cycle completion of *C. gigas* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

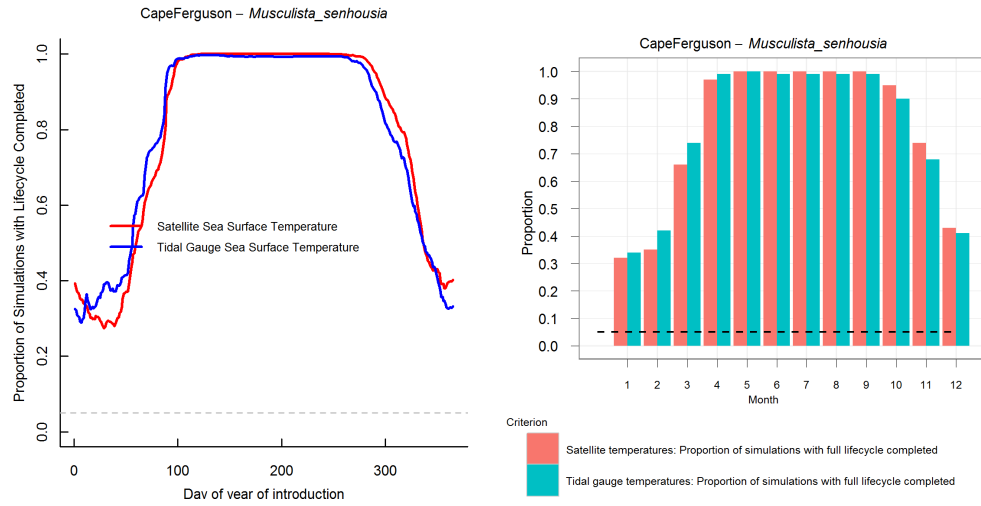
## A.4 *Musculista senhousia*



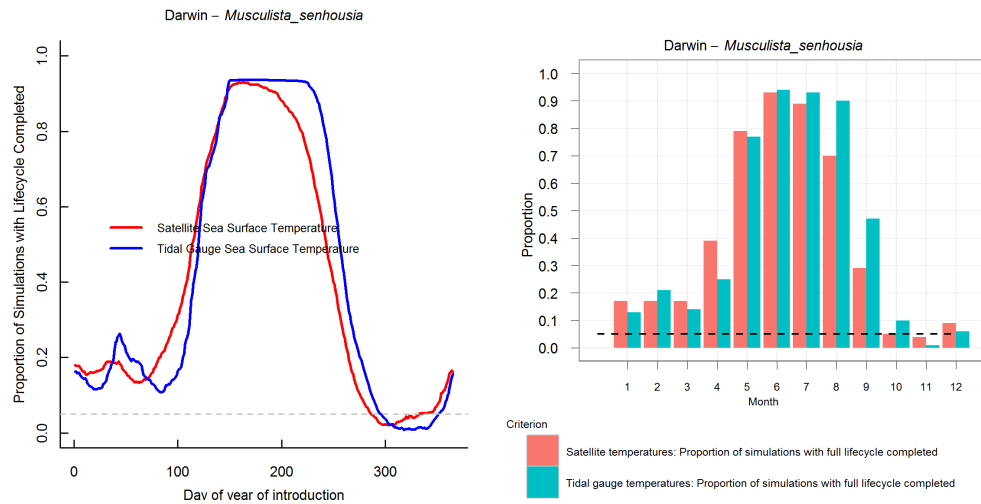
**Figure A.40:** Simulation results for life cycle completion of *M. senhousia* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



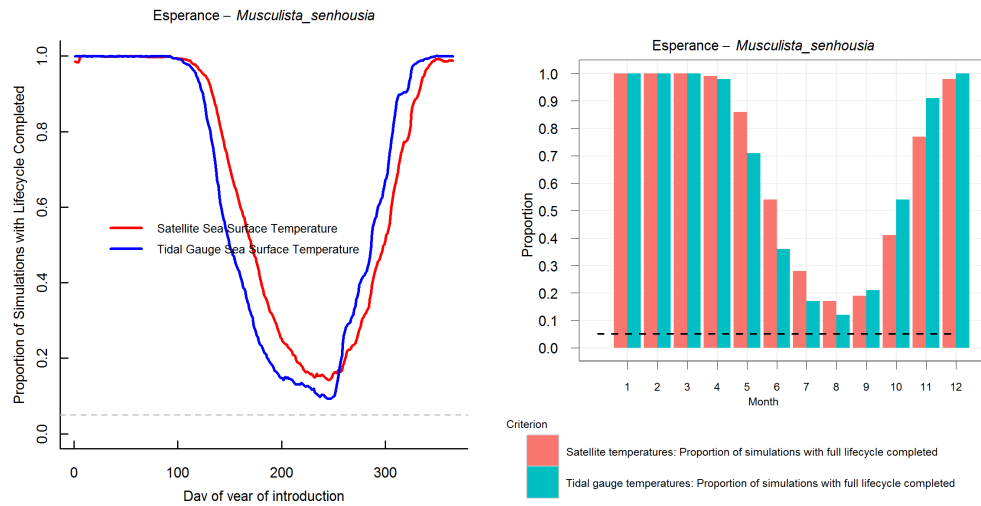
**Figure A.41:** Simulation results for life cycle completion of *M. senhousia* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



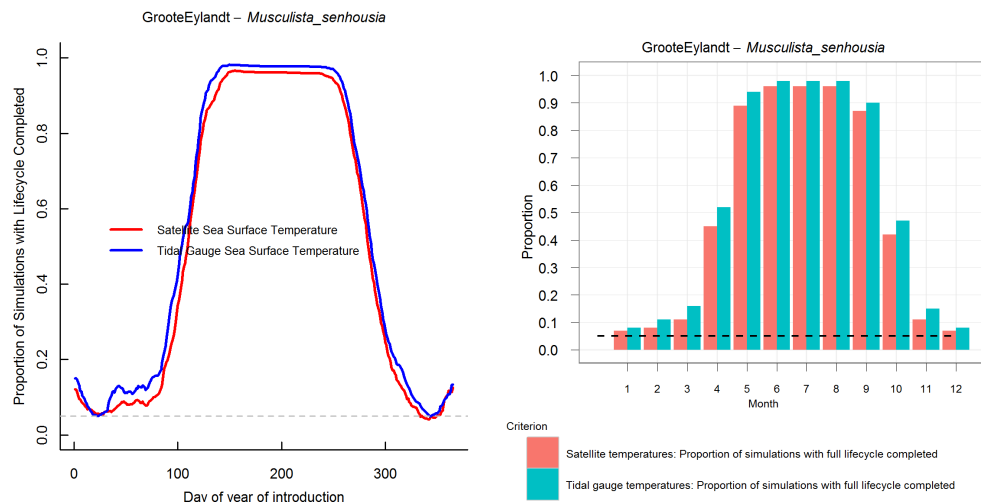
**Figure A.42:** Simulation results for life cycle completion of *M. senhousia* in CapeFerguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



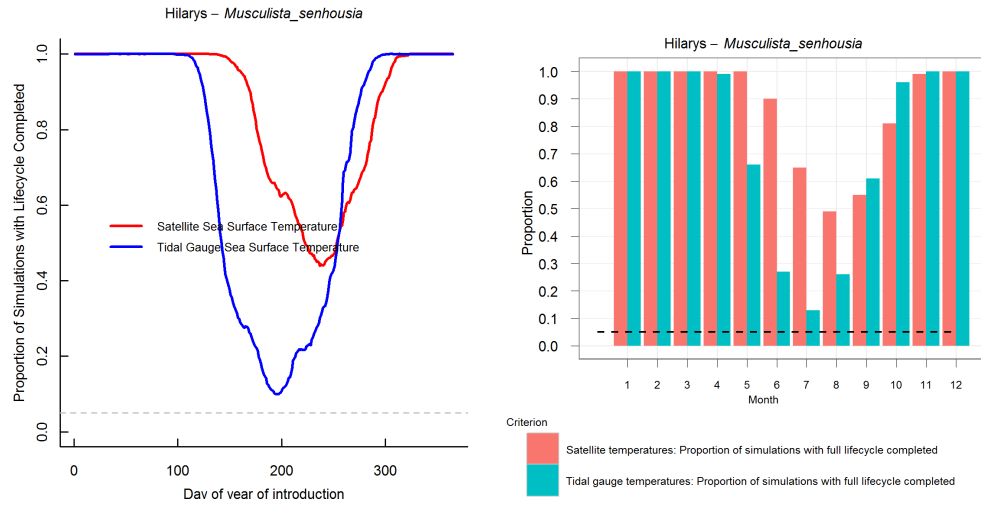
**Figure A.43:** Simulation results for life cycle completion of *M. senhousia* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



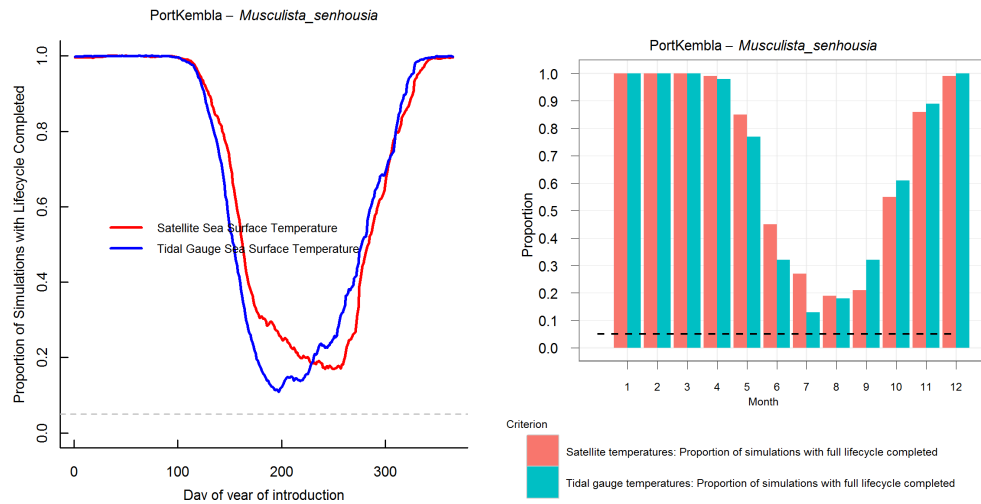
**Figure A.44:** Simulation results for life cycle completion of *M. senhousia* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.45:** Simulation results for life cycle completion of *M. senhousia* in Groote Eylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

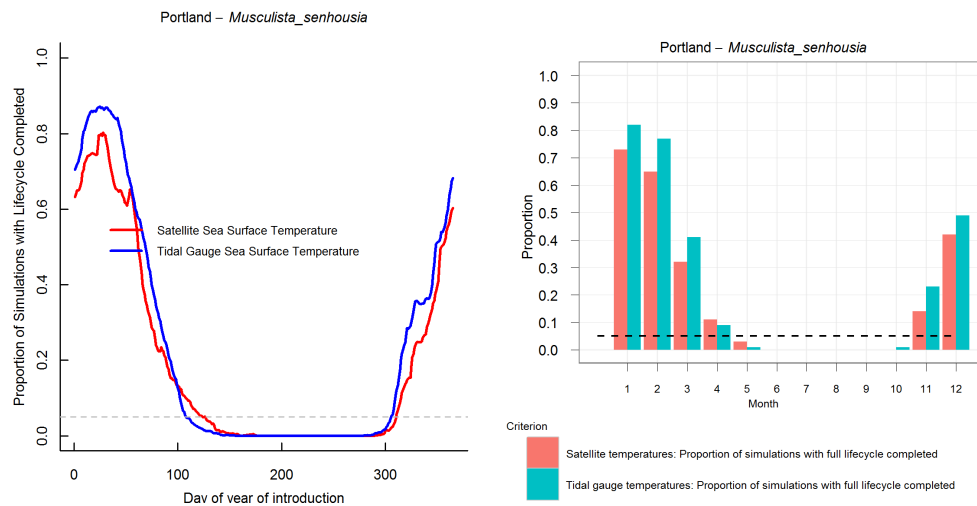


**Figure A.46:** Simulation results for life cycle completion of *M. senhousia* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

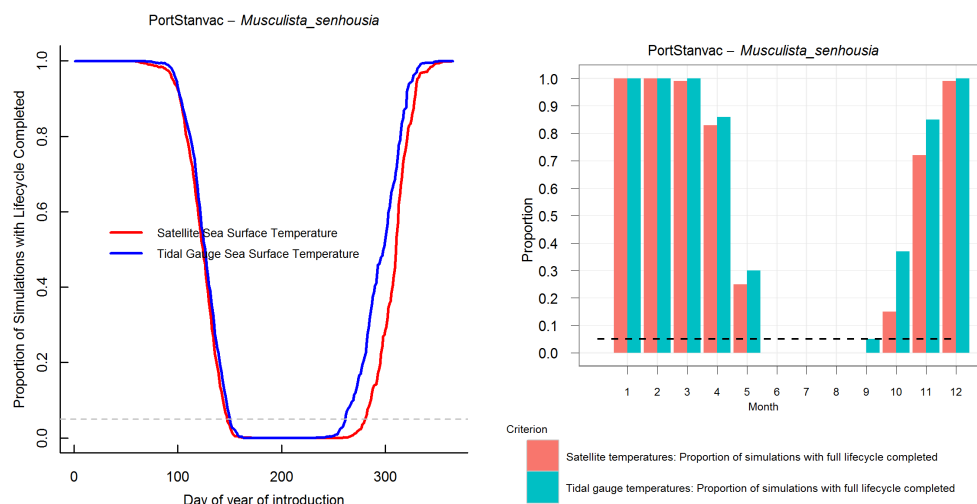


**Figure A.47:** Simulation results for life cycle completion of *M. senhousia* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

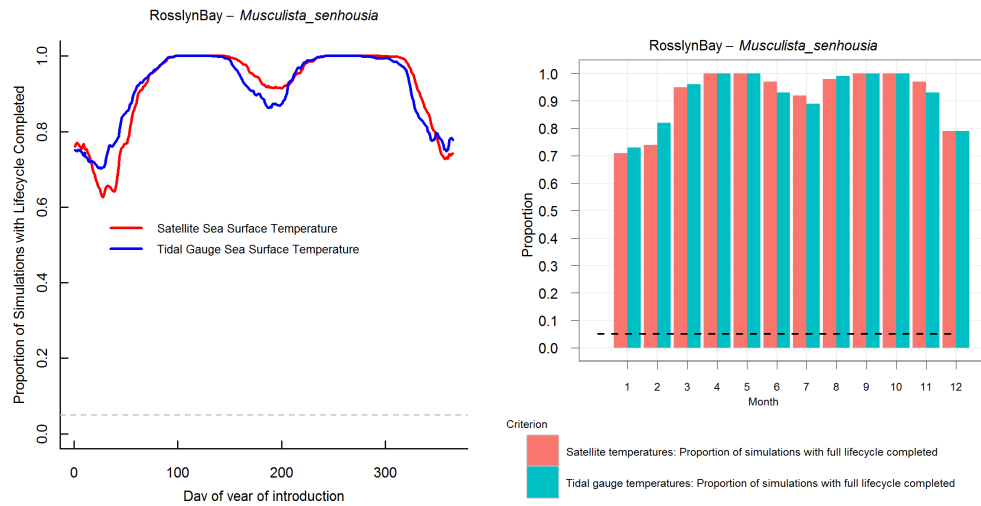




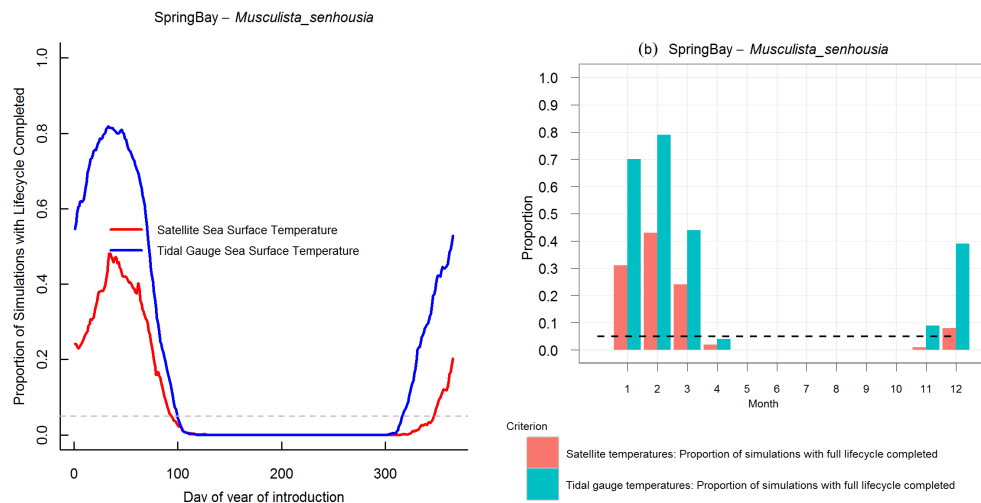
**Figure A.48:** Simulation results for life cycle completion of *M. senhousia* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



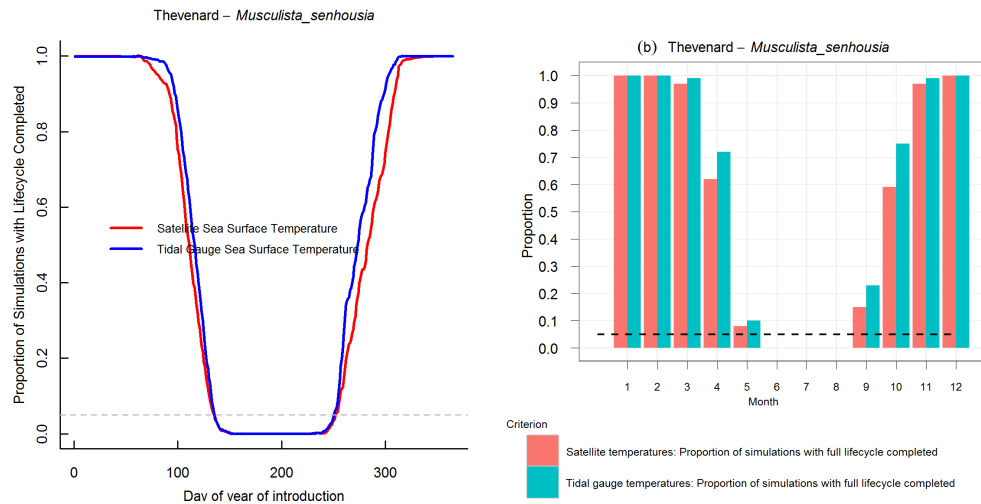
**Figure A.49:** Simulation results for life cycle completion of *M. senhousia* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.50:** Simulation results for life cycle completion of *M. senhousia* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

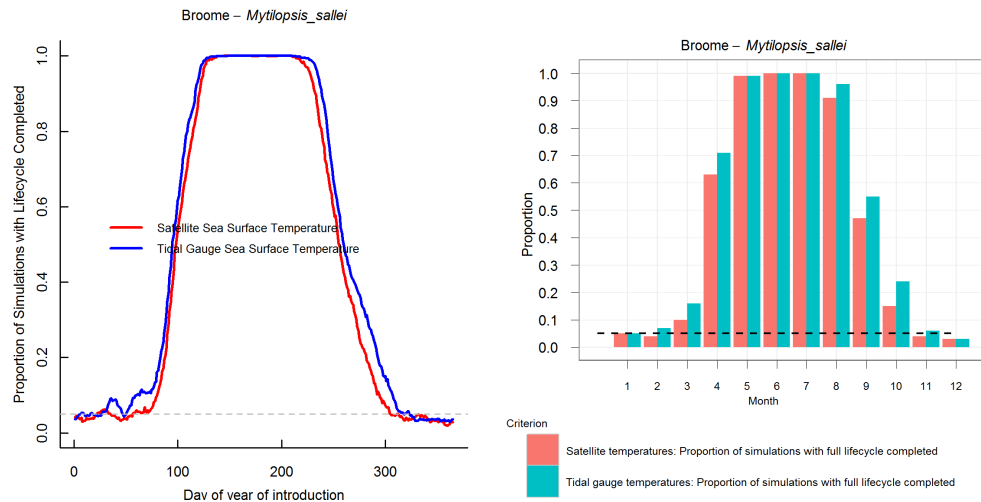


**Figure A.51:** Simulation results for life cycle completion of *M. senhousia* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

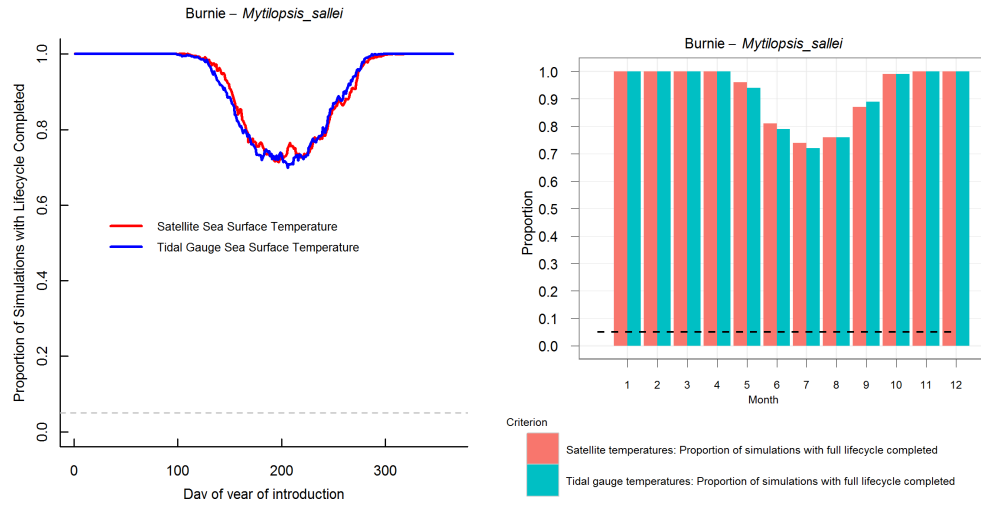


**Figure A.52:** Simulation results for life cycle completion of *M. senhousia* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

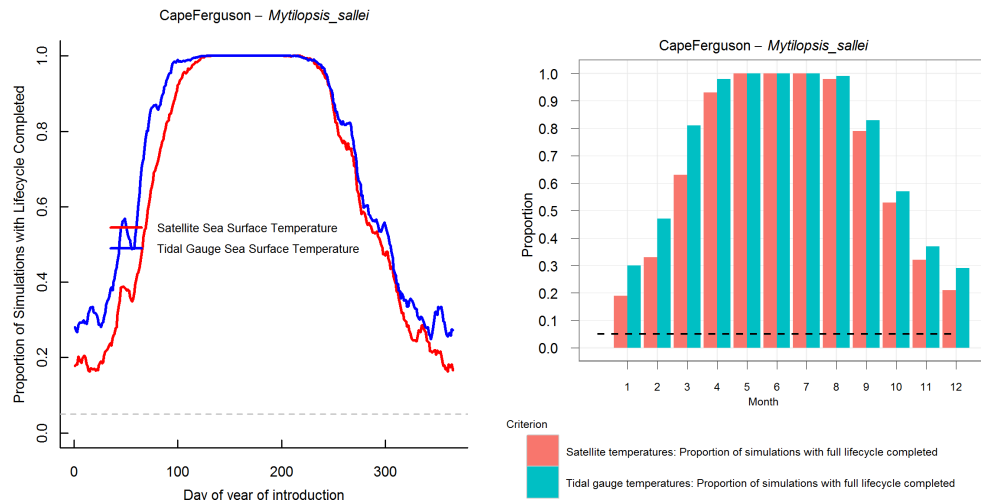
## A.5 *Mytilopsis sallei*



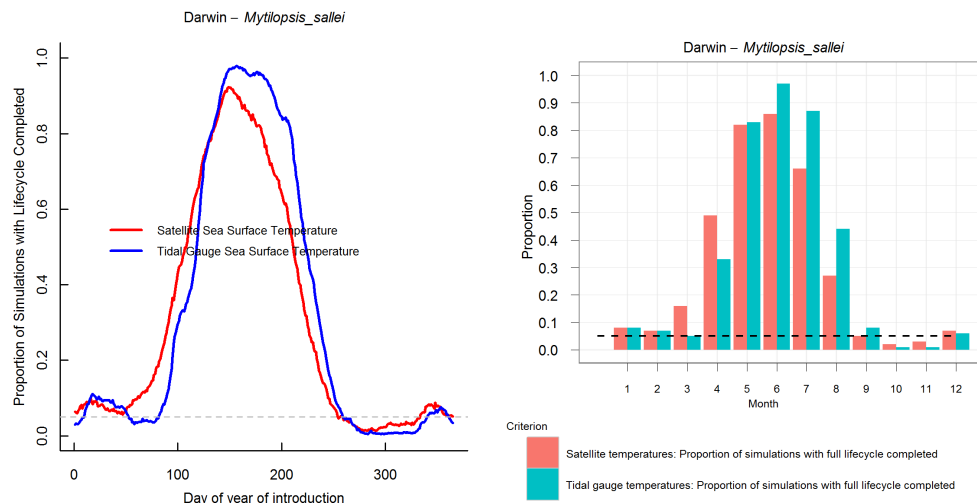
**Figure A.53:** Simulation results for life cycle completion of *M. sallei* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



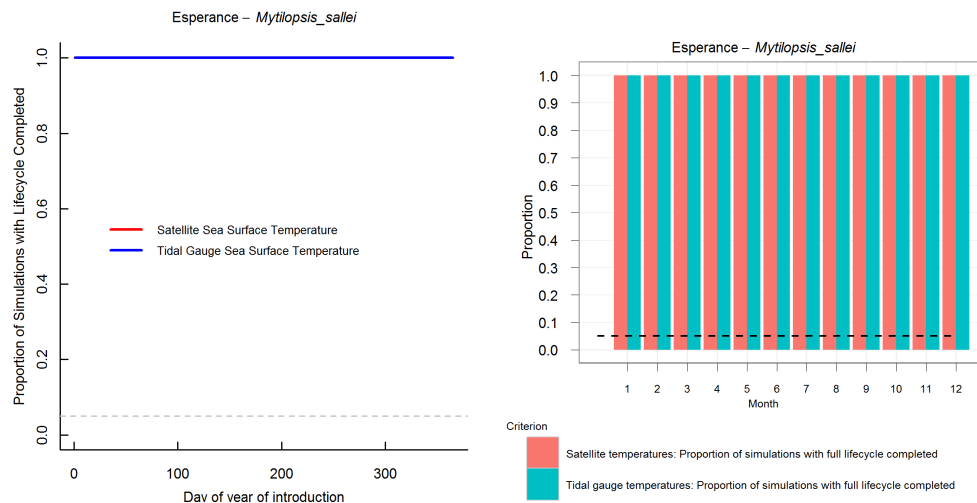
**Figure A.54:** Simulation results for life cycle completion of *M. sallei* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



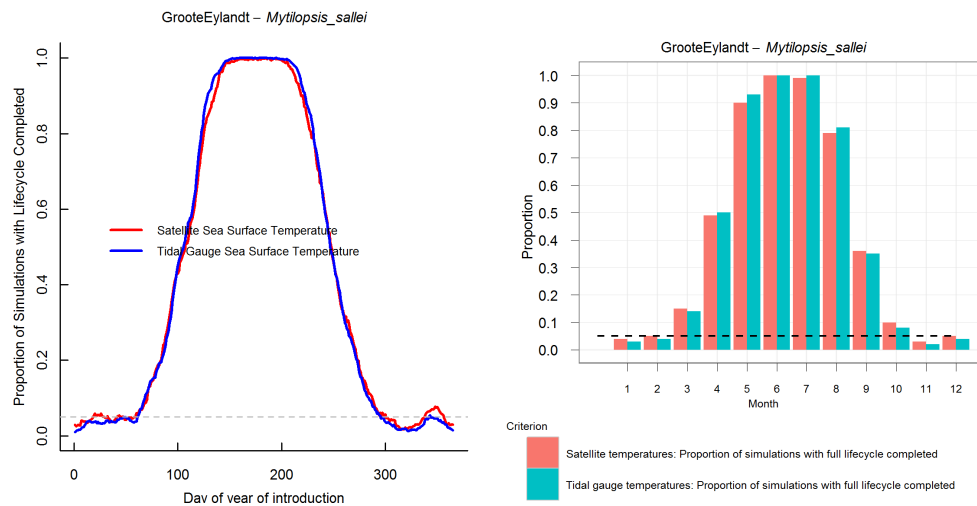
**Figure A.55:** Simulation results for life cycle completion of *M. sallei* in Cape Ferguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



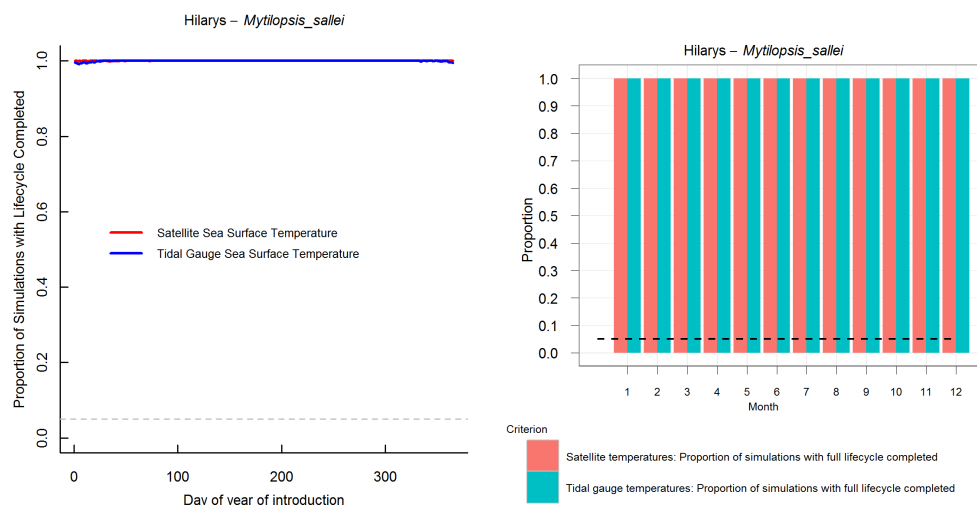
**Figure A.56:** Simulation results for life cycle completion of *M. sallei* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



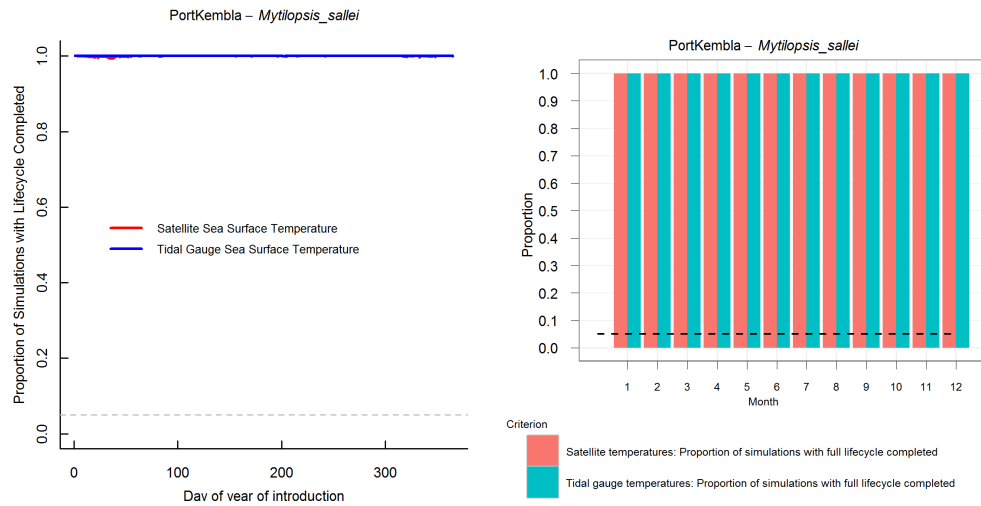
**Figure A.57:** Simulation results for life cycle completion of *M. sallei* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



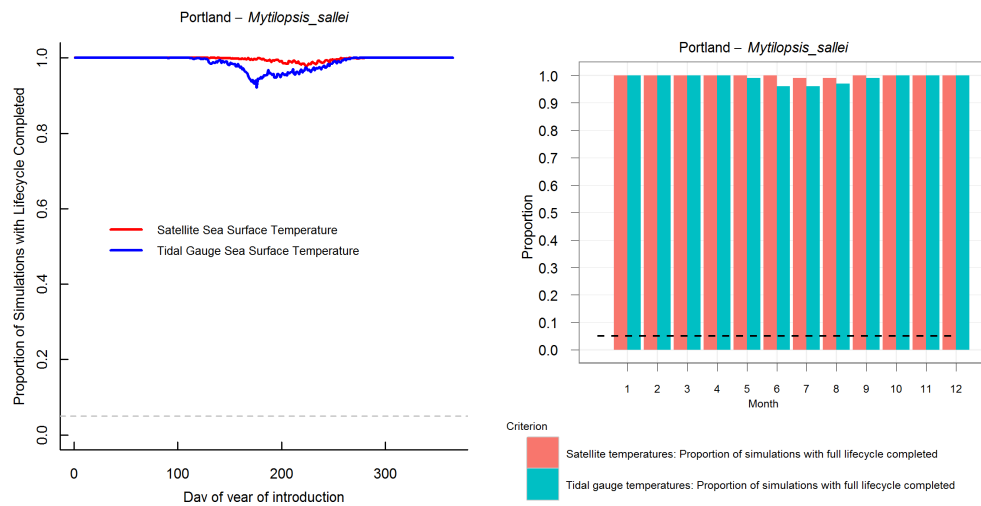
**Figure A.58:** Simulation results for life cycle completion of *M. sallei* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



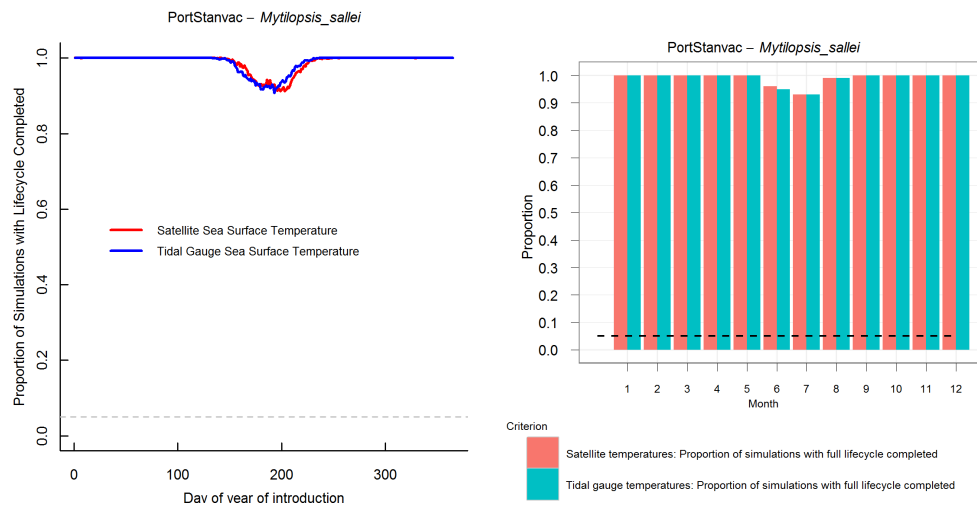
**Figure A.59:** Simulation results for life cycle completion of *M. sallei* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



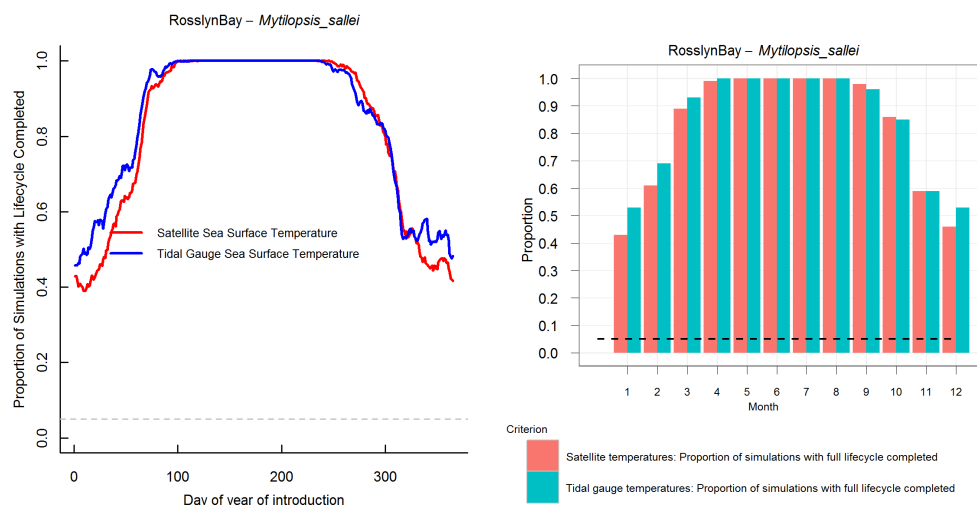
**Figure A.60:** Simulation results for life cycle completion of *M. sallei* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.61:** Simulation results for life cycle completion of *M. sallei* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

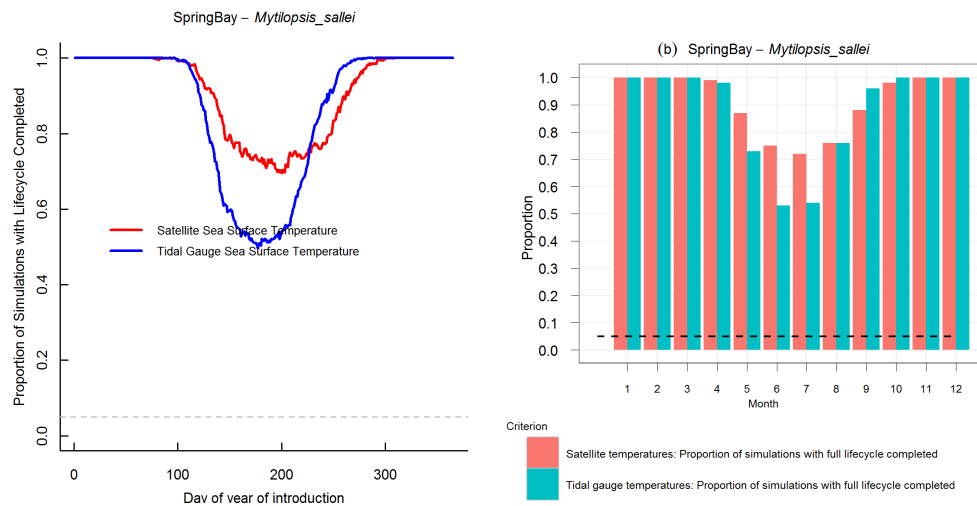


**Figure A.62:** Simulation results for life cycle completion of *M. sallei* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

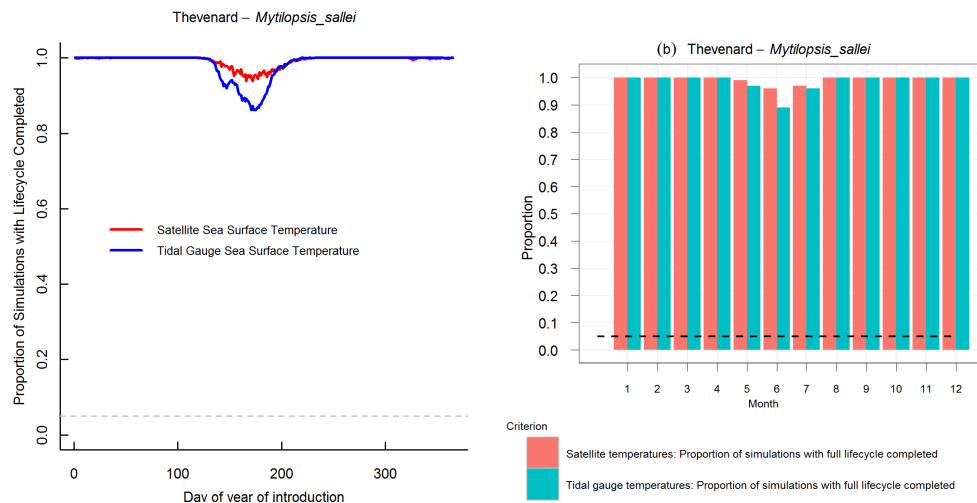


**Figure A.63:** Simulation results for life cycle completion of *M. sallei* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



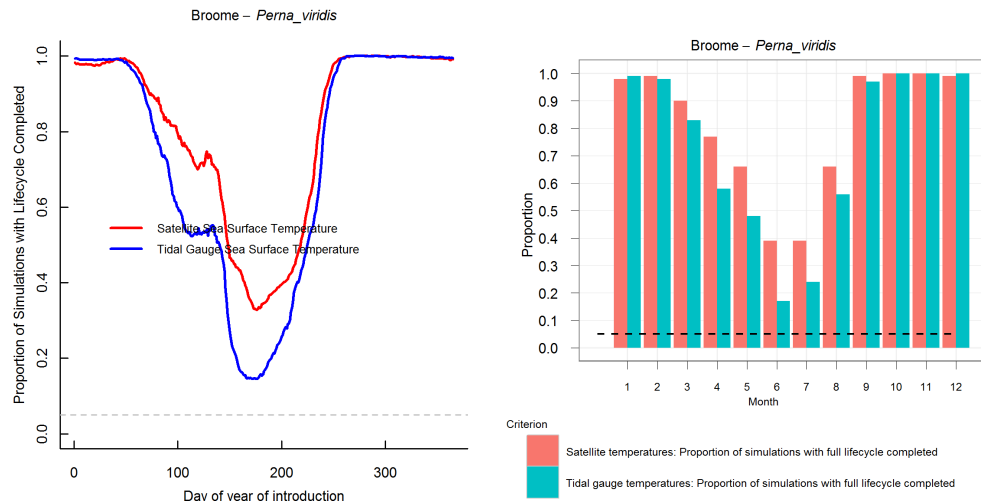


**Figure A.64:** Simulation results for life cycle completion of *M. sallei* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

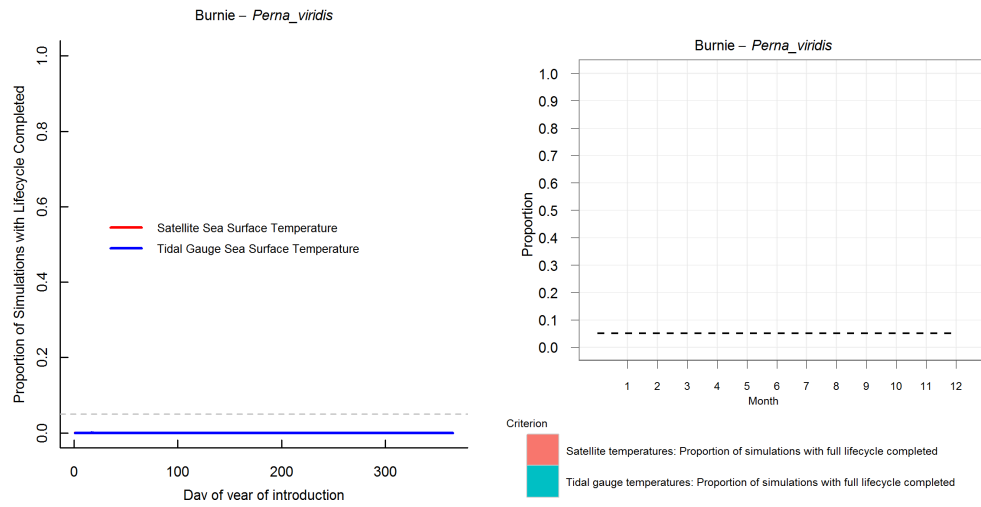


**Figure A.65:** Simulation results for life cycle completion of *M. sallei* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

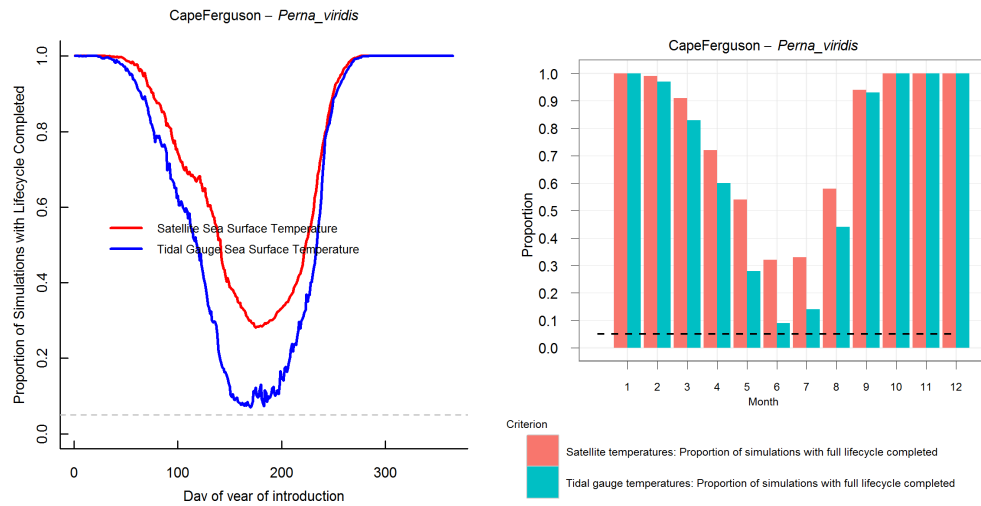
## A.6 *Perna viridis*



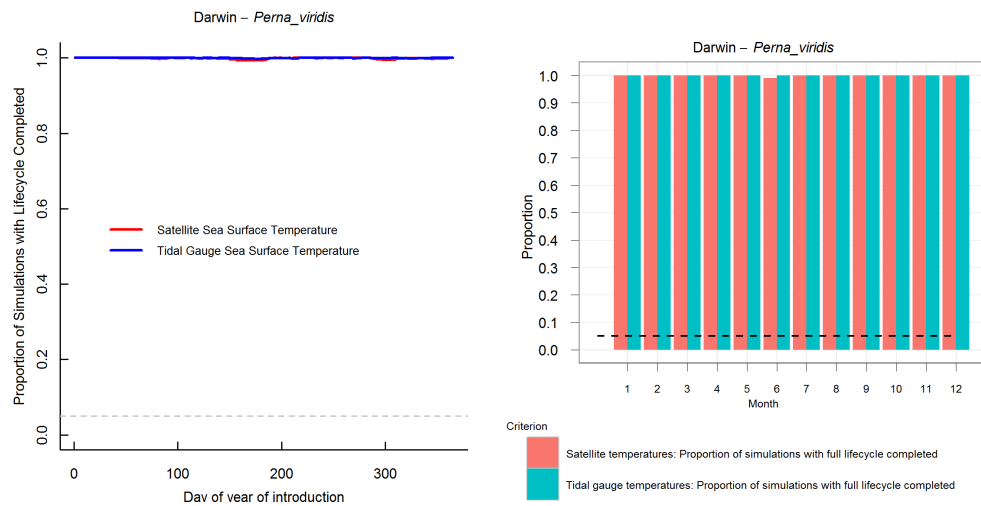
**Figure A.66:** Simulation results for life cycle completion of *P. viridis* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



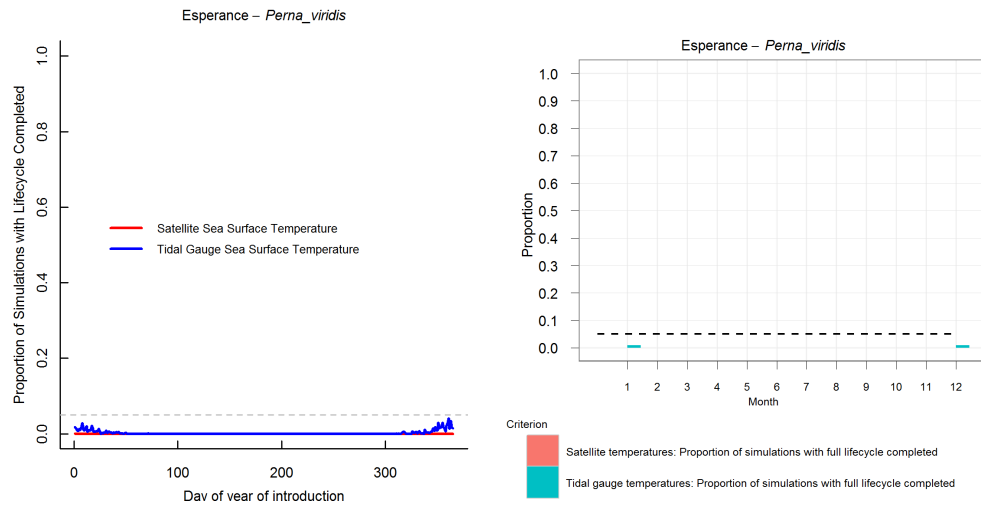
**Figure A.67:** Simulation results for life cycle completion of *P. viridis* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



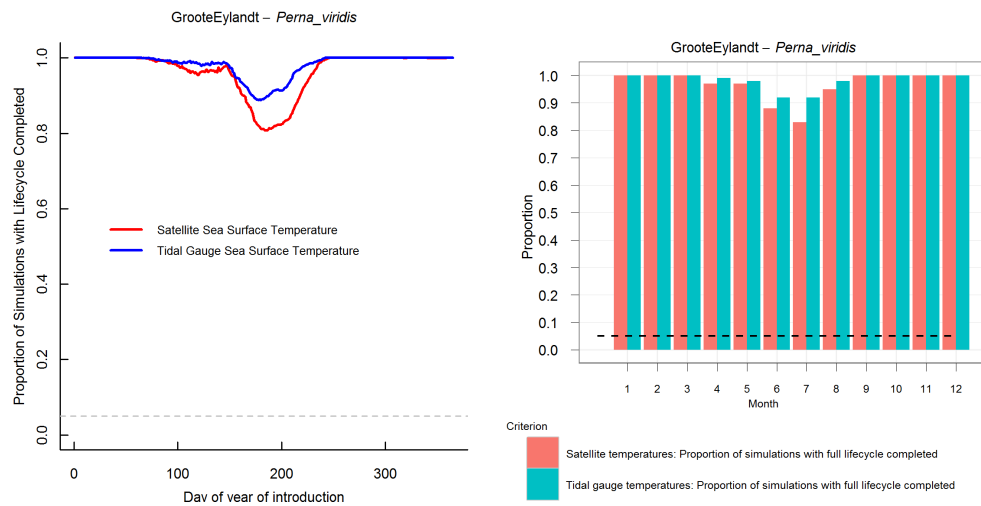
**Figure A.68:** Simulation results for life cycle completion of *P. viridis* in CapeFerguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



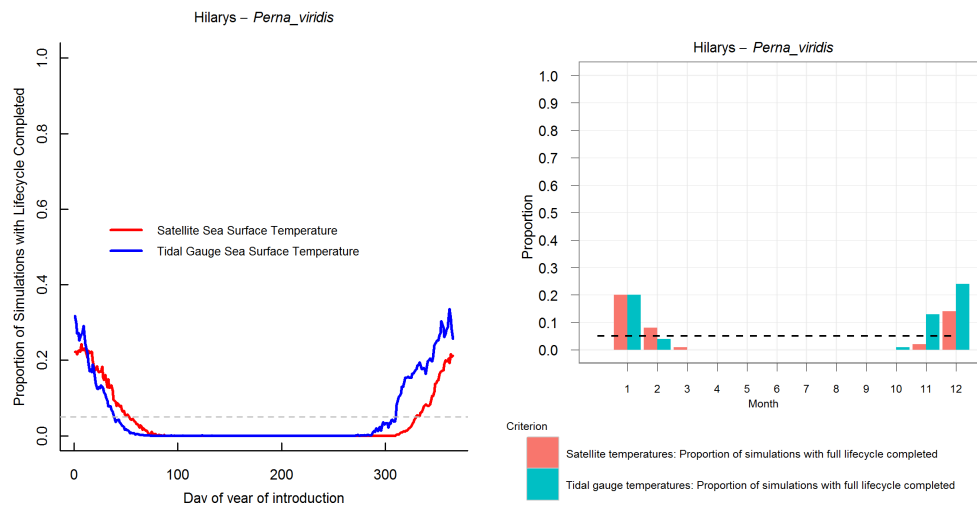
**Figure A.69:** Simulation results for life cycle completion of *P. viridis* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



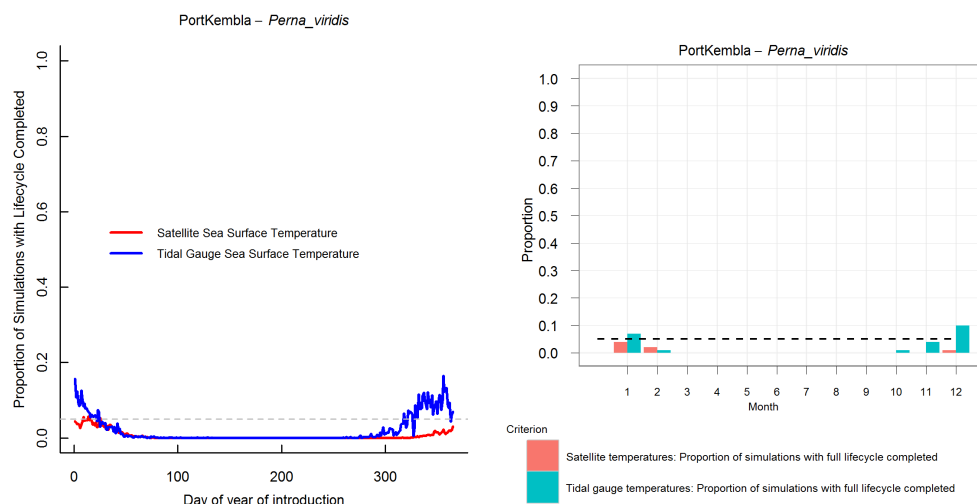
**Figure A.70:** Simulation results for life cycle completion of *P. viridis* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



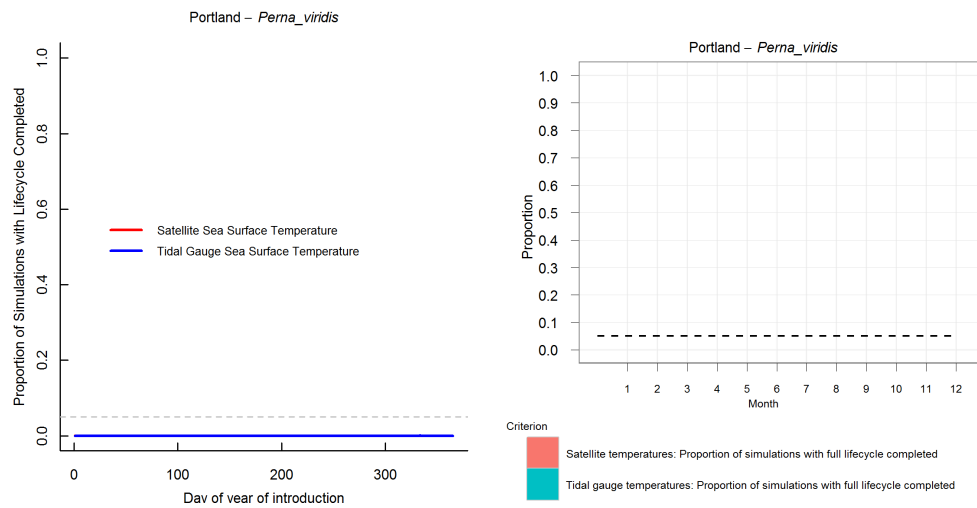
**Figure A.71:** Simulation results for life cycle completion of *P. viridis* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



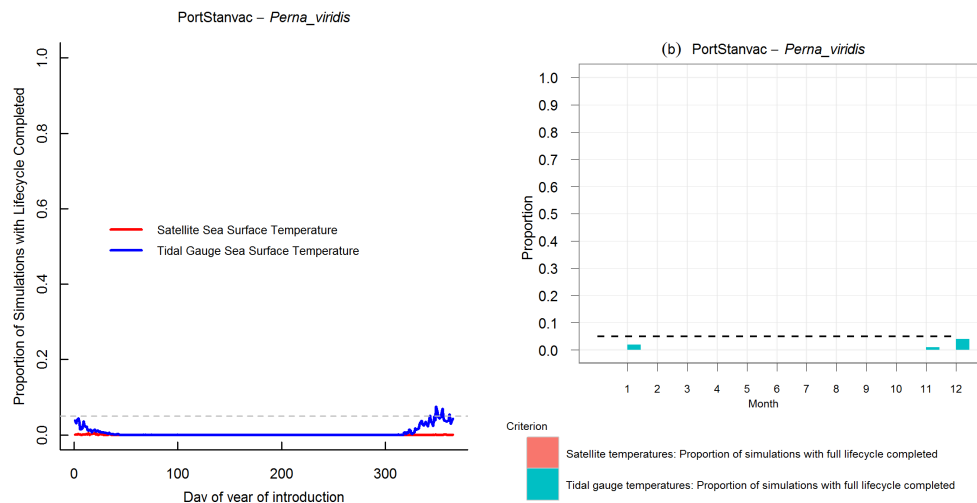
**Figure A.72:** Simulation results for life cycle completion of *P. viridis* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



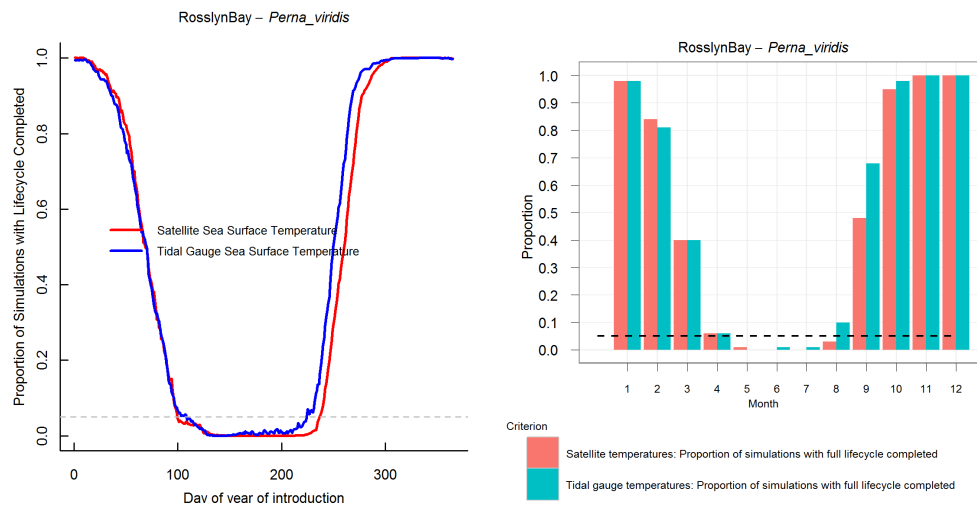
**Figure A.73:** Simulation results for life cycle completion of *P. viridis* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



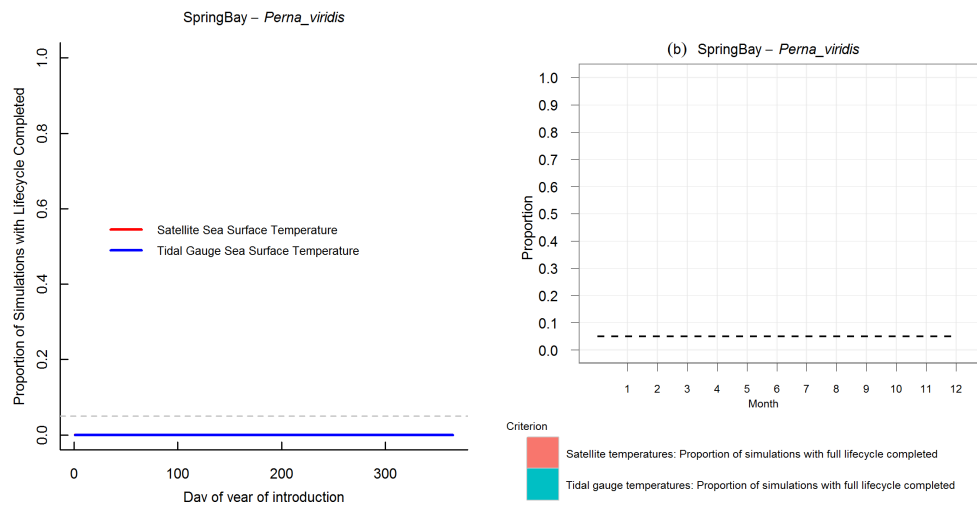
**Figure A.74:** Simulation results for life cycle completion of *P. viridis* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



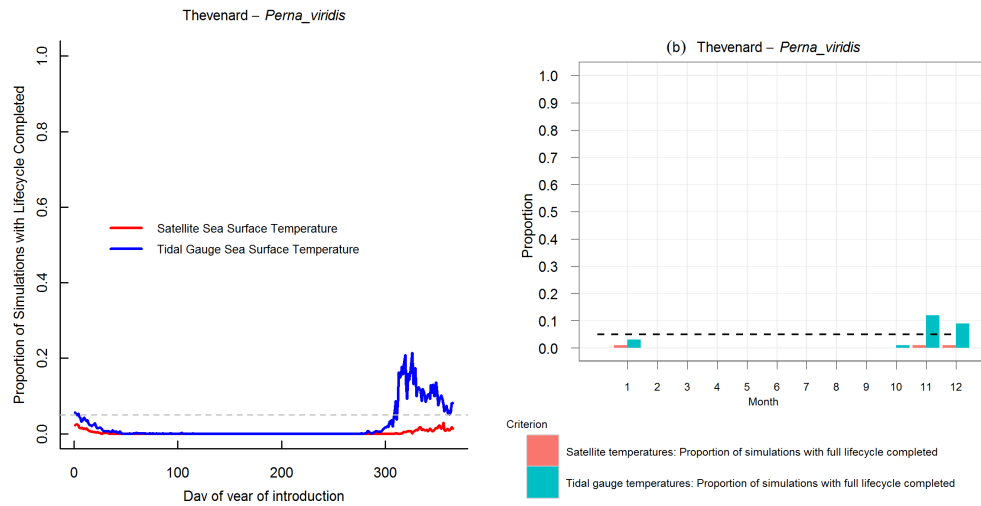
**Figure A.75:** Simulation results for life cycle completion of *P. viridis* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.76:** Simulation results for life cycle completion of *P. viridis* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

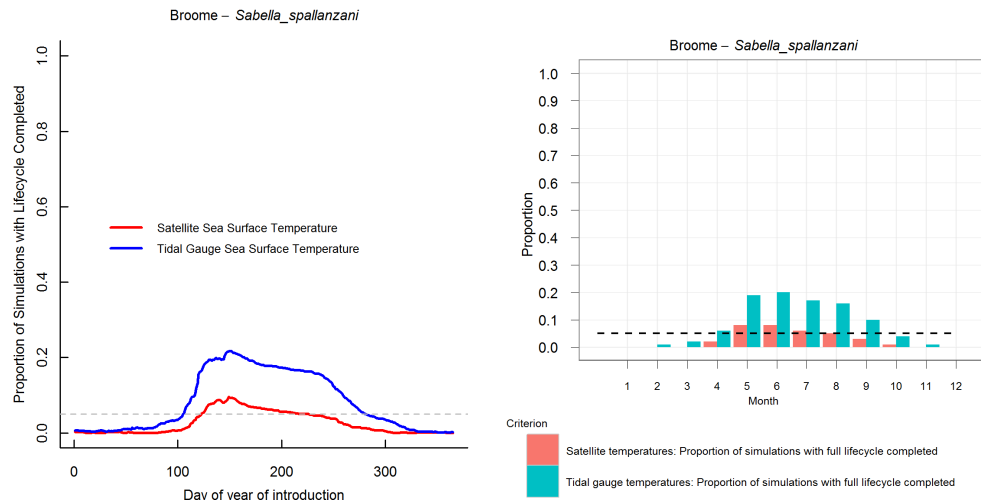


**Figure A.77:** Simulation results for life cycle completion of *P. viridis* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



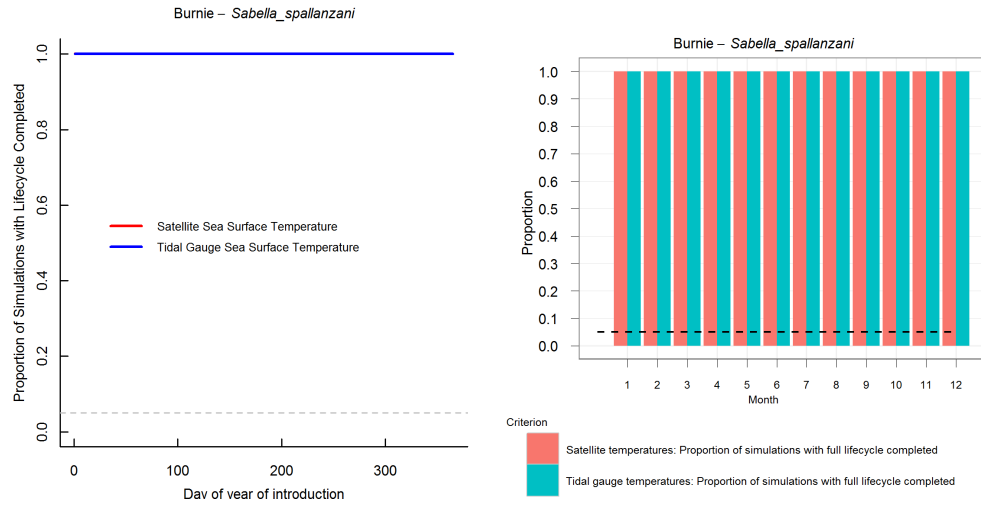
**Figure A.78:** Simulation results for life cycle completion of *P. viridis* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

## A.7 *Sabella spallanzani*

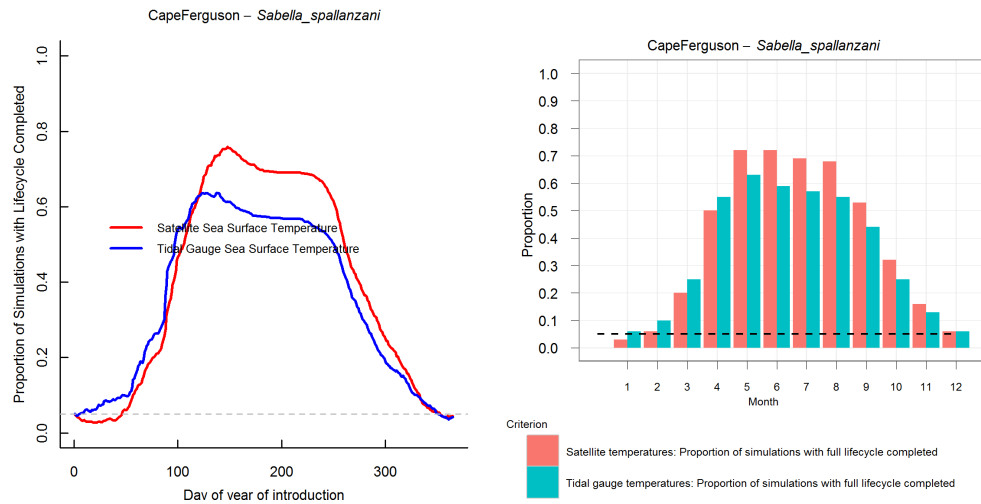


**Figure A.79:** Simulation results for life cycle completion of *S. spallanzani* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

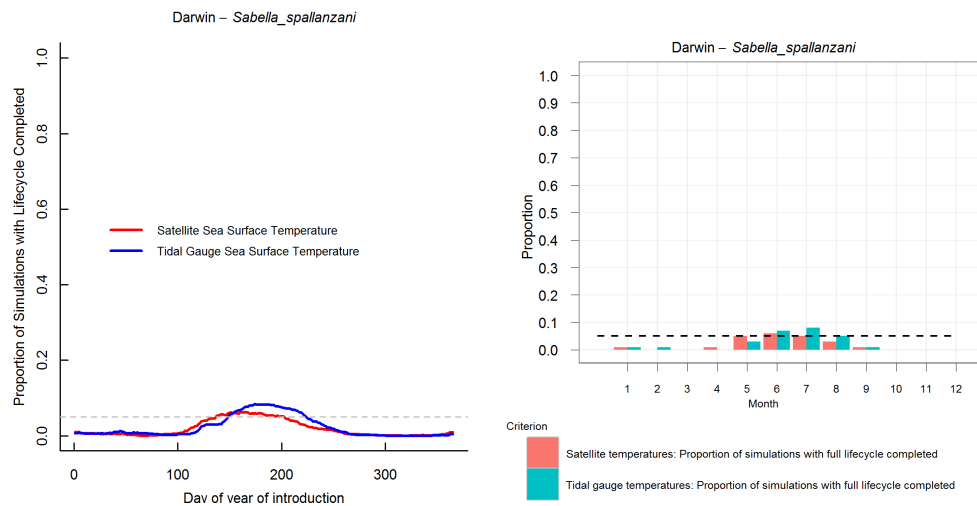




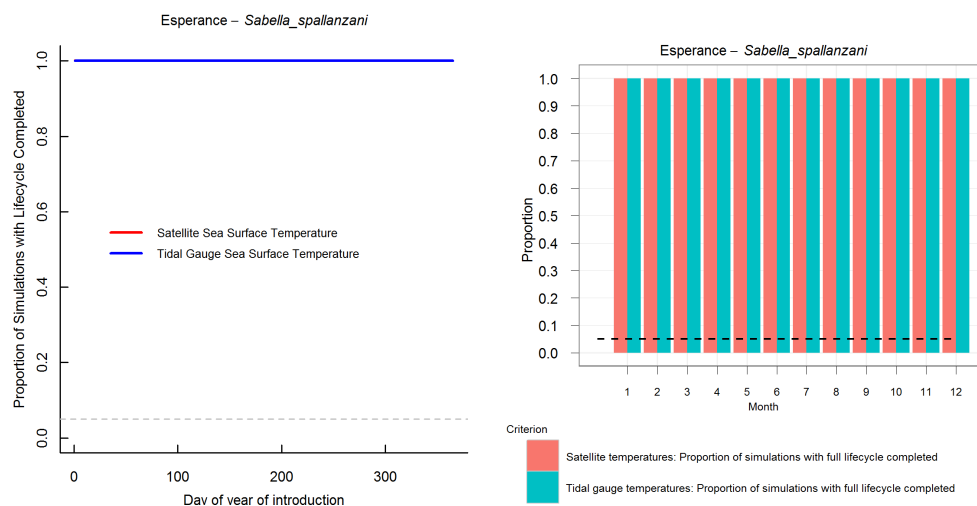
**Figure A.80:** Simulation results for life cycle completion of *S. spallanzani* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



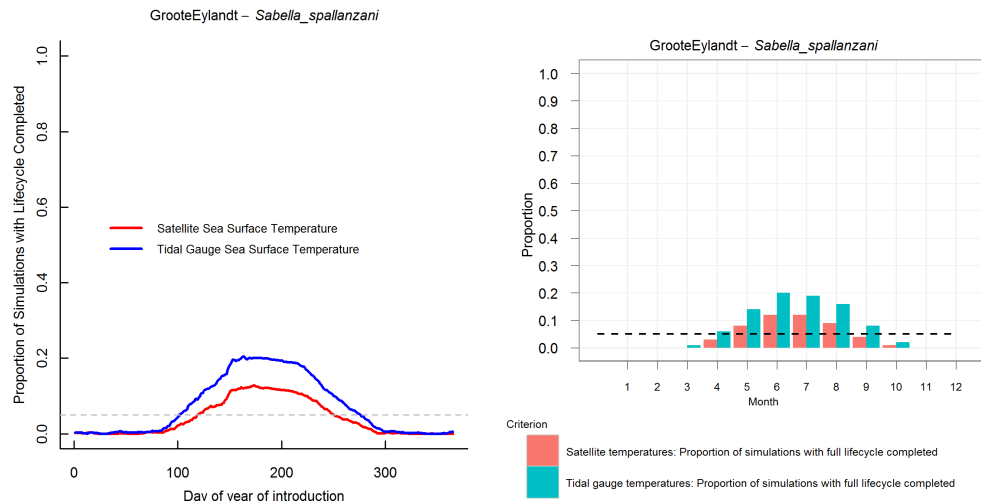
**Figure A.81:** Simulation results for life cycle completion of *S. spallanzani* in Cape Ferguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



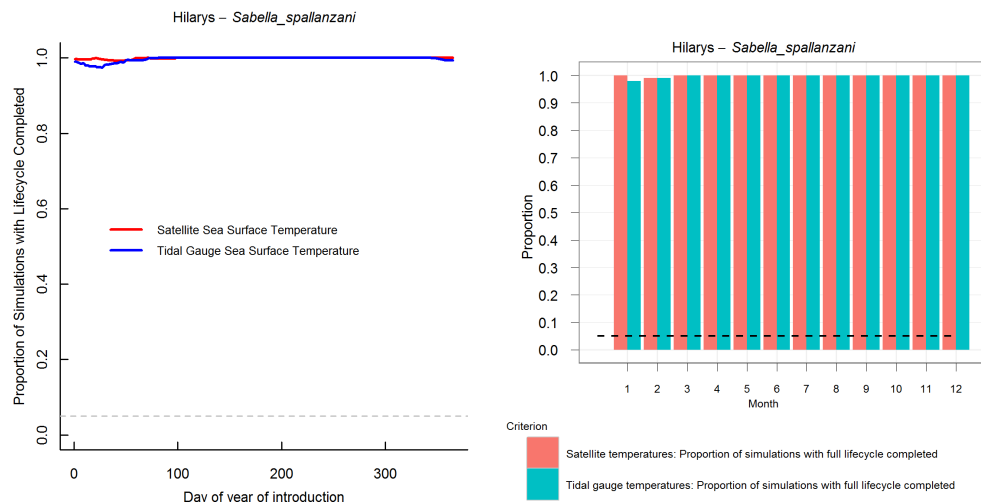
**Figure A.82:** Simulation results for life cycle completion of *S. spallanzani* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



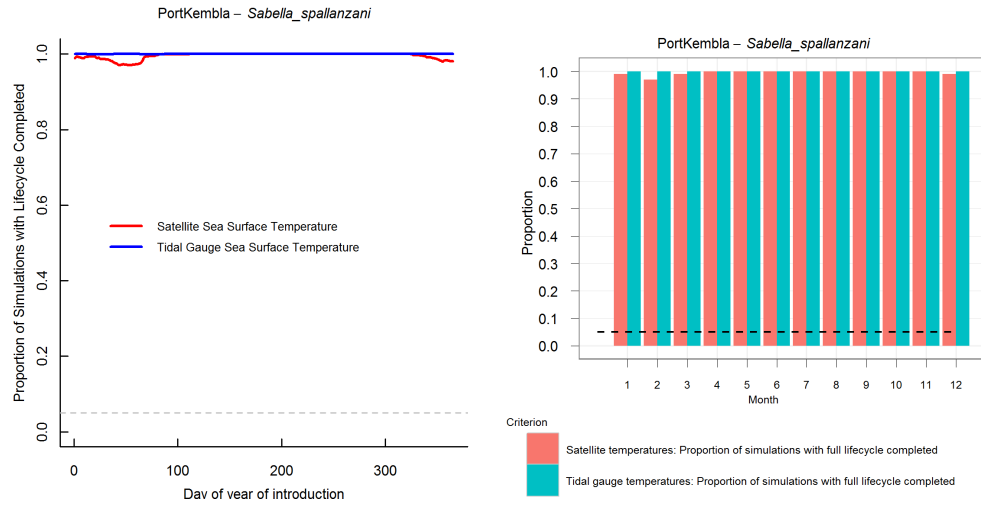
**Figure A.83:** Simulation results for life cycle completion of *S. spallanzani* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



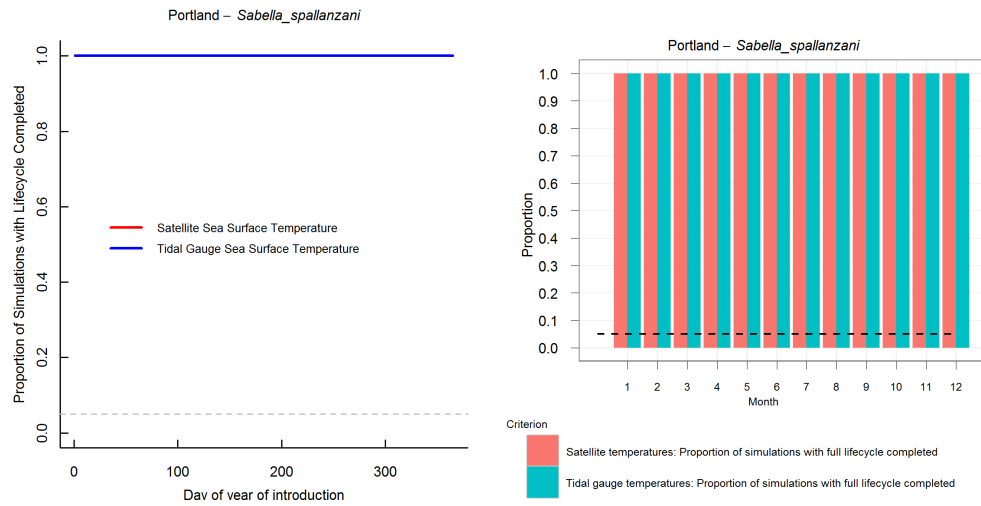
**Figure A.84:** Simulation results for life cycle completion of *S. spallanzani* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



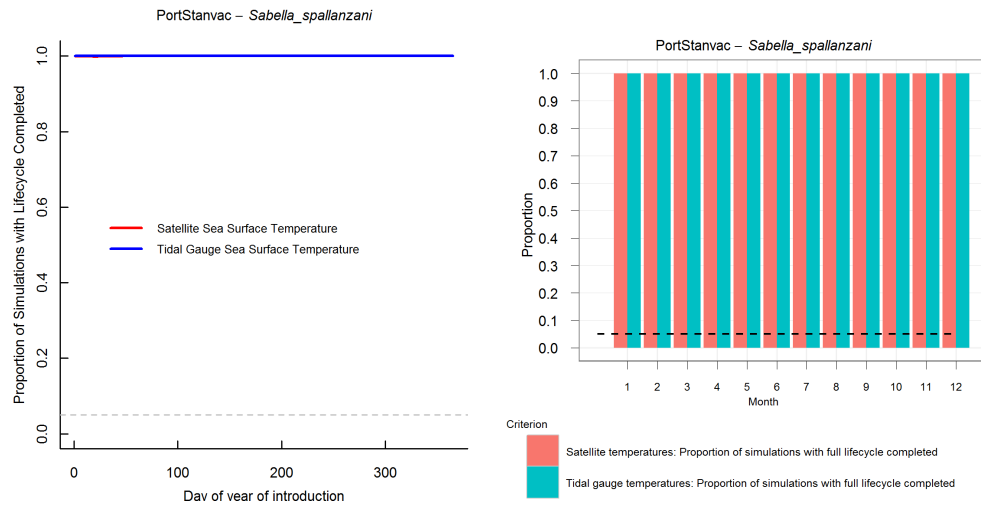
**Figure A.85:** Simulation results for life cycle completion of *S. spallanzani* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



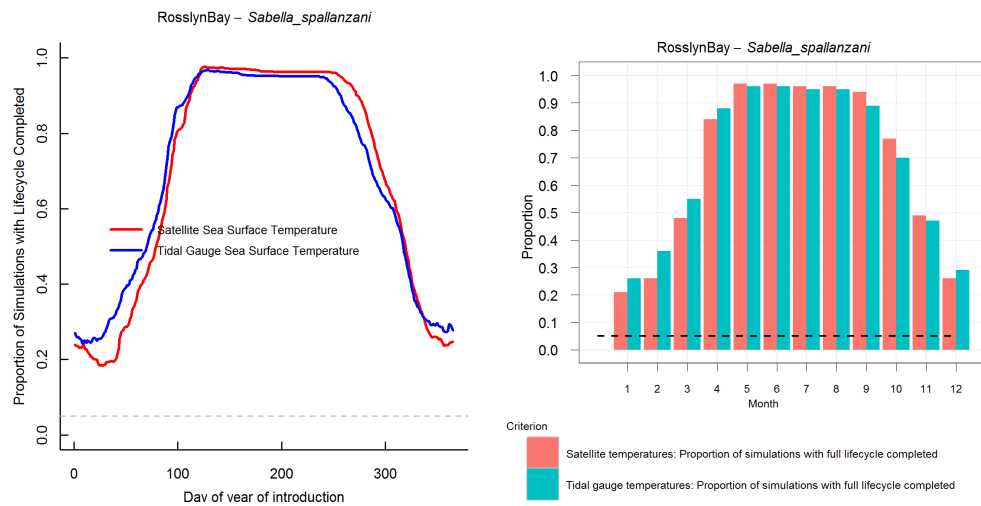
**Figure A.86:** Simulation results for life cycle completion of *S. spallanzani* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



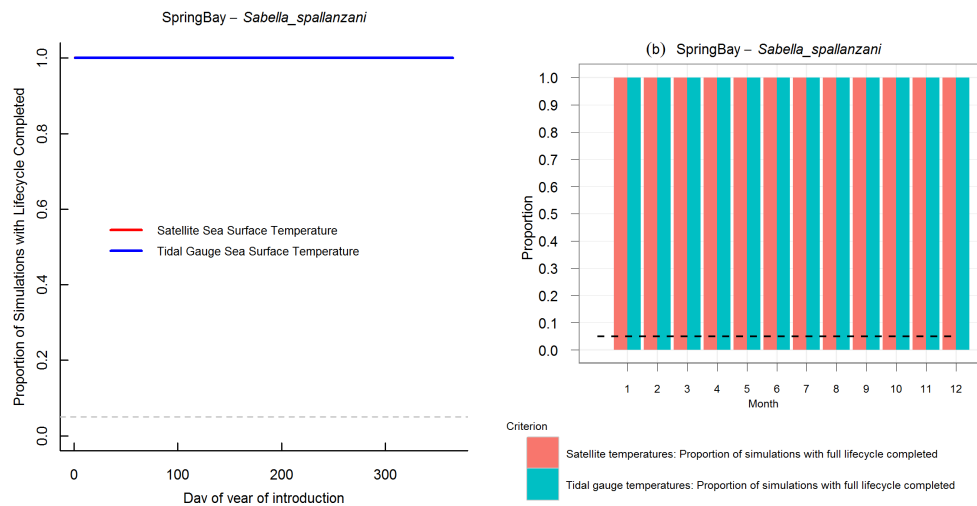
**Figure A.87:** Simulation results for life cycle completion of *S. spallanzani* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



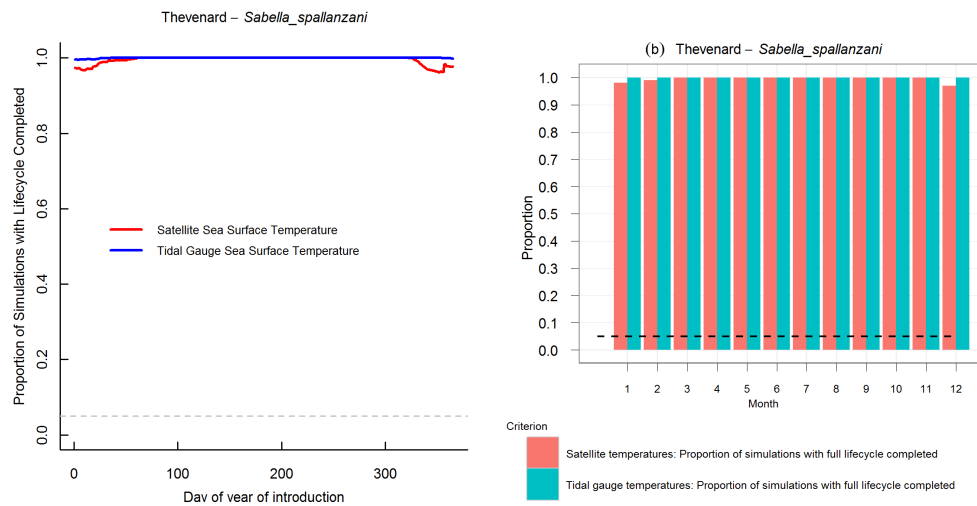
**Figure A.88:** Simulation results for life cycle completion of *S. spallanzani* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.89:** Simulation results for life cycle completion of *S. spallanzani* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

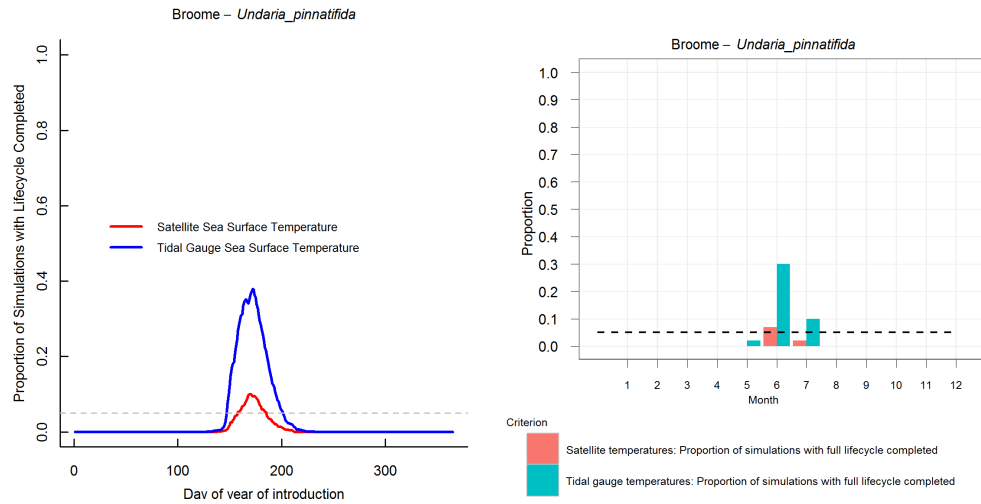


**Figure A.90:** Simulation results for life cycle completion of *S. spallanzani* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

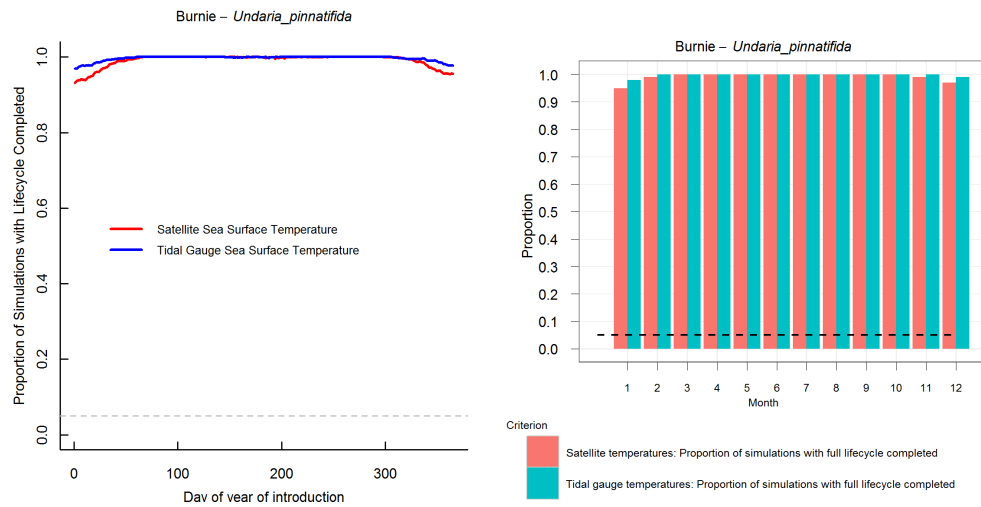


**Figure A.91:** Simulation results for life cycle completion of *S. spallanzani* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

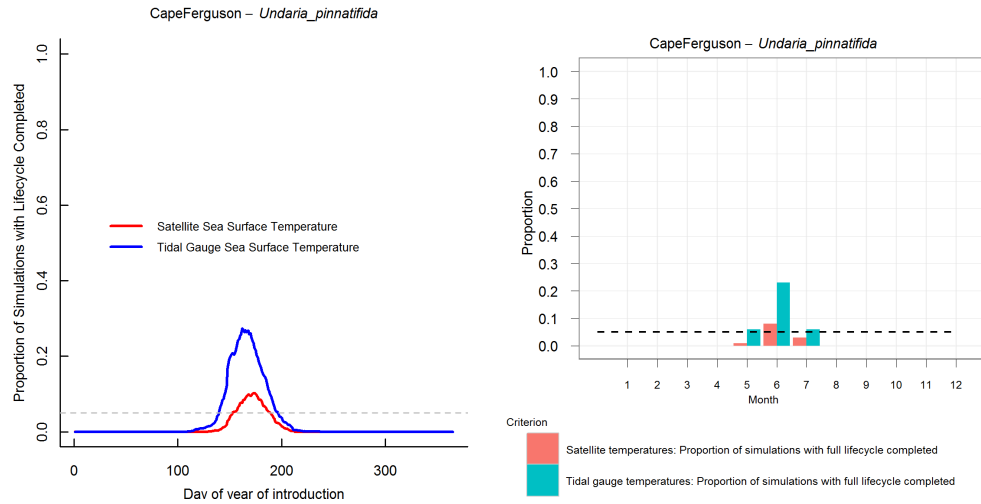
## A.8 *Undaria pinnatifida*



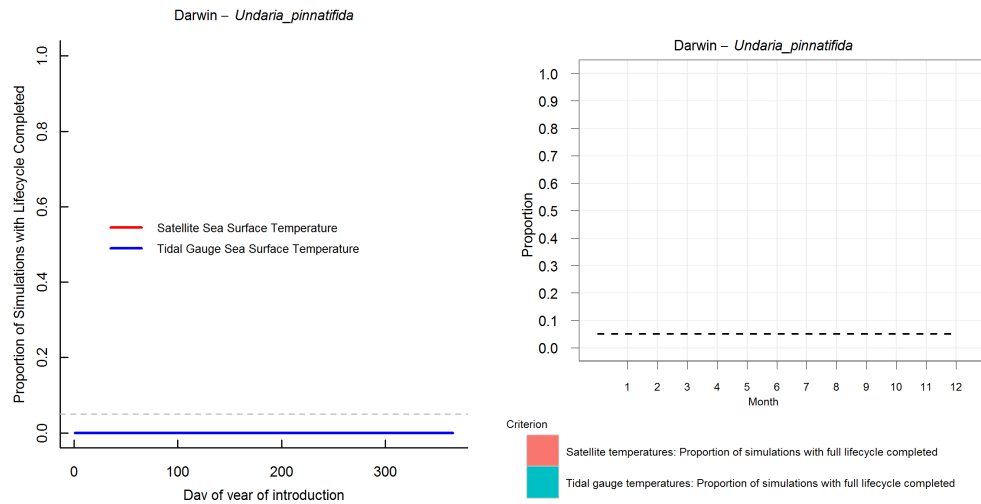
**Figure A.92:** Simulation results for life cycle completion of *U. pinnatifida* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.93:** Simulation results for life cycle completion of *U. pinnatifida* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

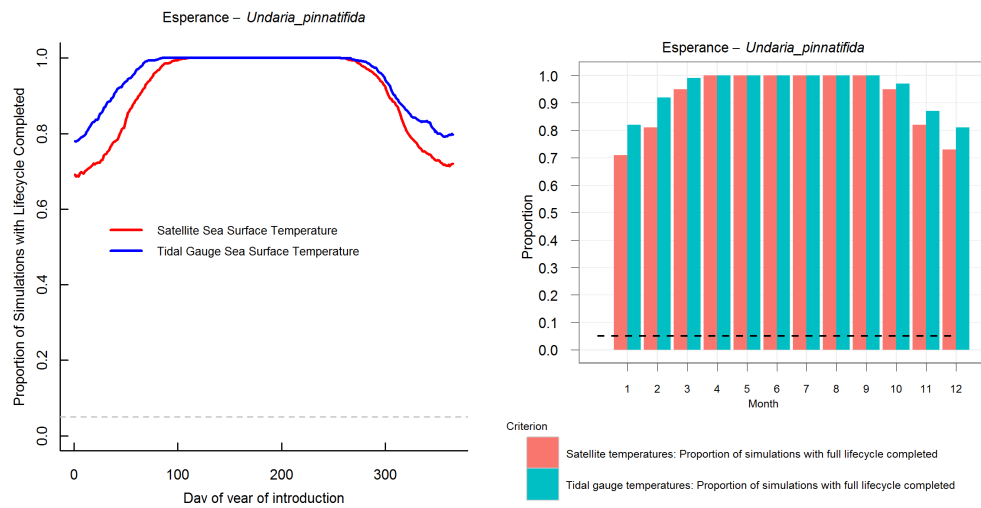


**Figure A.94:** Simulation results for life cycle completion of *U. pinnatifida* in Cape Ferguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

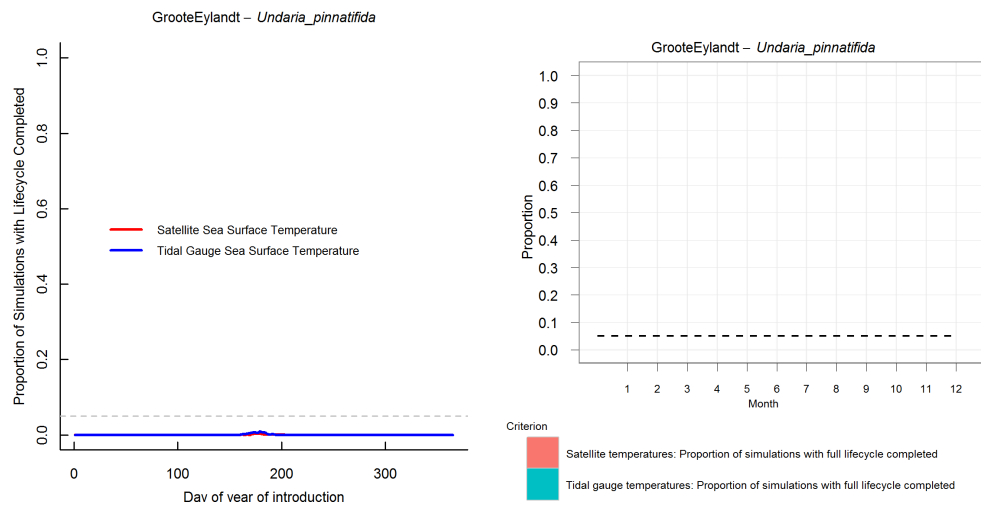


**Figure A.95:** Simulation results for life cycle completion of *U. pinnatifida* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

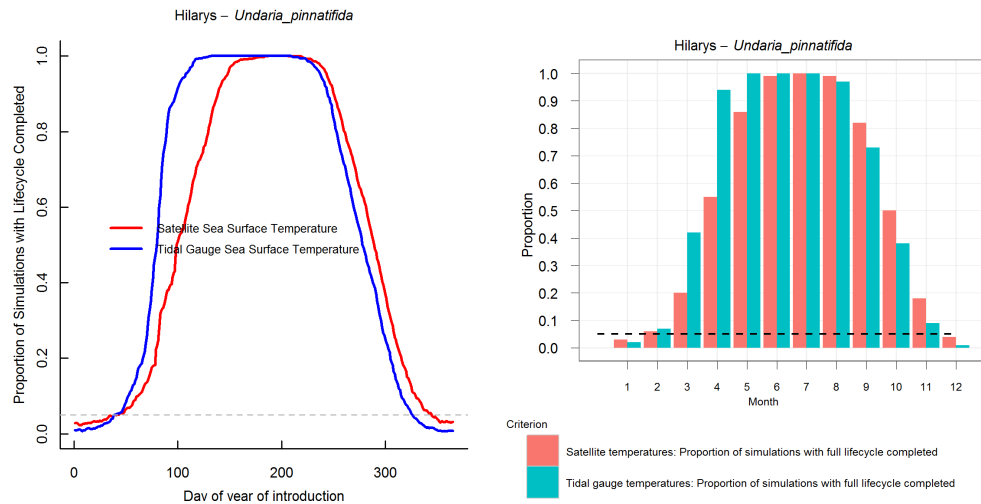




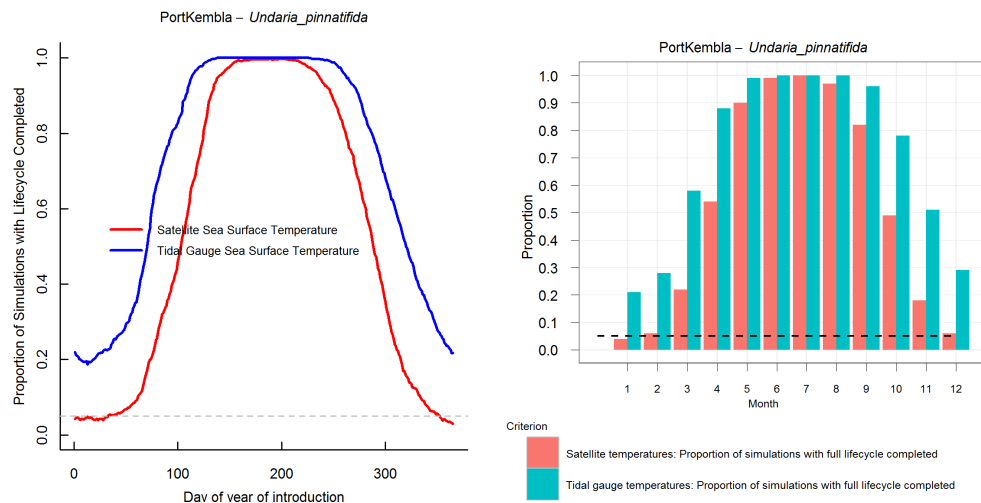
**Figure A.96:** Simulation results for life cycle completion of *U. pinnatifida* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



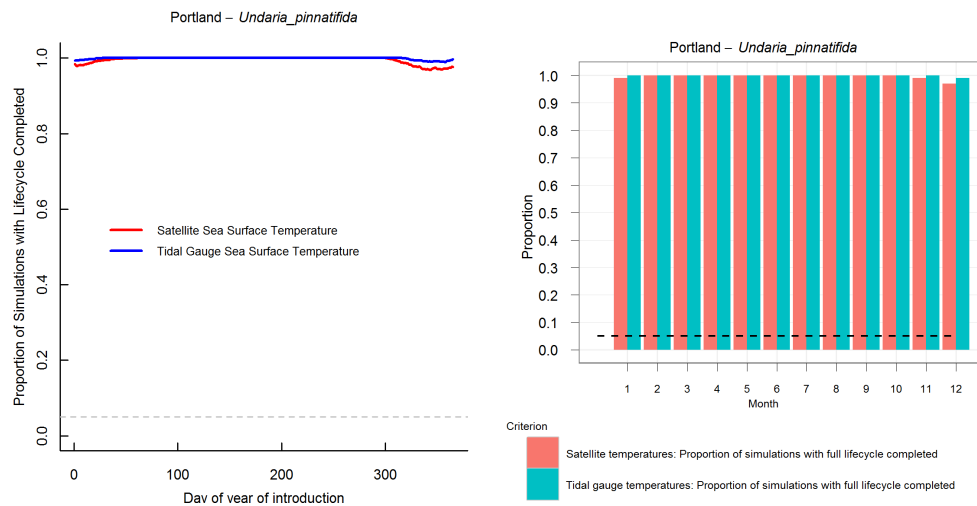
**Figure A.97:** Simulation results for life cycle completion of *U. pinnatifida* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



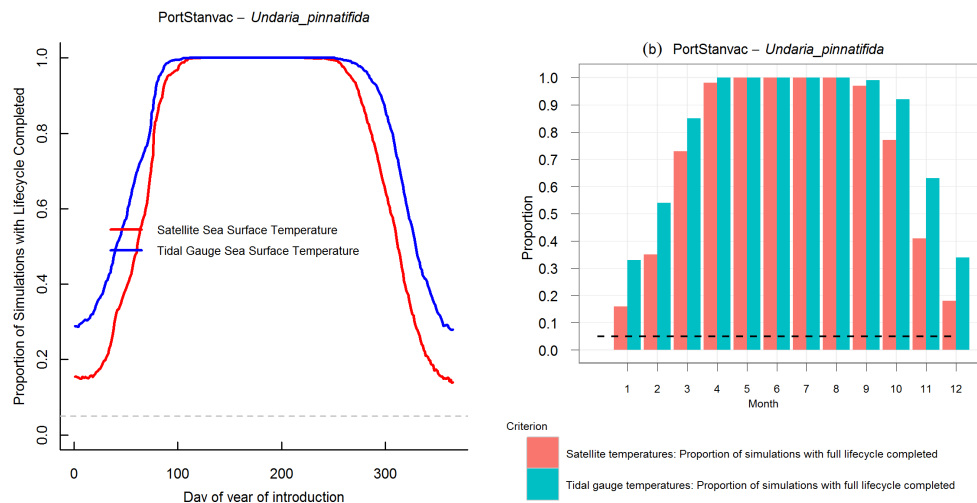
**Figure A.98:** Simulation results for life cycle completion of *U. pinnatifida* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



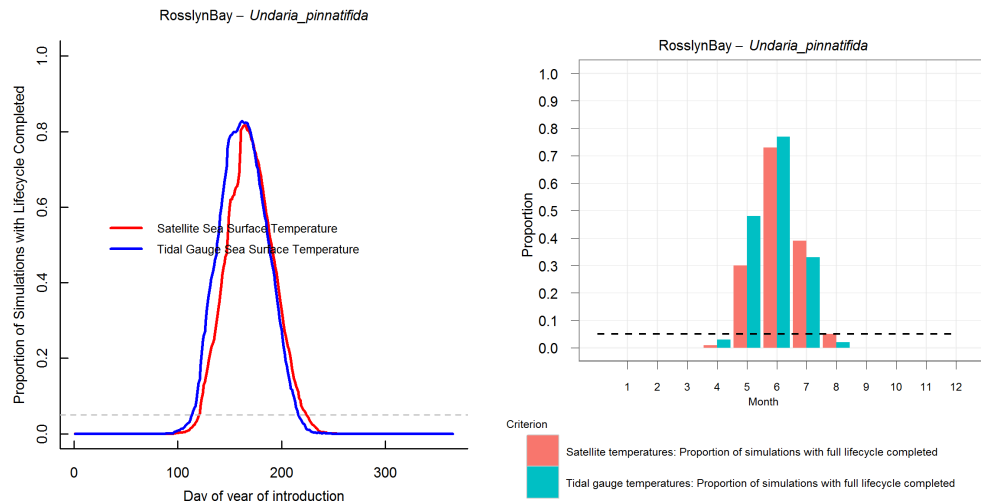
**Figure A.99:** Simulation results for life cycle completion of *U. pinnatifida* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



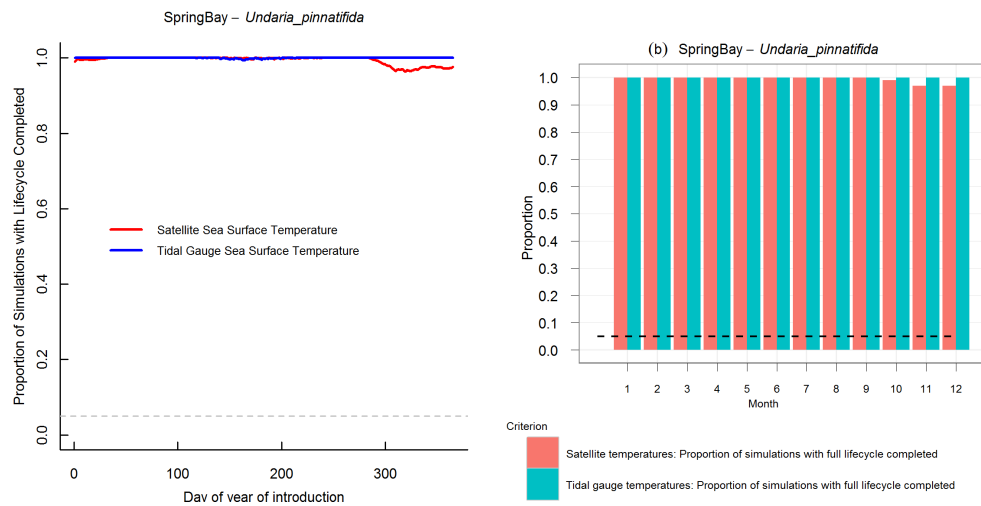
**Figure A.100:** Simulation results for life cycle completion of *U. pinnatifida* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



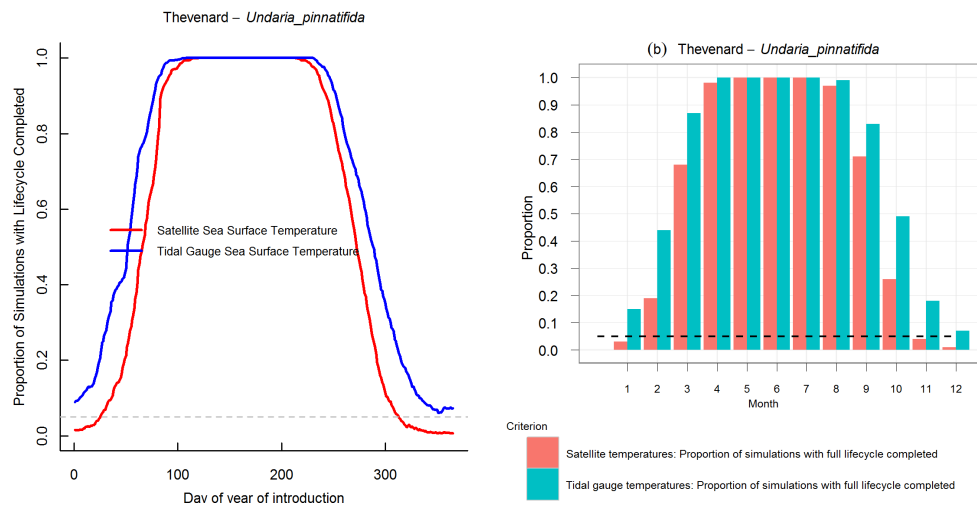
**Figure A.101:** Simulation results for life cycle completion of *U. pinnatifida* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.102:** Simulation results for life cycle completion of *U. pinnatifida* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

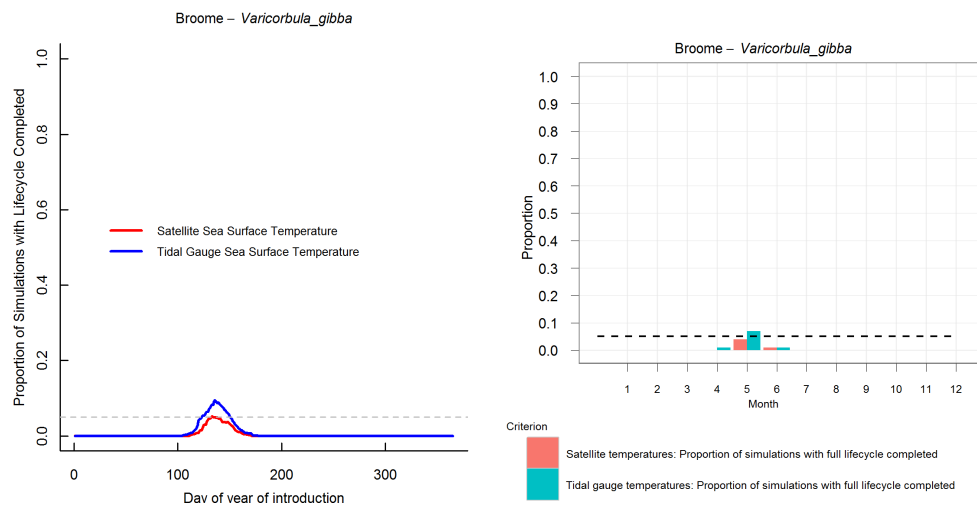


**Figure A.103:** Simulation results for life cycle completion of *U. pinnatifida* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

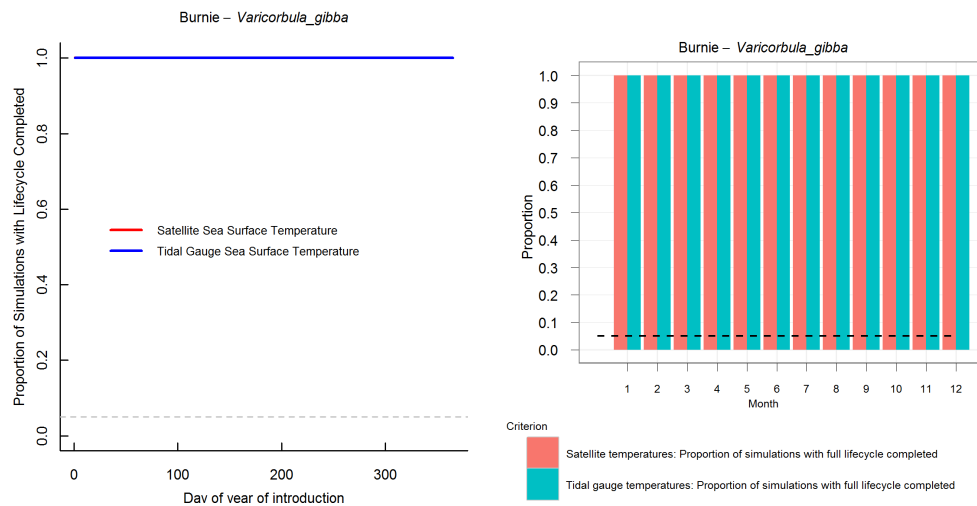


**Figure A.104:** Simulation results for life cycle completion of *U. pinnatifida* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

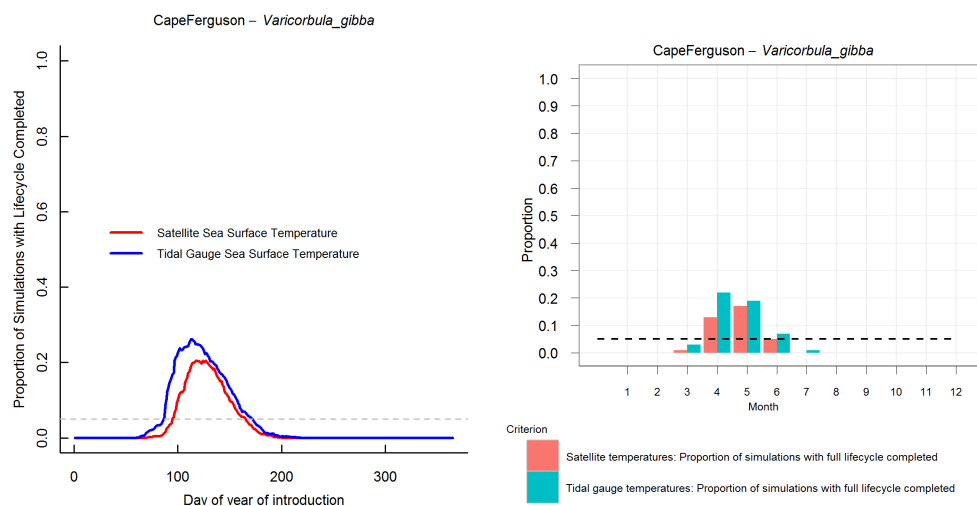
## A.9 *Varicorbula gibba*



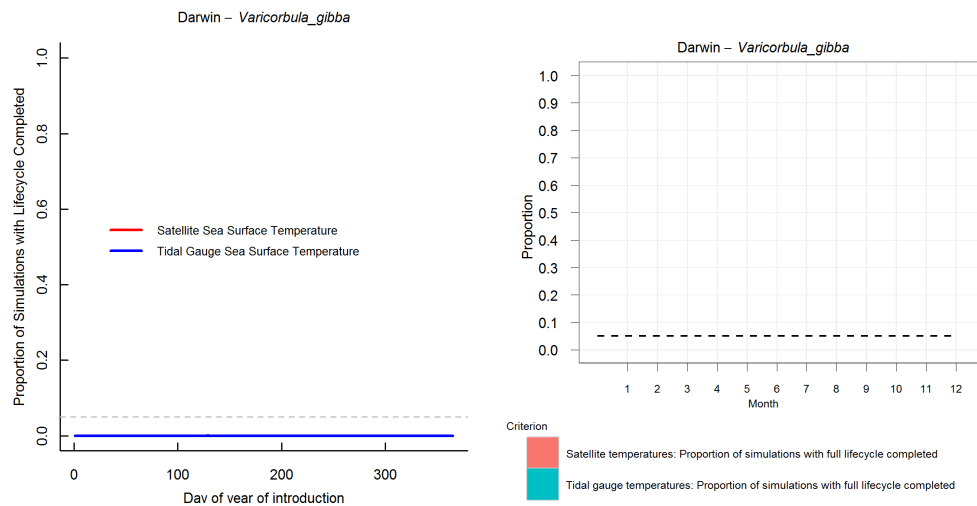
**Figure A.105:** Simulation results for life cycle completion of *V. gibba* in Broome. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



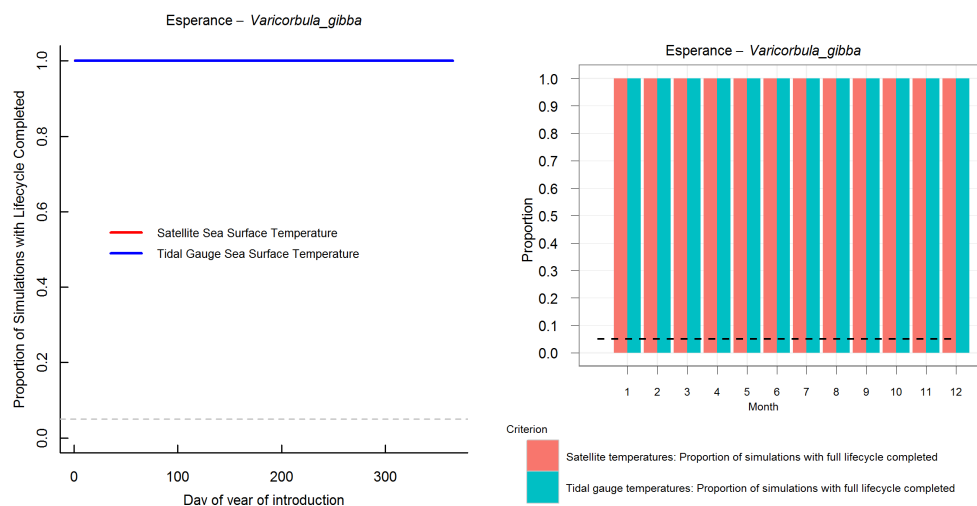
**Figure A.106:** Simulation results for life cycle completion of *V. gibba* in Burnie. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



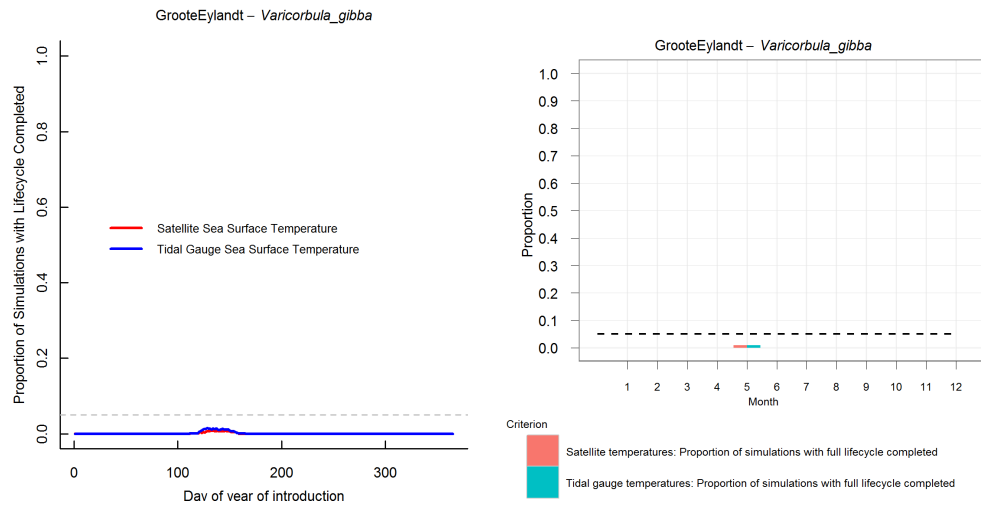
**Figure A.107:** Simulation results for life cycle completion of *V. gibba* in Cape Ferguson. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



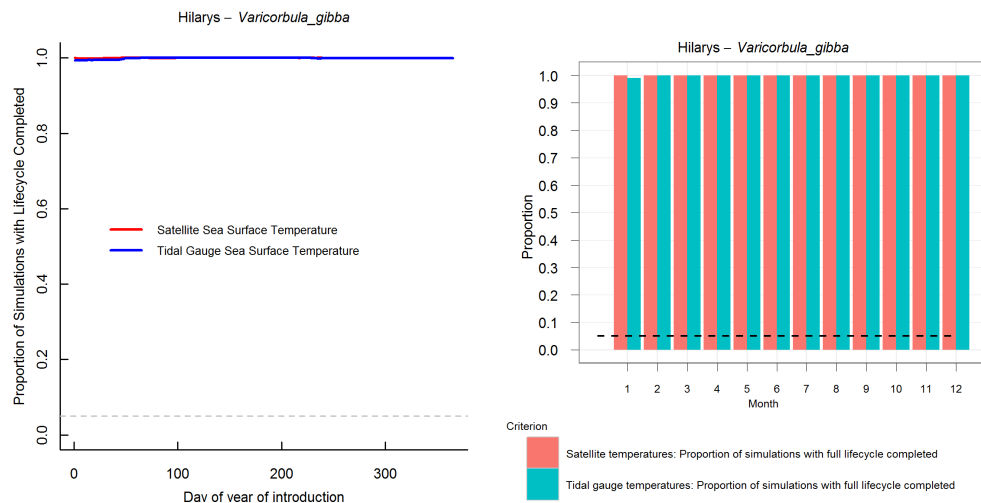
**Figure A.108:** Simulation results for life cycle completion of *V. gibba* in Darwin. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.109:** Simulation results for life cycle completion of *V. gibba* in Esperance. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

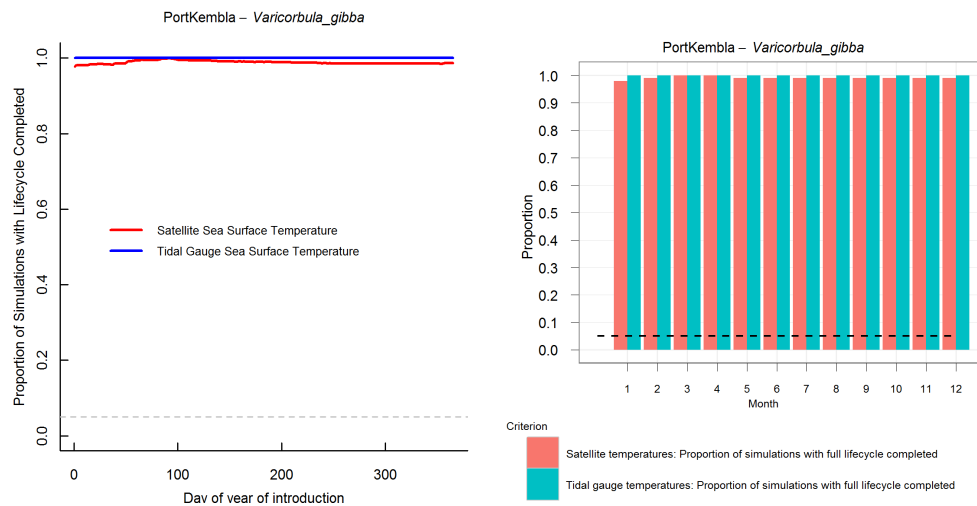


**Figure A.110:** Simulation results for life cycle completion of *V. gibba* in GrooteEylandt. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

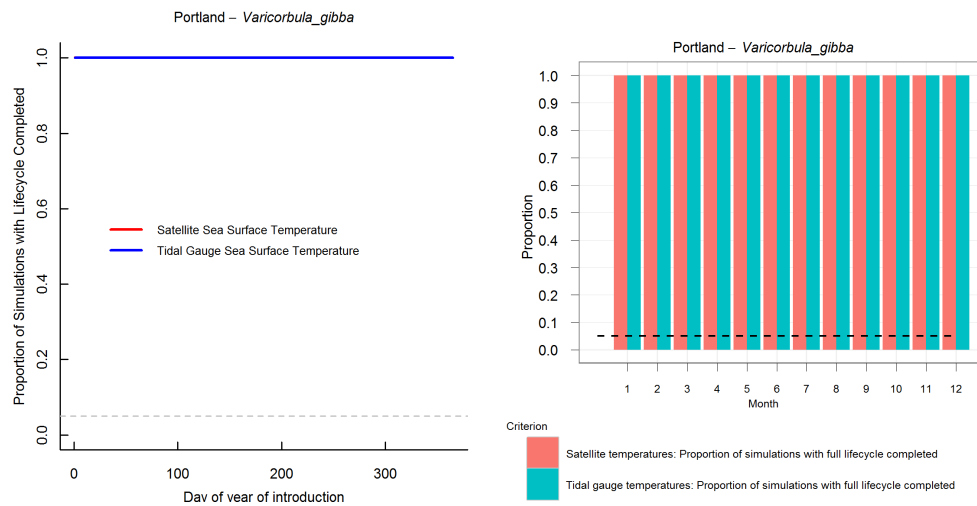


**Figure A.111:** Simulation results for life cycle completion of *V. gibba* in Hilarys. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

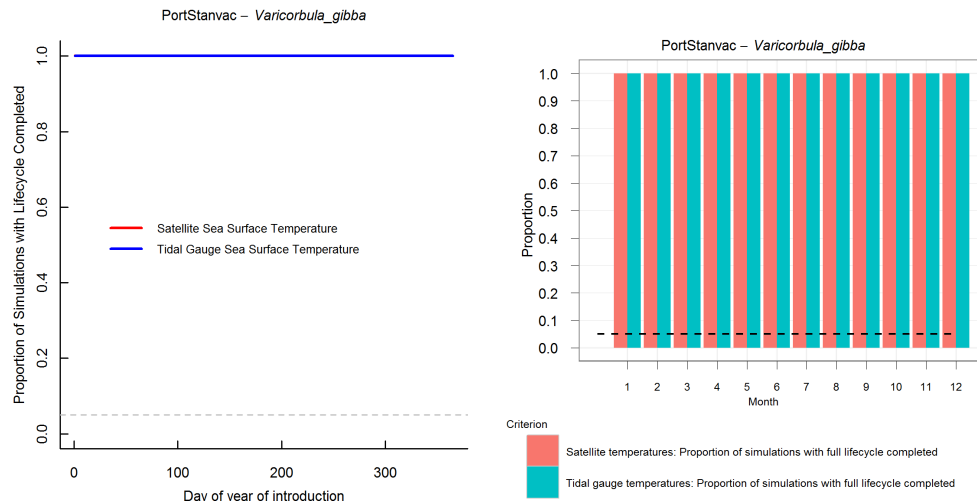




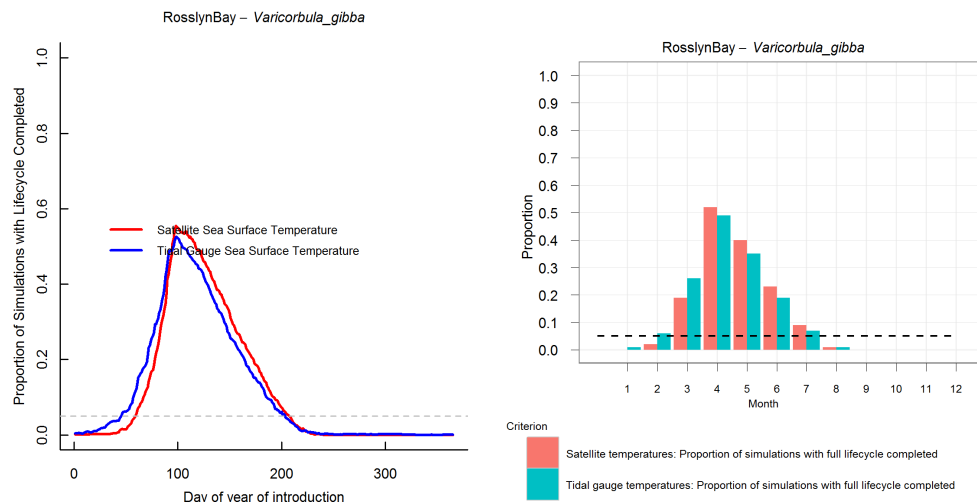
**Figure A.112:** Simulation results for life cycle completion of *V. gibba* in PortKembla. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



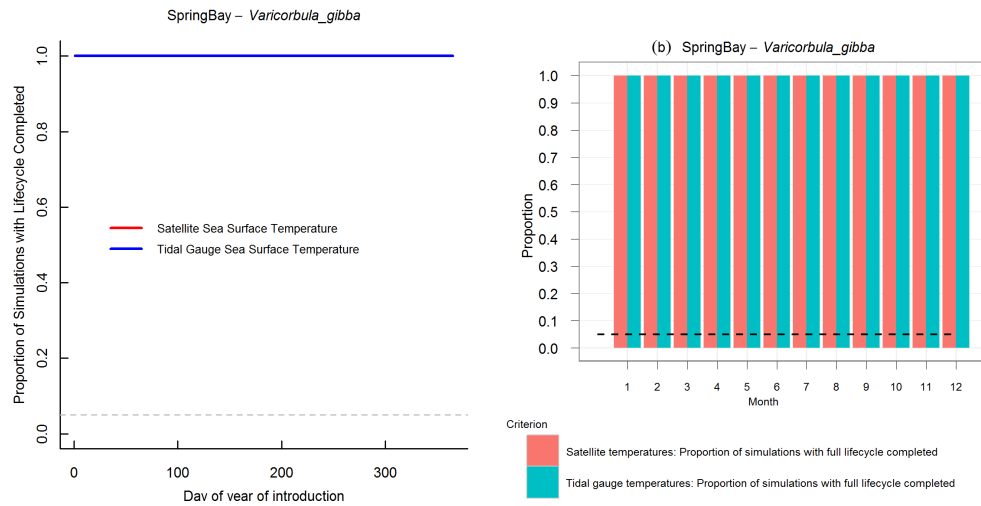
**Figure A.113:** Simulation results for life cycle completion of *V. gibba* in Portland. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



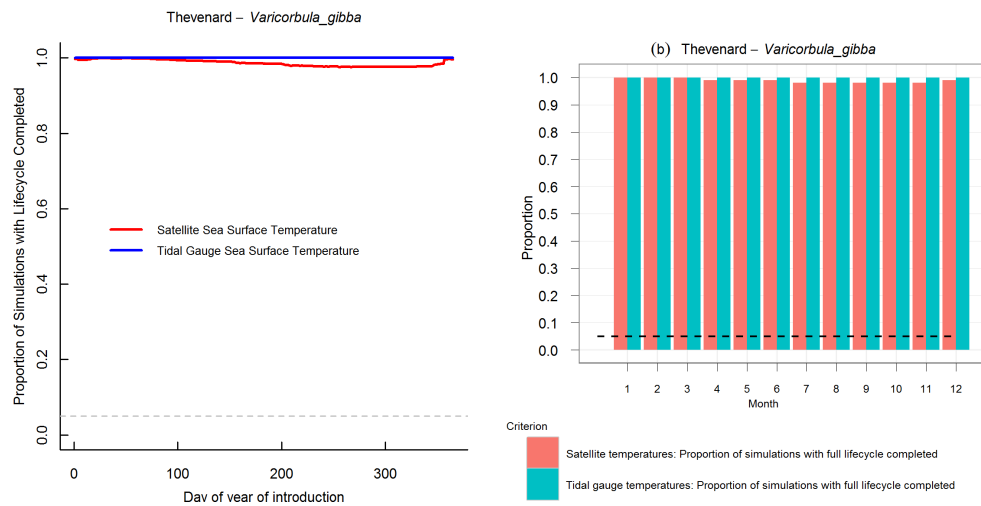
**Figure A.114:** Simulation results for life cycle completion of *V. gibba* in PortStanvac. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



**Figure A.115:** Simulation results for life cycle completion of *V. gibba* in RosslynBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



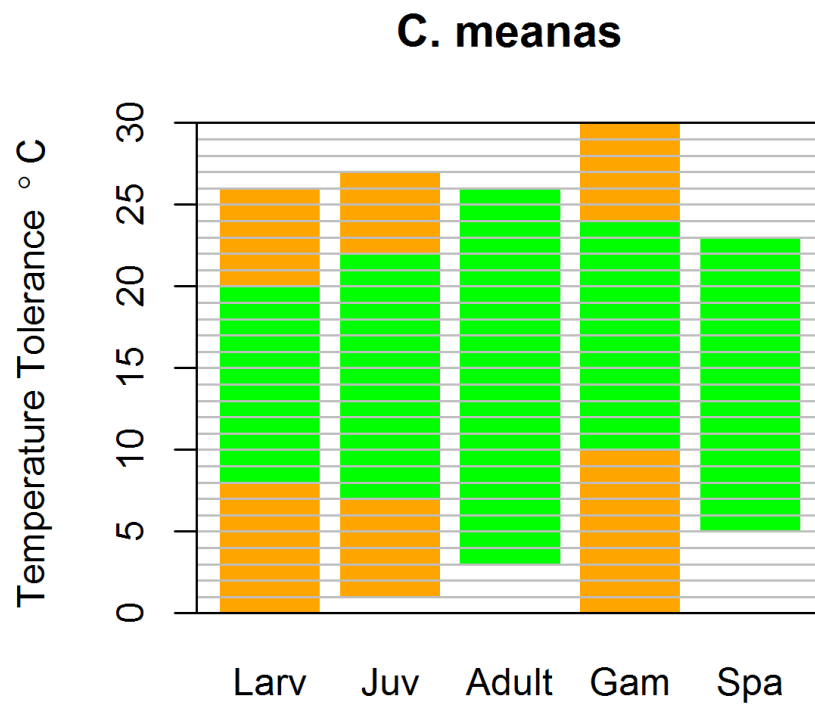
**Figure A.116:** Simulation results for life cycle completion of *V. gibba* in SpringBay. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.



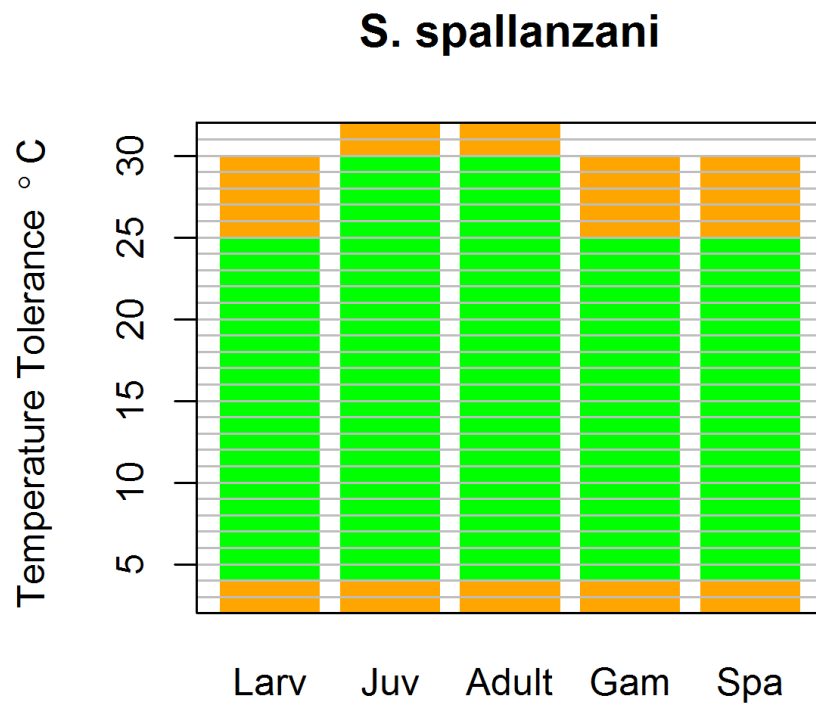
**Figure A.117:** Simulation results for life cycle completion of *V. gibba* in Thevenard. The horizontal line shows a 0.05 cutoff. (left) daily; (right) monthly.

## Appendix B

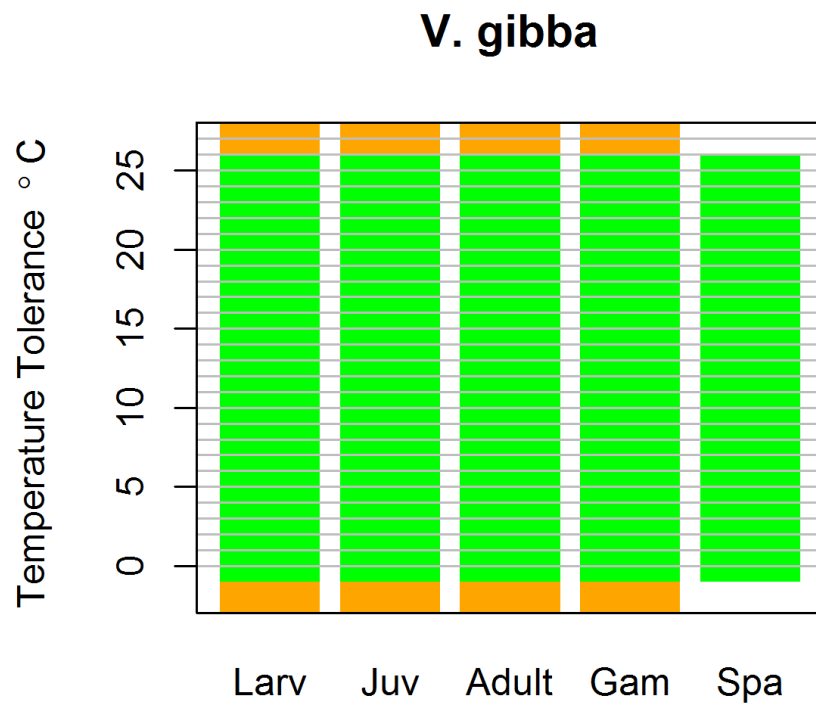
### Temperature tolerances of species life stages used in simulations



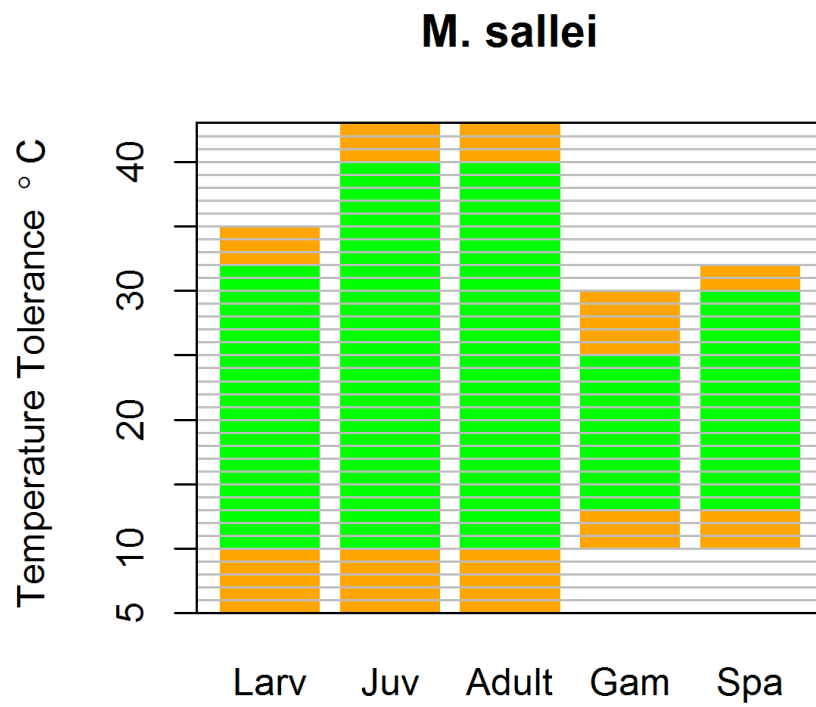
**Figure B.1:** Temperature tolerance of *C. maenas* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.



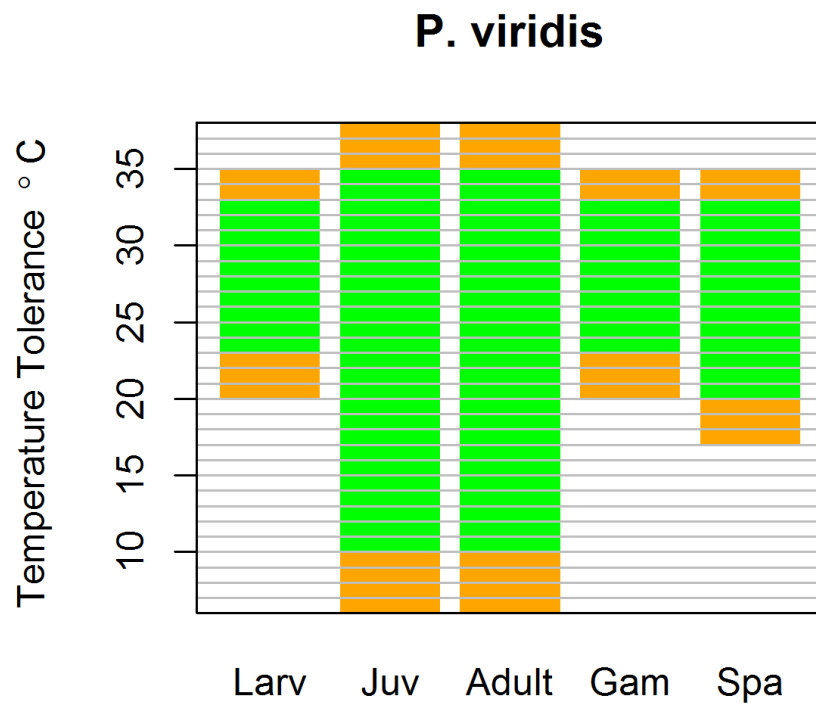
**Figure B.2:** Temperature tolerance of *S. spallanzani* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.



**Figure B.3:** Temperature tolerance of *V. gibba* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.

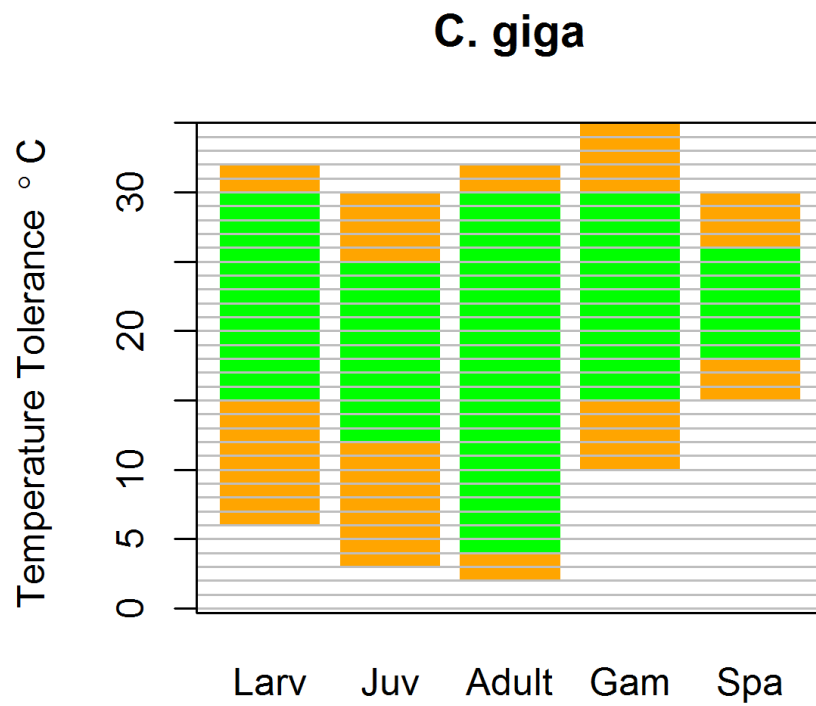


**Figure B.4:** Temperature tolerance of *M. sallei* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.

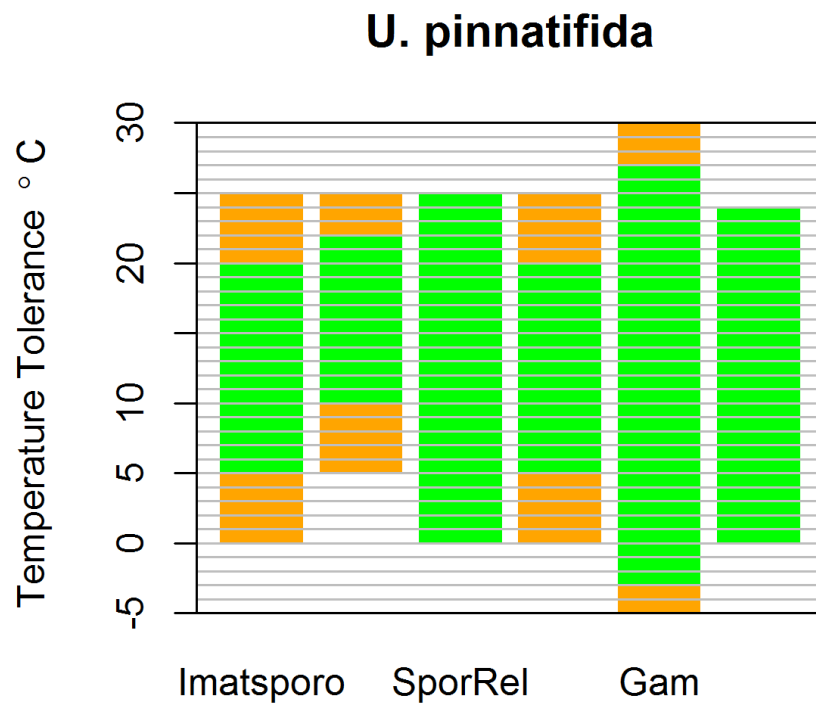


**Figure B.5:** Temperature tolerance of *P. viridis* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.





**Figure B.6:** Temperature tolerance of *C. gigas* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages larva, juvenile, adult, gamete, and for spawning suitability.



**Figure B.7:** Temperature tolerance of *U. pinnatifida* by life stage. The orange coloured regions are temperature ranges that the associated life stages can possibly tolerate - for each simulation a cut-off is chosen from within these regions. The green coloured regions show temperatures that are always considered suitable for the life stages. From left to right, the abbreviations are for the life stages: immature sporophyte, mature sporophyte, released spores, zoospores, gametophyte, and for fertilization.