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Understanding recruitment variation (including the collapse) of Ballot's saucer scallop stocks in Western Australia and assessing the feasibility of assisted recovery measures for improved management in a changing environment. FRDC Project No. 2015/026

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FRDC Project No. 2015/026

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Abbreviations

AI	Abrolhos Islands
AIMWTMF	Abrolhos Islands and Mid-West Trawl Managed Fishery
BOM	Bureau of Meteorology
CPUE	Catch Per Unit Effort
DoF	Department of Fisheries (Western Australia)
DPIRD	Department of Primary Industries and Regional Development
DS	Denham Sound
ENSO	El Niño Southern Oscillation Index
FIS	Fishery-Independent Survey
FSL	Fremantle Sea-level
FRDC	Fisheries Research and Development Cooperation
LC	Leeuwin Current
MHW	Marine Heatwave
RI	Rottnest Island
SB	Shark Bay
NSB	Northern Shark Bay
SBSMF	Shark Bay Scallop Managed Fishery
SC	South Coast
SCTF	South Coast Trawl Fishery
SH	Shell Height
SOI	Southern Oscillation Index
SRE	Stock-Recruitment-Environment
SST	Sea Surface Temperature
SWTMF	South West Trawl Managed Fishery
WA	Western Australia

Executive Summary

This study examined possible contributing environmental factors to the recruitment variability of the Ballot's saucer scallop *Ylistrum balloti* across the main stocks in Western Australia. The project was undertaken to explain the variation observed between years and between regions as well elucidating the potential cause of a major decline in scallop stocks following an extreme marine heatwave, with these findings intended to improve future management advice.

Secondly this project was to examine the feasibility of using assisted recovery through seeding of hatchery produced juveniles or translocation of mature breeding stock or immature scallops.

Background

Scallop recruitment is often characterised by a high level of natural variability. In 2011 in Western Australia (WA), scallop stock surveys in Shark Bay and Abrolhos Islands indicated extremely low levels of both juveniles and adults. This was after an extreme marine heatwave (MHW) occurred along the WA coastline between December 2010 and February 2011. It was therefore considered that natural recovery could be impeded due to insufficient spawning stock to produce successful recruitment even under ideal environmental conditions. These two fisheries were closed as a result of the very low scallop abundance and to protect the spawning stock which had a major financial impact on the industry. This led to a workshop of scallop experts, industry and managers to discuss the potential cause; whether these conditions are likely to remain and what actions may facilitate recovery.

An urgent need was identified at this workshop to better understand recruitment variation including causes of the major stock decline, to investigate the potential of assisted recovery measures (such as restocking and reseeding from hatchery production) to re-establish founder populations in these extremely depleted stocks and to provide management and industry with a cost-benefit evaluation of these potential measures to aid recovery.

Objectives

1. Understanding factors influencing recruitment variations in existing scallop WA stocks, particularly the collapse of the stocks in 2011.
2. Determine the feasibility of re-establishing founder population of scallops in the Abrolhos Islands and Shark Bay through seeding of hatchery produced juveniles
3. Determining feasibility of re-establishing founder population of scallops in the Abrolhos Islands through translocations.

Methodology

Initial FRDC 2015/026 funding approval was for a phased approach to addressing the objectives. Phase 1a was a desktop study on the environmental factors that influence scallop recruitment and to improve our understanding of spawning cycles in the different regions. The second component involved opportunistic field sampling for scallops during surveys and with fishers providing samples of scallops to investigate spawning cycles.

The environmental factors considered were; sea surface temperatures (SST), Fremantle Sea level (FSL) a proxy for the strength of the Leeuwin Current that flows north-south along the WA coastline, and wind speed and direction. These factors were correlated against juvenile recruits (0+) and adult (1+, spawning stock) abundance through fishery independent surveys for the major scallop fisheries and using annual landings as a proxy when only commercial catch and effort data was unavailable. Lags of up to 24 months were used in the correlations to encompass periods of spawning and post settlement phase of scallops. Pigmented rings on

juvenile scallops were counted using a microscope to estimate settlement (and spawning) time for each fishery. The reproductive condition of scallops were visually determined during surveys and female size of sexual maturity was also estimated.

Phase 1a served as a stop-go point for consideration of the provision of additional FRDC funding for Phase 1b) (conditioning of broodstock to produce viable juveniles) with any further funding for Objectives 2 and/or 3 to be sourced through a new application to the FRDC. A new application to FRDC was not submitted, however components of Objectives 2 and 3 were investigated and included in this report. A pilot-scale translocation project (part of Objective 3) was conducted in the Abrolhos Islands during this study which involved moving sub-adult scallops (after tagging them) from one part of the Abrolhos Islands to another about 2 hours steaming away at a time when natural recovery was already apparent in the fishery and it was evident that the environmental conditions had become conducive to the survival of recruiting scallops. This small scale experiment provided useful information on capture, handling, transport and deployment techniques and some information on growth and survival of translocated scallops.

In addition, a pilot study commenced at DPIRD prior to the FRDC funding that was focused on hatchery production of juveniles (Objective 2). Broodstock was collected from fisheries that still had scallops in moderate abundance and broodstock transport and handling methods were tested, different feed regimes and holding mediums were also tested and there were several successful spawning events. The health and condition of scallops from the four fisheries were also assessed during this period. Insufficient larvae were produced to conduct replicated experiments. Therefore, Objective 2 was not pursued further. However, information gained during the pilot project contributed to the direction of this study.

Results/key findings

The Ballot's saucer scallop larval period is approximately two weeks during which water temperatures and currents play a critical role in larval survival and growth while geographical and/or oceanographic barriers enable larval entrapment and settlement. Therefore, recruitment variability is primarily dependent on the biophysical processes that retain larvae within primarily self-populating spawning grounds when spawning stock is sufficient.

In this study we found that seasonal water temperatures, wind strength and direction, the ENSO cycle, ocean currents and geographical barriers are important factors influencing scallop recruitment. However, it was clearly evident for several scallop fisheries that, post MHW, the extremely low level of spawning stock was a significant contributor to low recruitment levels. A key stock-environment relationship across all stocks was associated with winter and/or summer water temperatures. Water temperature appears to play a crucial role in the timing of spawning and length of the spawning period. In general, positive and above average recruitment years were associated with an optimal water temperature range between 18 and 23 °C and below average recruitment associated with temperatures below or above this thermal range. Water temperatures are highly influenced by the ENSO cycle where strong and extended La Niña events have led to two MHWs. The timing, duration and intensity of MHWs are important considerations when assessing their impact on scallop recruitment. For example, *Y. balloti* at their most southern distribution on the SC experienced positive recruitment events after both MHWs while scallops at their northern range distribution in Shark Bay suffered catastrophic recruitment and stock declines.

Assisted recovery strategies were identified as currently not being feasible. The small scale translocation experiment was not sufficient to test the efficacy of translocation of scallops to increase breeding stock levels.

Implications for relevant stakeholders

The WA coastline is a climate change hotspot and therefore the trends documented in this report highlight the need to consider climate change in management, fishery harvest strategies and for reviewing collection of long-term data sets (both fishery dependent and independent) in order to be able to fully evaluate stock status and likely production trends in these fisheries.

The project identified environmental factors that explain more than 50% of the variability in scallop recruitment, recognising that the underlying mechanisms are not clearly known.

The project has clearly identified that the environmental changes observed to date are not stable and continue to cycle or trend up or down and behave differently between regions. This knowledge has management implications as to what spatial units may constitute fishing grounds/region and 'individual fisheries' in the medium to longer term.

The project clearly provides justification for management of scallop stocks within WA and reinforces the need for regular environmental monitoring and application of this information to inform management decisions. The Shark Bay fishery has adopted a mid-year review of the management measures to ensure proper management of the stocks.

The project highlights the ongoing research gaps that needs addressing to further improve our understanding of scallop recruitment variability.

The project identifies a clear correlation of the spawning stock size and environmental factors contributing to the variability in scallop recruitment. This enables the development of robust limit reference points in the harvest strategies for these fisheries.

Recommendations

- Scallop stock abundance measures, commercial catch and effort (catch rates) and size (and quality) composition and scallop health monitoring will continue to be important alongside environmental monitoring to enable strategic management of these stocks.
- Develop additional harvest control rules based on improved understanding of stock-recruitment-relationships combined with current measurable environmental factors influencing scallop recruitment.
- Continue regular environmental monitoring, particularly SST as a high priority and collaborate with climate scientists in terms of future projections to improve management of the scallop stocks in WA.
- Further research into Shark Bay's habitat and productivity as reasons for non-recovery in northern SB.
- Incorporate Chl-a and salinity monitoring to the water sampling programs in SB and AI to assess if these are important factors in scallop production.
- This study has highlighted the value of monitoring 0+ and 1+ cohorts within the two major fisheries in understanding environmental influences and therefore recommend the development of FIS in other scallop fisheries. Discuss with industry the potential to develop Cost-effective fishery-independent surveys in the SCTF and SWTMF.
- Conduct ongoing scallop health condition sampling and analyses within SB to assist with understanding the disconnect between stock recovery in DS and lack of recovery in NSB.

- Repeat the larval advection modelling that was completed as part of (FRDC 2007/051) to determine any changes in circulation patterns and outflows within SB, particularly in northern SB.
- Conduct larval advection modelling in the other fishery regions to improve understanding of scallop settlement patterns and processes.

Keywords

Scallops, *Ylistrum balloti*, recruitment, environment, spawning stock, marine heatwave

2. Introduction

The perception that fisheries collapse or recruitment failure is the result of overfishing reflects badly on industry, researchers and managers. It is important to understand the cause of recruitment variation (and particularly failures) to be able to factor it into management settings, and to be able to clearly explain these to stakeholders. In light of scallop stock surveys in 2011 in Shark Bay and Abrolhos Islands indicating extremely low levels of recruits and adults, it was likely that natural recovery was impeded due to insufficient spawning stock to produce successful recruitment even under ideal environmental conditions. Closure of these fisheries as a result of the very low abundance and to protect the spawning stock has had a major financial impact on the industry. This led to a workshop of scallop experts, industry and managers to discuss the cause of the collapse; whether these conditions are likely to remain and if they will improve to permit some recovery. Due to very low stock abundance it could be that the breeding stock was too low or the survival of larvae/juveniles has been reduced to compromise a significant stock recovery.

An urgent need was identified at this workshop to understand recruitment variation including the initial stock collapse, investigate the potential of assisted recovery measures (such as restocking and reseeding from hatchery production) to re-establish founder populations in these extremely depleted stocks, and provide management/industry with a cost-benefit evaluation of these measures to aid recovery. Fishery restoration through assisted recovery (FRDC 2011/762) has shown some success with Roe's Abalone in Western Australia (WA) and may lend itself as a management tool in a changing marine environment.

2.1 Scallop stocks in Western Australia

Ballot's saucer scallops (*Ylistrum balloti*) have a distribution that spans most of the Western Australian coast, having been recorded from Broome in the north to Esperance in the south, however, they are fished using demersal otter trawls in only four separate fisheries in WA (Kangas et al. 2011). The Shark Bay Scallop Managed Fishery (SBSMF) is WA's most valuable scallop fishery followed secondly by the Abrolhos Islands and Mid-West Trawl Managed Fishery (AIMWTMF). The South West Trawl Managed Fishery (SWTMF) is a multi-species fishery that primarily target scallops and the South Coast Trawl fishery (SCTF) targets scallops on the South Coast intermittently, subject to favorable environmental conditions. For the remainder of this report, scallops from these fisheries will be referred to by their respective regional occurrence i.e. Shark Bay, Abrolhos Islands (AI), Rottnest Island (RI) and South Coast (SC).

2.1.1 Shark Bay

Shark Bay is located 800 km north of Perth, along the Gascoyne coastline of Western Australia and covers an area of approximately13 000 km^2 (Figure 1). Shark Bay is the largest marine embayment in Australia and supports the most extensive and diverse seagrass meadows in the world (Arias-Ortiz et al., 2018). It is an inverse estuary formed by an elongate chain of three islands; Dirk Hartog, Bernier and Dorre Island (Nahas, 2005). The southern half of the embayment is divided by the Peron Peninsula into the Eastern and Western gulfs, characterised by narrow inlets and basins. The embayment is for the most part relatively shallow, with an average depth of 9 m and deepest depth at 29 m in the north (Francesconi and Clayton, 1996) There are two separate scallop stocks within Shark Bay; Northern Shark Bay (NSB) and Denham Sound (DS) where very little larval mixing has been shown to occur between these areas (Kangas et al. 2012) (Figure 1).

Shark Bay has a semi-arid climate, with mild winters and hot, dry summers punctuated by infrequent cyclones and with a low mean annual rainfall. The hydrology of Shark Bay is to some extent influenced by the Leeuwin Current which intrudes into the Bay through the broad Naturaliste and Geographe channels, while a lesser intrusion occurs in the Western gulf through the narrow South Passage. Shallow bathymetric features in the inner Bay restrict water movement and these areas are characterised with seagrass meadows which further restrict movement by increasing bottom friction, causing increased deposition of suspended sediments that over time have produced large sedimentary banks (Francesconi and Clayton, 1996). Therefore, the limited exchange of oceanic water, minimal freshwater input and high evaporation rates has resulted in Shark Bay containing three distinct water body types: oceanic (salinity of 35 –40 ‰) in the northern waters and upper gulf regions, metahaline (40 –56 ‰) in the middle gulf regions and hypersaline (56 –70 ‰) in the lower gulfs.

Ballot's saucer scallops are generally found in the deeper central oceanic areas of the Bay on sandy bottoms (Figure 1). They are targeted by dedicated scallop trawlers (11 licenses), the Shark Bay Scallop Managed Fishery (SBSMF), which account for 70% of catch and by prawn trawlers (18 licenses) from the Shark Bay Prawn Managed Fishery (SBPMF), which primarily target prawns with scallops as a secondary target species.

Annual catches are highly variable which is typical of short-lived scallop fisheries. Since 1984, the annual catches have varied from 121 t (1989) to 4,414 t (1992) meat weight, however in 2011, following the 2010/11 Category 4 marine heatwave (MHW) catches fell to 59 t, well below the historical range and catch prediction for that year, and the stock suffered a major collapse. In 2012 the fishery was closed for three years until 2015 (Figure 2). Prior to its closure, the fishery was managed using input controls which included limited entry, seasonal and area closures and gear controls. When the fishery reopened in 2015, a trial quota management system was introduced with a total allowable catch (TAC) allocated as individual transferable quotas (ITQs) amongst all license holders, maintaining the 70/30% catch allocation between the two trawl sectors. Catches have slowly increased since 2015, however most of the landings have come from Denham Sound rather than Northern Shark Bay which historically was the more consistent area for scallop production (Figure 2).

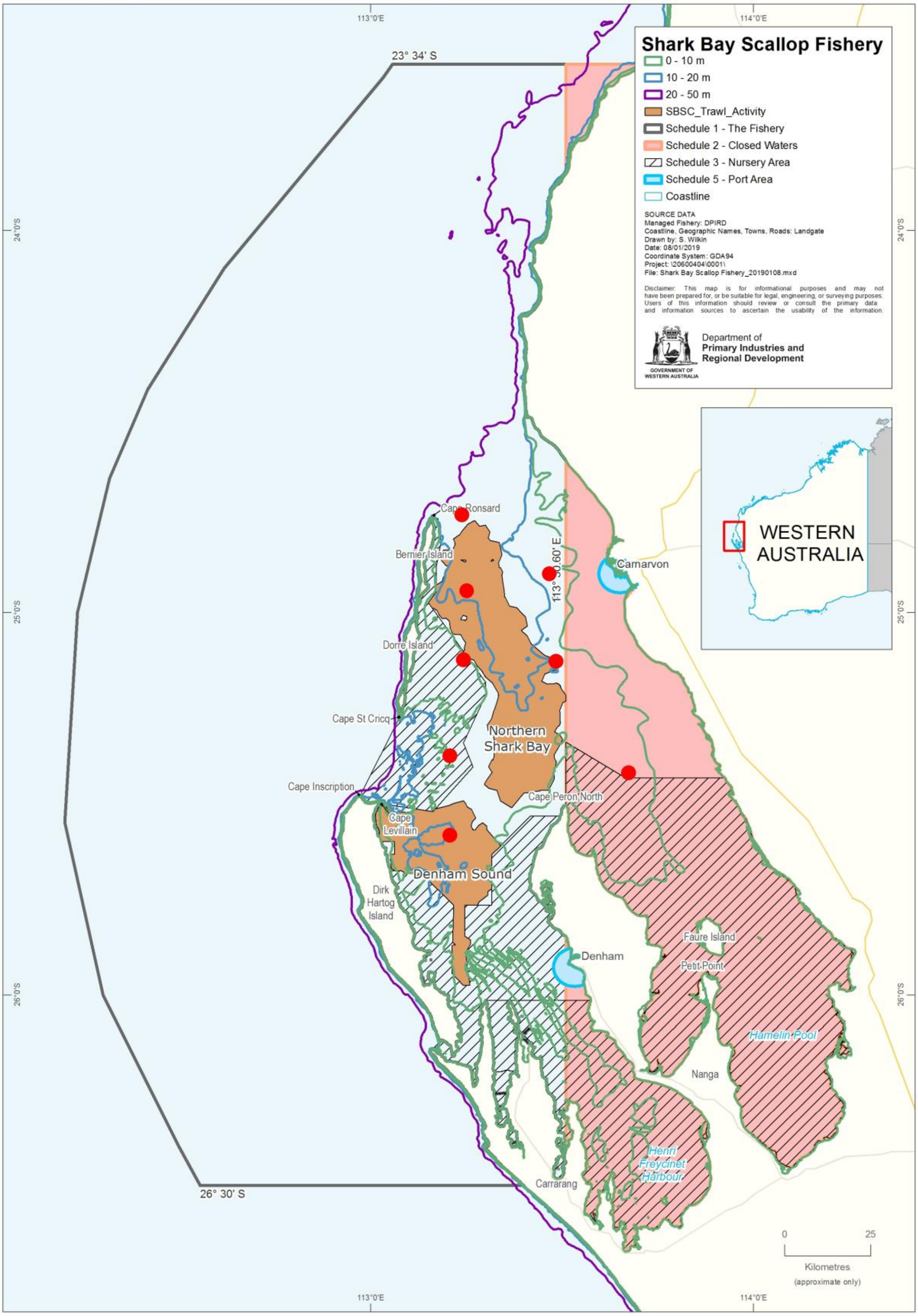

Figure 1. Map showing the main fishing grounds for scallops in Northern Shark Bay and Denham Sound within the boundary of the Shark Bay Scallop Managed Fishery. Locations used for satellite SST analyses are indicated by red dots.

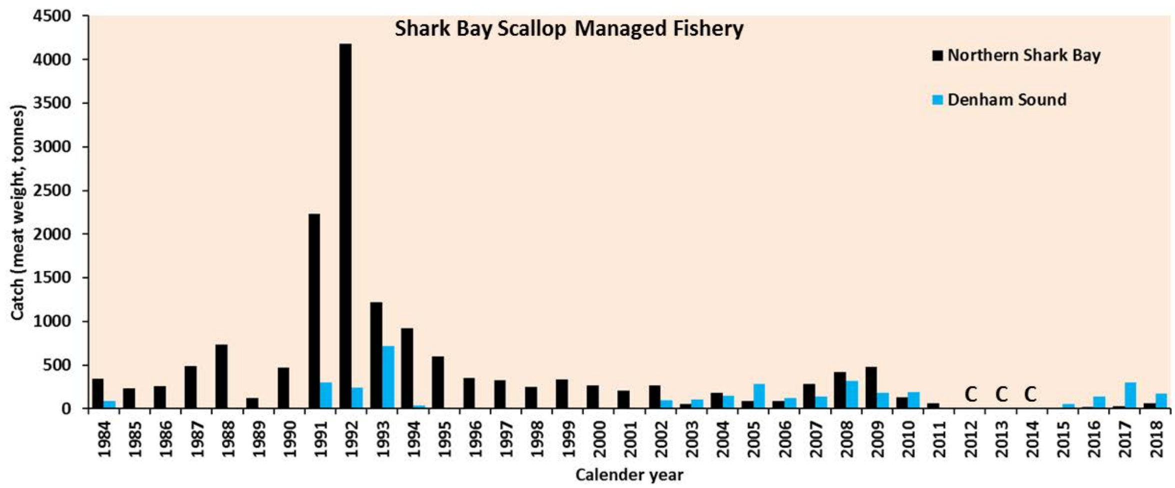

Figure 2. Catch (t, meat weight) history of *Y. balloti* from the Shark Bay Scallop Managed Fishery 1984-2018. Fishery closed between 2012 and 2014.

2.1.2 Abrolhos Islands

The Houtman-Abrolhos Islands (Abrolhos) are a complex of 122 low-lying islands and reefs located on the edge of the continental shelf where the 50 m isobath curves around to encompass the islands (Johannes et al. 1983). There are three major island groups, the North Island-Wallabi Group, the Easter Group and the Pelsaert (Southern) Group, separated by the Middle and Zeewijk Channels, respectively (Figure 3). The Abrolhos Islands are well-known for their high species diversity, coral reefs and unique mixture of temperate and tropical species. The Abrolhos Islands are considered to be an ecological mid-point in a gradient that extends from the tropical ecosystems in the north, south along the shelf to the temperate communities at Rottnest Island (see below). However, being 60 km offshore, these islands are more exposed to the flow of the Leeuwin Current than coastal lagoons and shorelines.

Scallops are found on the sandy bottom in the leeward side of the islands. The AIMWTMF operates under an input control and constant escapement based management system with specific gear configurations and a catch rate threshold to cease fishing to provide carry-over of stock for spawning. There are currently 10 licenses and up to 5 or 6 vessels operate in the fishery each year. The fishing season usually operates between March and September. Annual landings have been highly variable (Figure 4) indicative of the variable recruitment dynamics. Catches have ranged from 8 to 1,284 t meat weight. Stock decline following the 2010/11 MHW led to the closure of the fishery for five years between 2012 and 2016 to allow for stock recovery. Commercial fishing resumed in 2017.

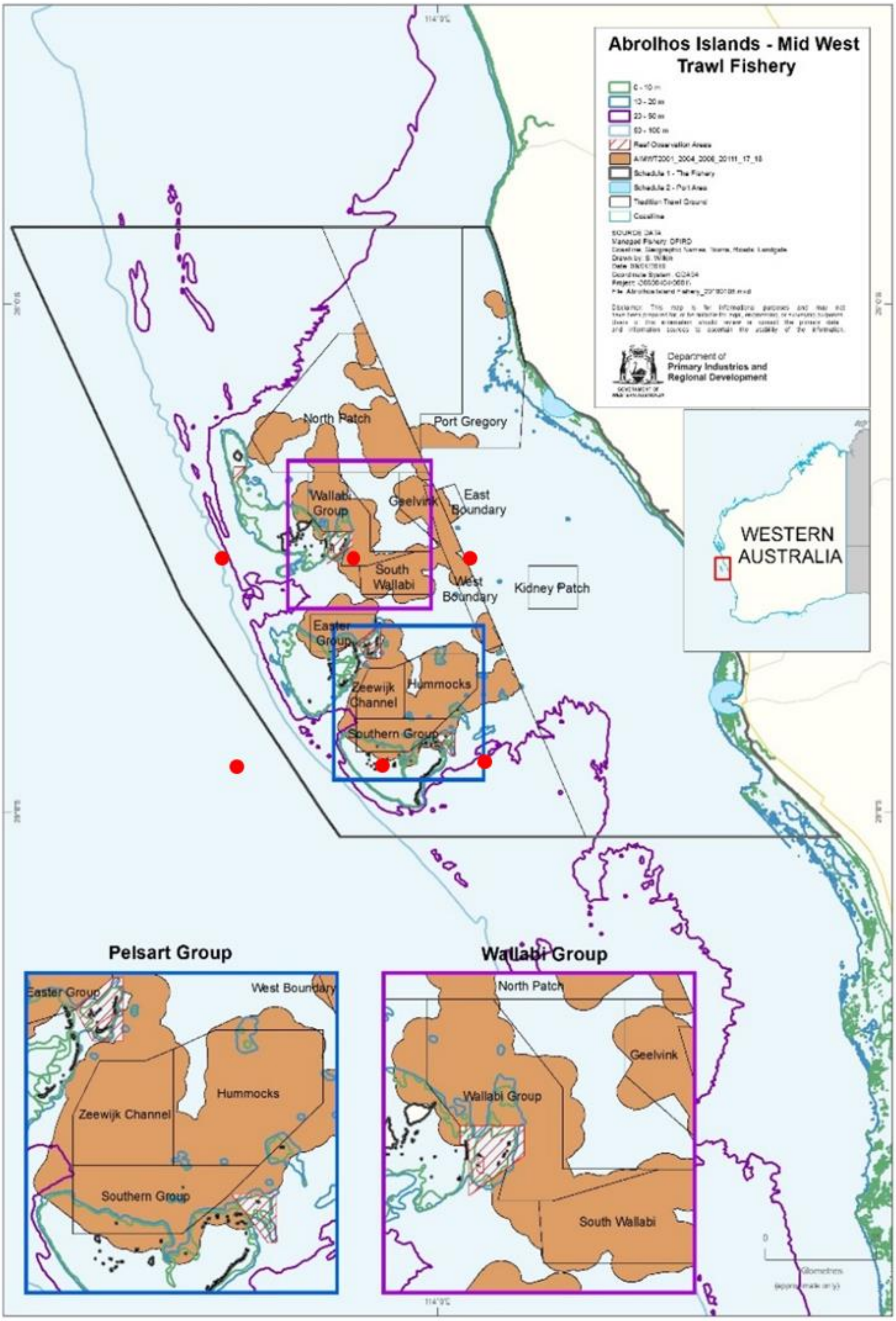

Figure 3. Main fishing grounds for scallops at the Abrolhos Islands within the boundary of the Abrolhos Islands and Mid-West Trawl Managed Fishery. Locations used for satellite SST analyses are indicated by red dots.

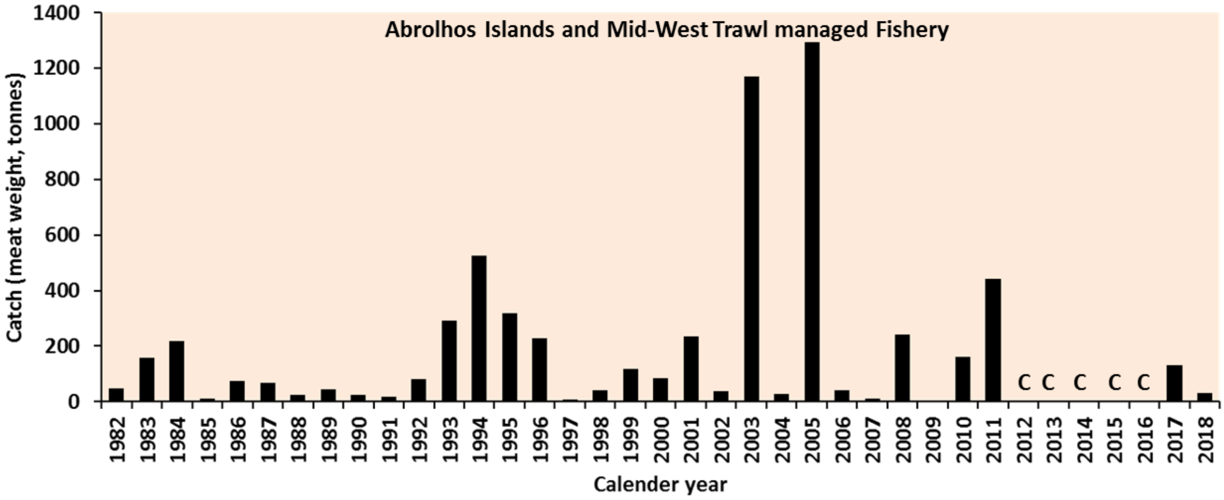

Figure 4. Catch (t, meat weight) history of *Y. balloti* from the Abrolhos Islands and Mid-West Trawl Managed Fishery 1982-2018. Fishery closed between 2012 and 2016.

2.1.3 Rottnest Island

Ballot's saucer scallops are landed as part of the multispecies South West Trawl Managed Fishery (SWTMF), predominantly captured north-east of Rottnest Island (Zone A) (Figure 5). When open, the fishing season is usually between January and November but the actual months vary annually depending on the abundance of target species and other operational factors. Therefore, effort in the SWTMF has been related to either the abundance of western king prawns or scallops. Since 2005, only 1-4 vessels have operated covering 1-3% of the allowable fishery area. Annual scallop catches in the SWTMF were < 5 t until 1986, catches then increased and fluctuated between 6 and 43 t until 1992 (Figure 6). Between 1993 and 2009, catches remained below 5 t and peaked again at 43 t during 2010. Catches of scallops have since declined, with 16 and 11 t landed in 2011 and 2012, respectively. No scallop fishing took place between 2014 and 2016 due to very low stock levels and only one boat has operated sporadically in 2017/18 to supply local niche markets.

2.1.4 South Coast

The South Coast Trawl Fishery (SCTF) is now a scallop fishery (target species) although historically operators also targeted a small amount of mixed finfish. While the boundary of the fishery covers a large section of the South Coast of WA, the fleet is effectively restricted to very small areas (1-3% of allowable fishery area) of higher scallop abundance in sandy areas near Bremer Bay, the Recherche Archipelago and Israelite Bay (Figure 7). When open, the SCTF operates from 1 April to 31 October each year. The spring/summer closure period allows for protection of spawning stock and recovery of post-spawned scallops. While there are no formal catch limits, the fishers cease fishing at threshold catch rates under limited entry with gear restrictions and seasonal closures. Effort in this fishery is related to the abundance of scallops in a given year, which are highly variable due to recruitment variability. Thus landings have ranged from <1 tonne (meat weight) in 1993 to as high as 544 t in 2000 (Figure 8).

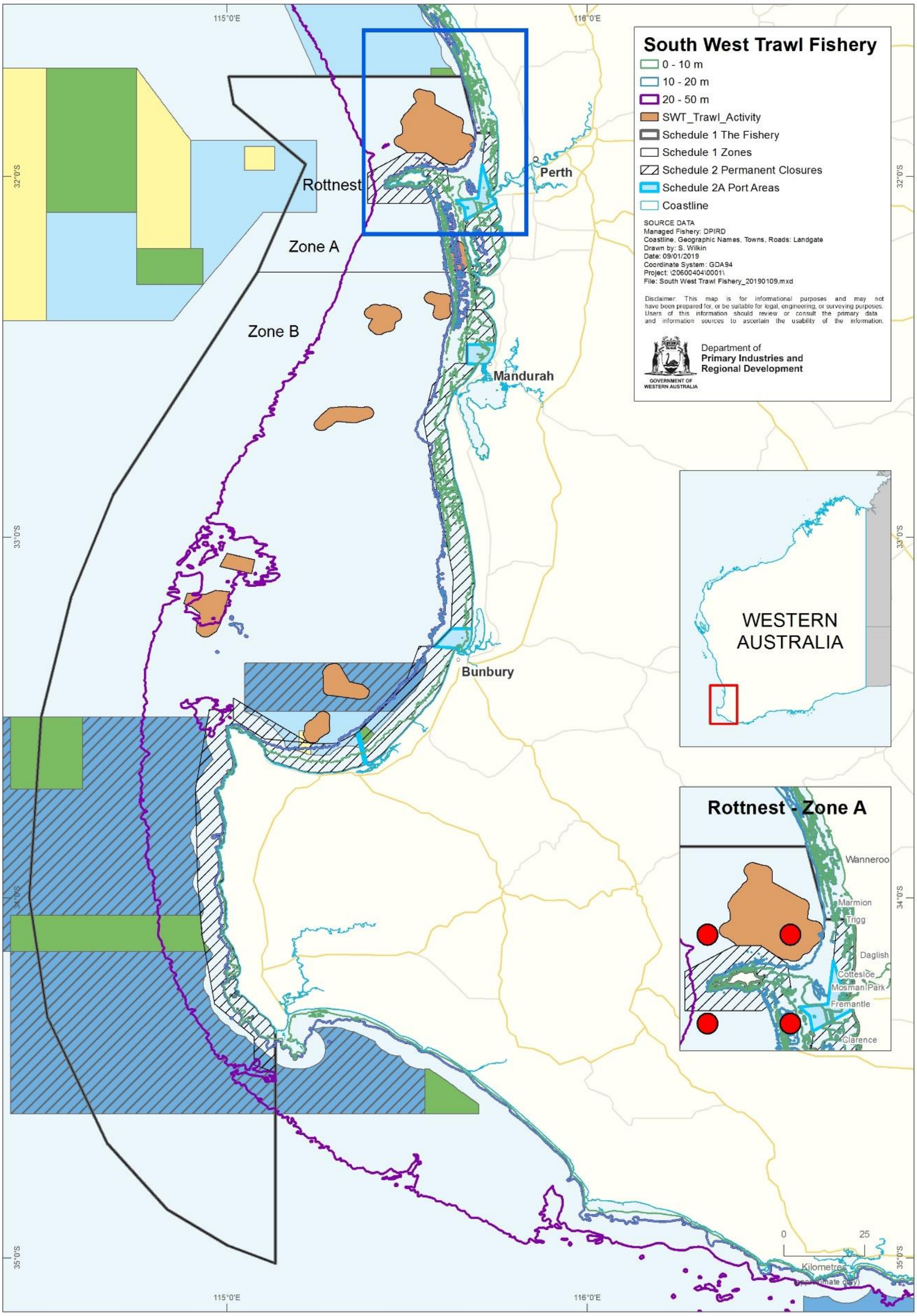

Figure 5. Main fishing grounds for scallops in the South West Trawl Managed Fishery. Most consistent scallop landings are from Zone A which includes the waters around Rottnest Island. Locations used for SST analyses are indicated by red dots.

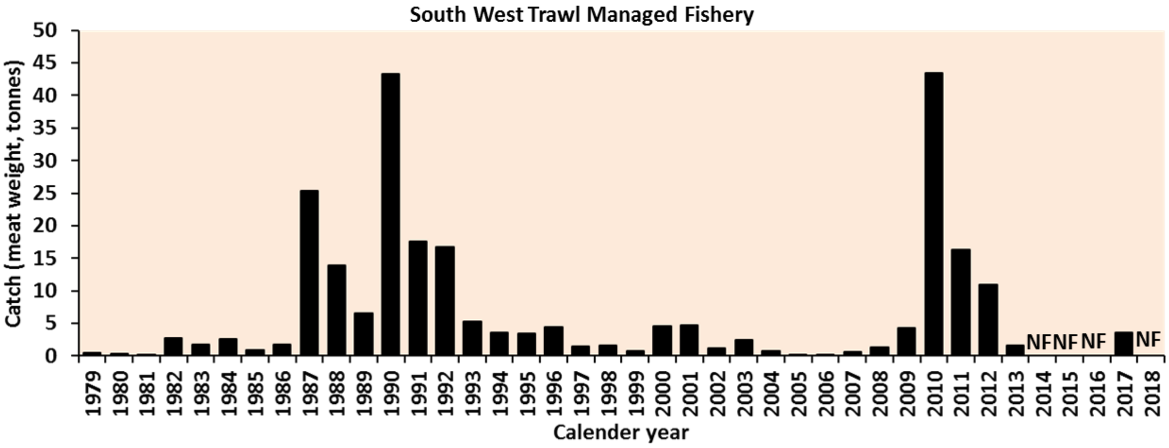

Figure 6. Catch (t, meat weight) history of *Y.balloti* from the South West Trawl Managed Fishery 1970-2018. No fishing took place 2014-2016 and 2018.

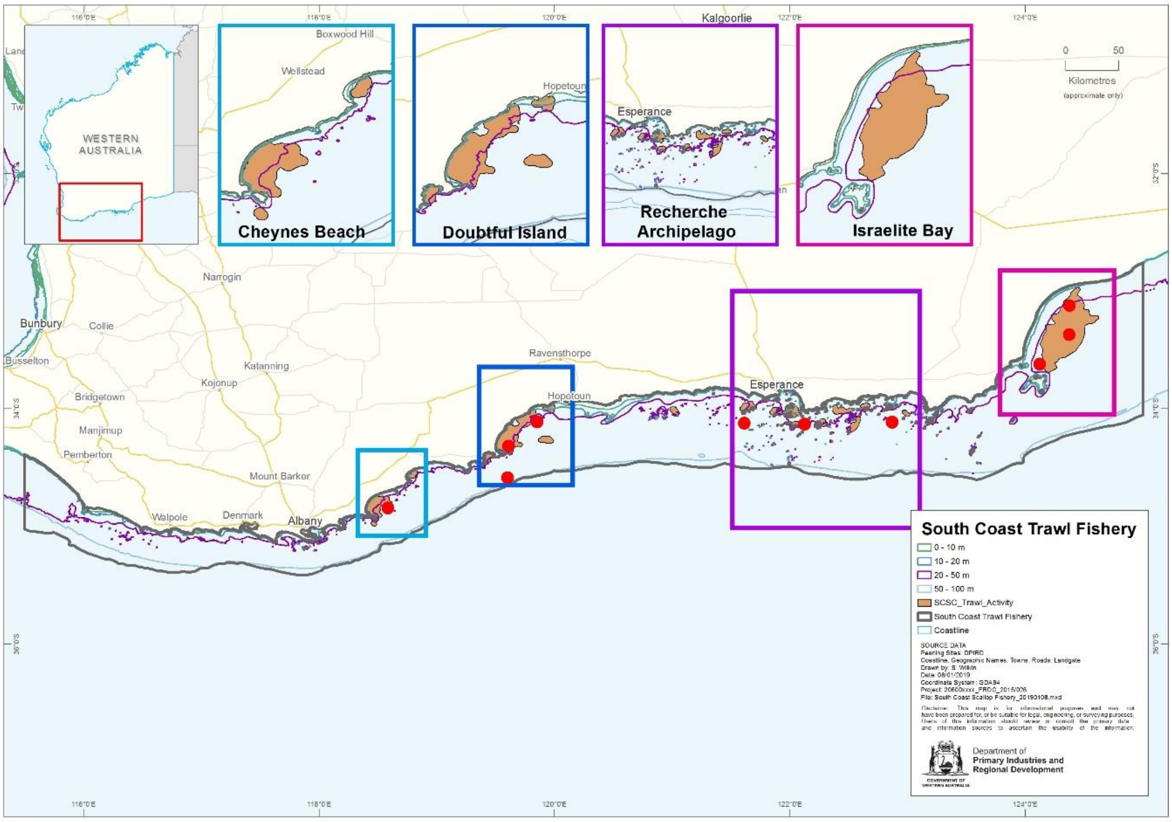

Figure 7. Main fishing grounds for scallops in South Coast Trawl fishery. Locations used for SST analyses are indicated by red dots.

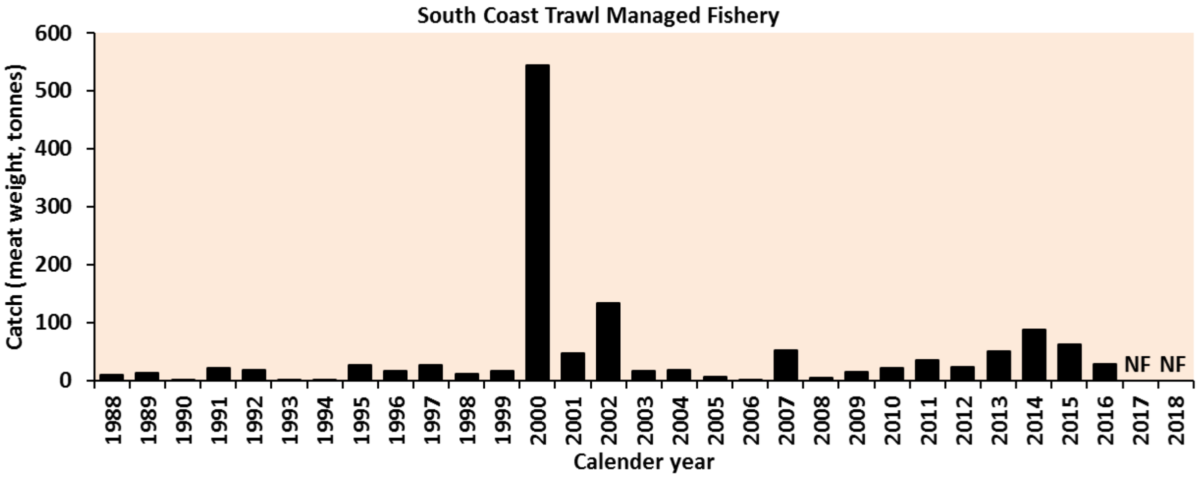

Figure 8. Catch (t, meat weight) history of *Y. balloti* from the South Coast Trawl Managed Fishery 1988-2018. No fishing occurred in 2017 and 2018.

2.2 Physical Oceanographic Processes

2.2.1 Leeuwin Current System

Physical oceanographic processes off the WA coastline are highly influenced by the Leeuwin Current (LC) system which is made up of three currents: the LC, the Leeuwin Undercurrent and shelf current systems consisting of the Ningaloo, Capes and Cresswell Currents (Woo et al. 2006) (Figure 9). The LC is a shallow and narrow (less than 300 m deep and 100 km wide) current which transports warm, low-nutrient water from the tropics southward along the shelf break and outer parts of the shelf (Church et al. 1989; Smith et al. 1991; Ridgway and Condie 2004). It is the longest boundary current in the world and extends from Exmouth to Cape Leeuwin and into the Great Australian Bight. The mean sea level at Fremantle (FSL) is commonly used as an indicator of the strength of the LC. This relationship exhibits a strong seasonality where the current flow is stronger (higher sea level and weaker winds) during the winter months (May – July) than it is during summer (October to March) when it flows against the maximum southerly winds (lower sea level) (Figure 10) (Pearce and Phillips 1988; Feng et al. 2003).

Inter-annual variability in the strength of the LC is however related to the El Niño-Southern Oscillation (ENSO) events in the Pacific Ocean (Feng & Meyers 2011). This phenomenon, derived from coupled processes in the ocean and atmosphere, occurs predominantly in the equatorial Pacific region although its influence can be observed over most of the globe. The term ENSO is used to describe the oscillation between the El Niño phase and the La Niña phase which tend to change between 3-8 years (BOM 2019a). A commonly accepted measure of the strength of ENSO is the Southern Oscillation Index (SOI), which is the normalised sea-level pressure difference between Darwin and Tahiti. The El Niño is the negative phase (sustained values < -8) of the ENSO and associated with cooler than average sea surface temperatures (SST) along the mid to south coast of WA. The La Niña is the positive phase (sustained values > +8) of the ENSO and associated with warmer than average water temperatures (Figure 11a). Generally during El Niño years, the LC is weaker and stronger during La Niña years (Figure 11b).

In the past, the major El Niño events (1982/83, 1987, early 1992 and 1997/98) have all been associated with lower sea levels (weaker LC) and cooler water, while during the strong La Niña periods (1988/89, 1998–2000, 2008/09 and 2010–2012), higher sea levels indicated that the LC was flowing strongly and higher than average water temperatures (Figure 12). There were

also occasions (such as 1994/95 and 1997) when the water was warmer despite lower sea levels and El Niño-like conditions, suggesting that other drivers such as air-sea heat flux (acting independently of the LC) also play an important role in influencing local ocean temperatures.

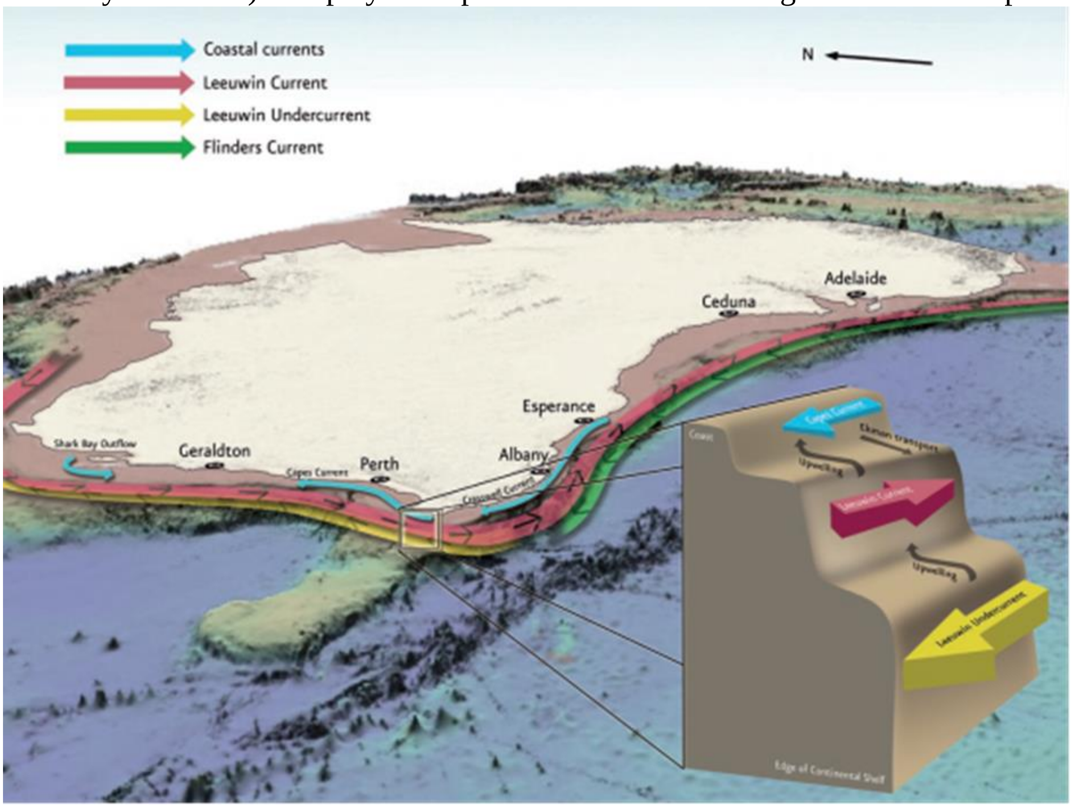

Figure 9. Schematic of major ocean currents flowing through the west and south coast regions of Western Australia. Insert: Local upwelling events by the major currents (Source: CoA 2008).

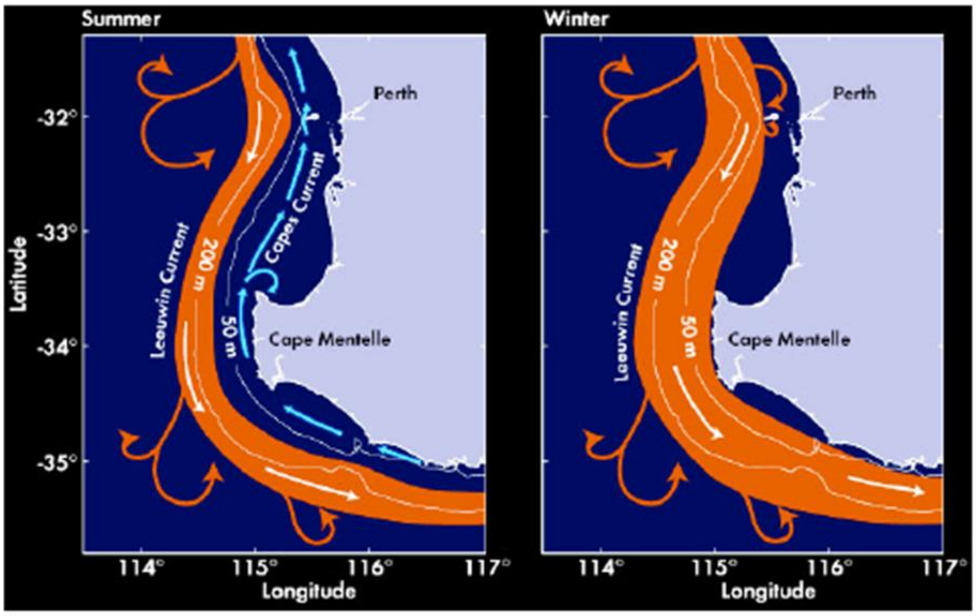

Figure 10. Schematic of the surface summer and winter current regime off south-western Australia (from Hanson et al. 2005).

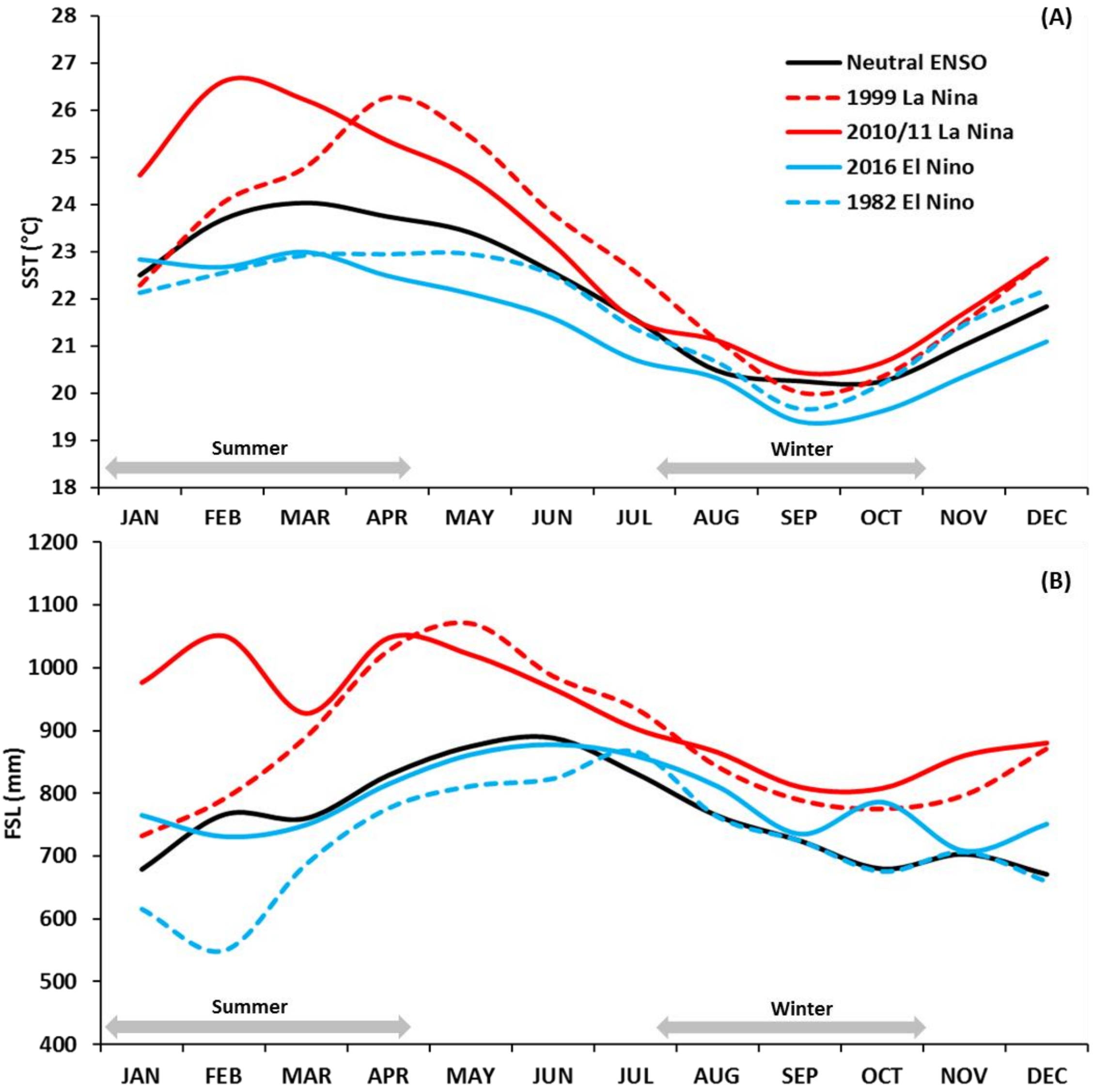

Figure 11. Examples of Monthly and Seasonal differences in the (A) SST and (B) FSL during neutral, El Niño and La Niňa phases of the ENSO cycles along the Western Australian coastline. The 1999 La Niňa is associated with the 1999 MHW and the 2010/11 La Niňa is associated with the 2011 MHW.

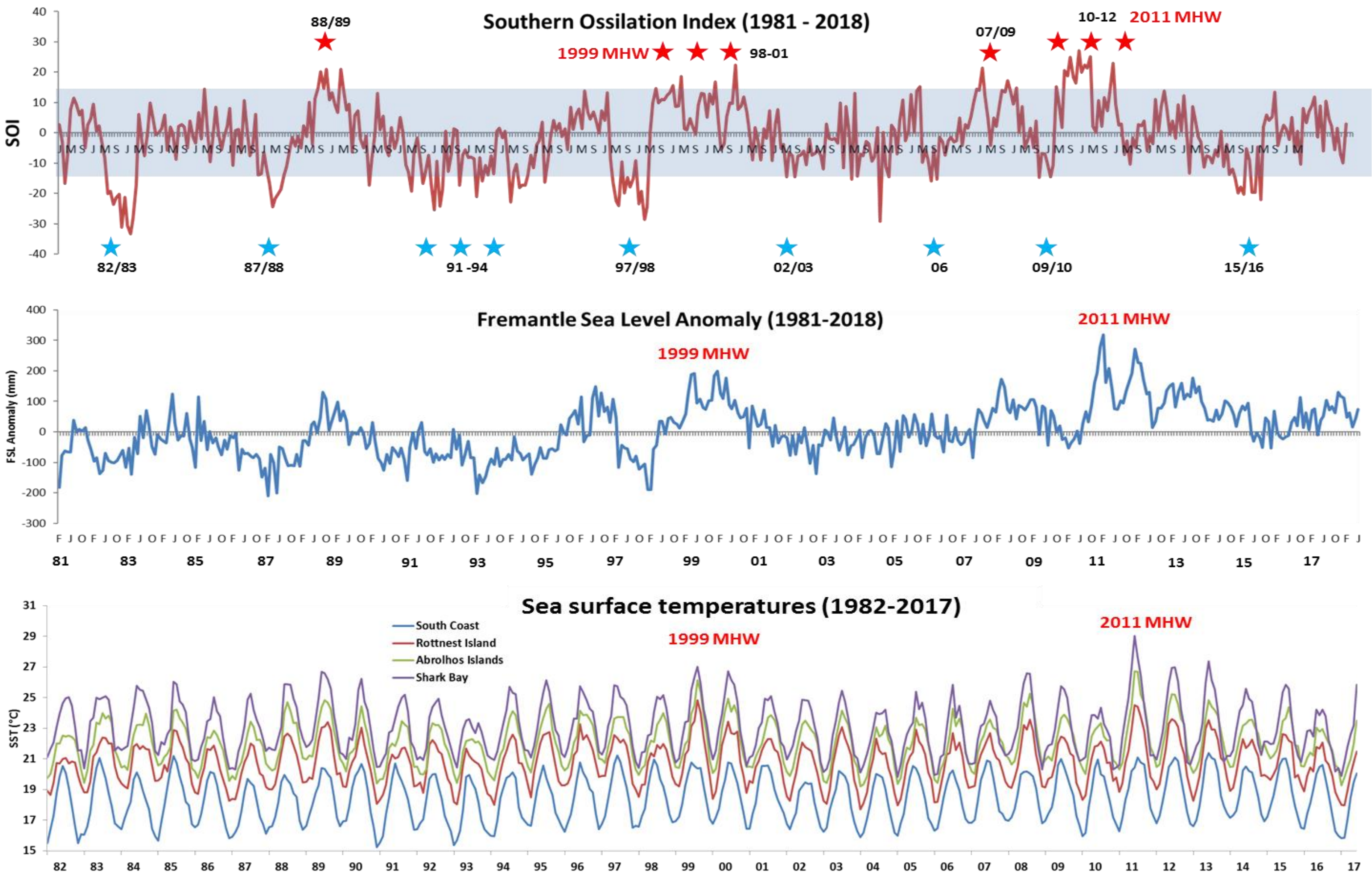

Figure 12. Monthly values of the Southern Oscillation Index (top), the Fremantle sea level (middle) and summer (January – March) sea surface temperatures (bottom) along the Western Australian coastline. La Niña events are indicated by green stars and El Niño events by blue stars. High values of the SOI indicate La Niña conditions and low values reflect El Niño conditions, while high sea levels indicate a strong Leeuwin Current. The record strength Leeuwin Current and record high temperatures in February/March 2011 constituted the unprecedented marine heat wave event.

2.2.2 Coastal Currents

Inshore from the southward flowing LC are two northward flowing cooler coastal currents, the Capes Current and the Cresswell Current. The wind forcing plays a crucial role in the annual cycle of these currents and is responsible for forcing coastal current systems on a variety of temporal and spatial scales such as coastal upwelling and vertical mixing of the water column. The Capes Current is a cooler inner shelf current, originating from the region between the Leeuwin and Naturaliste capes, which moves along the south-western Australian coast in summer towards the equator (Pearce and Pattiaratchi 1999). This current can extend as far north as the Abrolhos Islands and is characterised as being more saline (35.37–35.53 ppt) and cooler (21.0 – 21.4°C) than the LC. The Capes Current is intermittent and seasonal which appears to be well established around November when winds in the region become predominantly southerly due to the strong sea breezes (Pattiaratchi et al. 1997) and continues until about March when the sea breezes weaken. The source water of the Capes Current arises from upwelling between Leeuwin and Naturaliste capes and is augmented by water from the south, to the east of Cape Leeuwin (Gersbach 1999).

Similar to the Capes Current, the Cresswell Current is another wind driven coastal current which moves westward with the south-easterly wind along the south coast of WA in summer (Cresswell & Domingues 2009). The dynamics of coastal circulation in the southern region are largely unknown but similar to the Capes Current, this causes upwelling of cold deep water in this region.

Interactions of the LC with seafloor features also leads to the formation of meso-scale eddies and meanders, which occur in predictable locations, such as the western edge of the Abrolhos Islands, south-west of Jurien Bay, the Perth Canyon, south-west of Cape Naturaliste and Cape Leeuwin, and south of Albany and Esperance (Pearce and Griffiths 1991; Feng & Morrow 2003; Feng et al. 2005; Fieux et al. 2005). In the Shark Bay region, the strength of the LC changes as the current speed weakens in the wider shelf off Shark Bay but the current accelerates as the continental shelf narrows and continental slope becomes steeper to the south (Woo et al. 2006). As the LC accelerates towards the western edge of the Abrolhos Island chain, the instabilities generated in the LC, together with interaction with the Leeuwin Undercurrent results in the generation of eddies in this region. Further south, the Perth Canyon (major topographic feature) also traps eddies in the canyon offshore from Rottnest Island. And finally at Cape Leeuwin, the dramatic change in directional flow from south to east generates eddies in this region. Along the south coast, the changes in bathymetry and the location of islands in this region also result in generation of eddies. These eddies also show strong seasonality where they tend to be less energetic during the austral spring/summer and high eddy kinetic energy observed during the winter months. There are also stronger eddies during La Niña years and weaker eddy energies during El Niño years. Eddy-induced upwelling, vertical mixing, horizontal stirring and cross-shelf exchange could all affect the ocean production and larval dispersal. Many of these regions are also in the proximity of where Ballot’s saucer scallops are distributed.

The annual and seasonal variability in the transport and circulation of all these currents and eddy formations along the WA coastline is considered to be the major influence on biological communities and especially the existence of tropical species being found as far south as Rottnest Island. These currents play a significant role in the larval dispersal of many marine species including Ballot’s saucer scallops. All four major scallop stocks along the WA coast are influenced by a combination of these oceanographic processes, and in Shark Bay, there are

additional unique factors such as strong tidal driven salinity outflows that also influence larval flushing (Hetzel et al. 2015; Kangas et al. 2012).

2.3 Marine Heatwaves (MHWs)

The 2010-12 La Niña event is considered one of the strongest on record (BOM 2019a) and consisted of two peaks over successive summers. During the first peak over the summer of 2010/11 (November to March), the nearshore water temperatures along the Gascoyne and mid-west coast of Western Australia were 2-3°C higher than mean historical levels and within Shark Bay the temperatures even exceeded 5°C above average for brief periods (Pearce et al. 2011; Pearce and Feng 2013). This occurred due to an alignment of inter-seasonal to inter-decadal processes, which resulted in an earlier surge of the LC during the austral summer which was associated with high temperatures which intensified by an anomalously high heat flux from the atmosphere entering the ocean (Feng et al. 2013; Pearce and Feng 2013) (Figure 11a; Figure 13c). The intensity and duration (66 days) of this event has recently been classified as a Category 4 (Extreme) and termed the "Western Australia 2011 MHW" (Hobday et al. 2018).
The immediate and short-term effects on the marine biota were devastating, with massive mortality of fish and invertebrate species in some areas, range extension of some tropical species with sightings well south of their normal ranges, coral bleaching events, phytoplankton blooms and significant loss of seagrass habitats in some regions (Pearce et al. 2011). The impact of the heatwave was most significant on the scallop stocks in Shark Bay and Abrolhos Island regions where the stock abundance reached record low levels by the end of 2011 leading to the closure of fisheries for the following 3-5 years (Caputi et al. 2016).

Hobday et al. (2018)'s MHW categorisation scheme now recognises the strong La Niña event between 1998 and 2001 being responsible for the "Western Australia 1999 MHW" Category 3 (Severe). This MHW lasted 132 days and peaked during the winter of 1999 between April and August, causing winter water temperatures to be 2-3°C higher than average (Figure 11a; Figure 13d). The impact of this event was far less devastating compared to the 2011 MHW and had been historically considered as a strong La Niña for the associated fisheries and biota in WA.

2.4 Scallop recruitment variability

The biggest challenge to managing scallop fisheries around the world has been the ability to understand recruitment dynamics. Scallop stocks are known to exhibit "boom and bust" trends in catch landings, a characteristic of high recruitment variability driven by inter-annual variability in environment drivers. Climate change is leading to greater frequency of extreme events (Frölicher and Laufkötter 2018), shifting seasonal patterns and introducing greater instability to ocean systems and processes. Environmental variability is now our 'new normal' creating greater uncertainty in our ability to assess, forecast and manage stocks.

Scallop catch landings across all four fisheries in WA are characterised by large spatial and temporal catch variation (Mueller et al. 2012). Scallop recruitment dynamics in WA is hypothesised to be driven by environmental factors (Heald and Caputi 1981, Joll 1994, Joll and Caputi 1995a, Lenanton et al. 1991, 2010) which is typical of scallop fisheries around the world and invertebrate fisheries in general (Caputi et al. 1998, 2014). Significant knowledge gaps in regard to scallop recruitment includes the timing and cues of spawning events and whether these are changing with changes in environmental conditions, the influence of tides and lunar phase and local-scale short-lived oceanographic processes. All five stocks have shown a range of responses to the 2011 MHW from increased catch on the SC to the closure of the fishery in Shark Bay and Abrolhos Is. This suggests there is a likely strong biophysical coupling that is driving recruitment variability of Ballot's saucer scallop stocks in Western Australia.

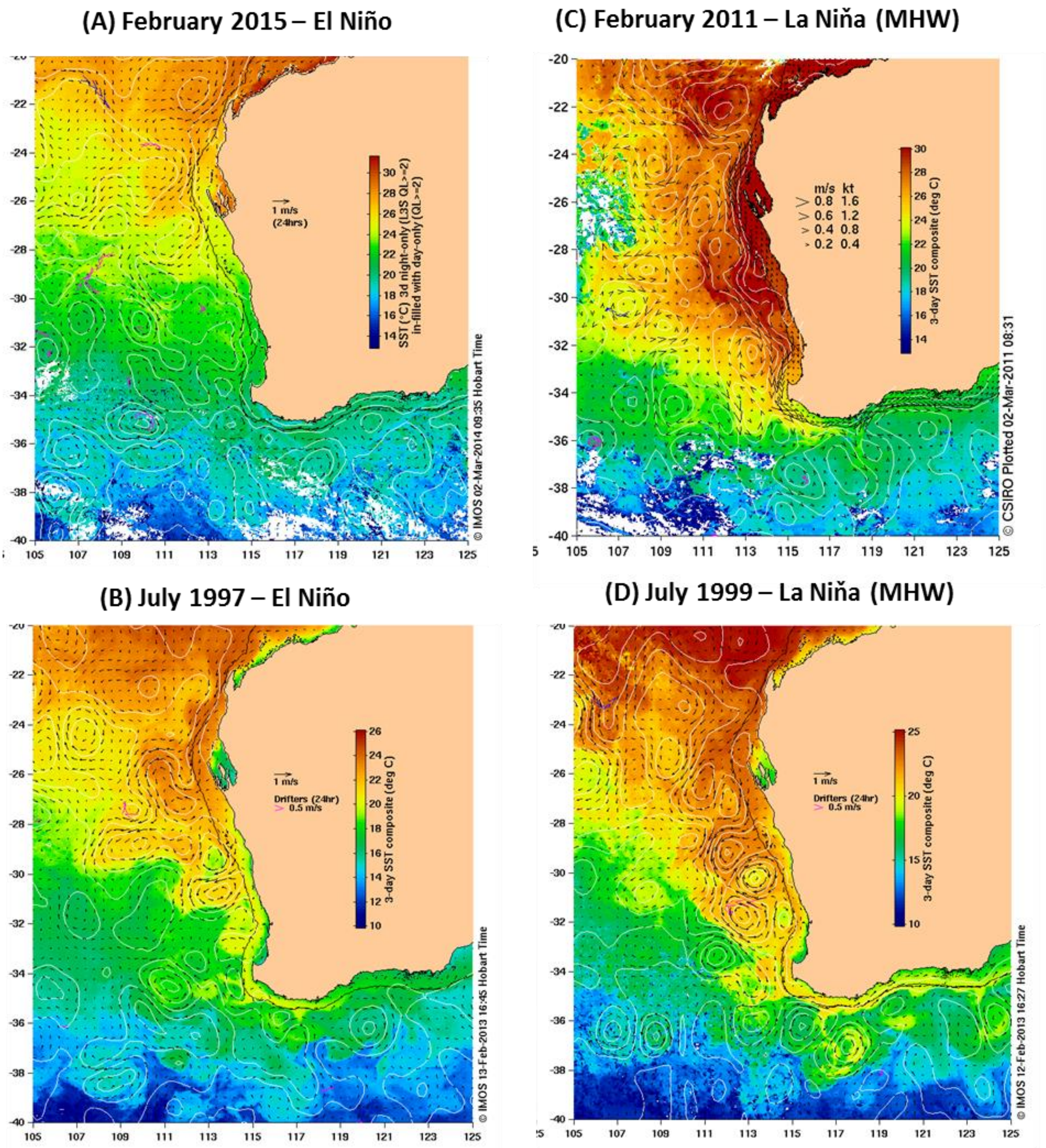

Figure 13. SST maps showing examples of oceans conditions during of El Niño (A, B) and La Niña events (C, D) along the mid to south coast of WA.

The 2011 MHW and the warmer than average summers in the following 2 -3 years is believed to have contributed to the poor stock abundance. The abundance of scallop stocks in the Abrolhos Islands were well below historical levels of that fishery. In northern Shark Bay, the scallop abundance was also well below historical levels with only Denham Sound, a separate stock with little connectivity with northern grounds, having previously experienced low levels of recruitment. After the MHW, there was been a moderate level of recovery in Denham Sound by 2014 but this has not been observed in northern Shark Bay. In particular, in northern Shark Bay the apparent lack of survival of juvenile recruits (0+) to adults (1+) is a major concern with

respect to spawning stock levels. The recent events and continuing concerns require a re-examination of stock-recruitment-environment relationships for the WA scallop stocks.

2.5 Assisted stock recovery

Stock enhancement or 'assisted recruitment' in Australia is still primarily in a R&D phase (Hart 2015). Most investigations focus on increasing production or smoothing highly variable recruitment. For Ballot's saucer scallops, enhancement trials have been conducted in Queensland (Dredge et al. 2002, O'Brien et al. 2005, Lucas et al. 2008) and WA (Cropp 1993, Scoones and McGowan 2006) with limited long-term success due to logistical and biological challenges as well as the inability to differentiate enhanced stock from natural populations and these projects have been discontinued. The objective in this project however was to assess the feasibility of stock recovery following a major decline in breeding stock and subsequent recruitment, not for an enhancement of an existing fishery.

Scallops are broadcast spawners and to maximise successful fertilisation, scallops need to have close proximity and exhibit synchronised spawning. When scallop abundances fall to very low levels, the likelihood of fertilisation success may be limited. Therefore, increasing scallop abundance through translocation of sub-adult individuals to historically known scallop settlement grounds may assist recovery.

3. Objectives

1. Understanding factors influencing recruitment variations in existing scallop WA stocks, particularly the collapse of the stocks in 2011.
2. Determine the feasibility of re-establishing founder population of scallops in the Abrolhos Islands and Shark Bay through seeding of hatchery produced juveniles
3. Determining feasibility of re-establishing founder population of scallops in the Abrolhos Islands through translocations.

Initially, funding was approved by the FRDC for Phase 1a of the project, to assist with addressing Objective 1. Phase 1a of the project was primarily a desktop study on the environmental factors that influence scallop recruitment and understanding spawning cycles in the different regions. The second component involved opportunistic field sampling for scallops and fishers providing samples of small scallops from each of the four scallop fisheries.

Phase 1a served as a stop-go point for consideration of the provision of additional FRDC funding for Phase 1b), with any further funding for Objectives 2 and/or 3 to be sourced through a new application to the FRDC. A new application to FRDC was not submitted, however components of Objectives 2 and 3 were investigated and included in this report.

A pilot study (funded by DPIRD and the scallop Industry) commenced prior to the FRDC funding and occurred in parallel to this project and primarily examined feasibility of producing robust juveniles in the hatchery facility of DPIRD. This included examining conditioning of mature scallops under various feeding regimes. The pilot study had ongoing challenges in obtaining a sufficient number of brood stock following the high mortalities observed during the heatwave, high transport mortality of brood stock and high mortality of larvae (DPIRD, unpublished). Therefore, Objective 2 was not pursued but the information gained during this pilot project contributed to the direction of this study.

Translocation (Objective 3) of sub-adults from one region to another was not possible during the pilot phase due to the very low scallop stock abundance in most regions at the time.

Subsequent natural recovery of stocks was observed in the southern part of the AI whilst there was poor recovery in the mid and northern parts of the AI. It was considered that the environmental conditions had become conducive to the survival of recruiting scallops but the low level of breeding stock may have been the key factor preventing significant recovery of the stock in the other parts of the islands. Therefore, there was scope to continue at least Phase 1b) in part, through a small-scale experiment to test translocation and assess capture, handling, transport and deployment techniques in the AI.

4. Methods

4.1 Scallop ring counts

The Joll (1988) tag recapture study of juvenile *Y. balloti* from Shark Bay suggested that the number of pigmented rings visible in the growth increment was closely related to the number of days at liberty and thus provided evidence that these rings are laid down on a daily basis. This technique provides a direct aging tool which was employed in the current study to determine the spawning or settlement date of scallops from Shark Bay (NSB and DS), AI, RI and the SC regions.

Juvenile scallops ranging from 20-70 mm SH were collected from the five scallop stock regions during fishery independent surveys and/or were provided by commercial fishers between 2010 and 2017 (See Appendix 4 for details). During collection at sea, the ventral valve (top shell) of scallops was carefully removed and pat dried for later examination in the laboratory. Individual scallops were measured to the nearest millimetre before the number of rings were counted.

There were notable differences in the pigmentation of the growth rings between the four key regions. Scallops from the SC and RI generally were darker overall due to a greater intensity of the ring pigmentation than those from the AI and SB regions which generally had paler ring pigmentation. The clarity of the ring formation decreased in scallops approaching 65 mm SH for most regions as the distance between the rings became highly compacted towards the outer edge. However, scallops from the SC were generally readable until 75 mm SH. Only those scallops with accurate estimates of ring counts were included in the analyses. Joll (1988) commented that the close-packing of the rings occur when scallops mature and enter their reproductive period.

A line was drawn from the umbo (hinge region of the valve where rings originate from) to the outer shell edge (Figure 14a,d) to aid in the counting process and to avoid miscounting. In some shells, the shell region closest to the umbo (where the initial rings were laid down) was too pale or overly pigmented to be read accurately under a dissecting microscope (Figure 14b). In these instances, a daily growth rate based on scallops that could be read to the very beginning (time of settlement) is used to estimate the number of rings within the umbo region that was unreadable. The final ring count measurement was adjusted by adding 14 days to account for the average larval phase (Rose et al. 1988) and was back-calculated from the date of collection to determine the approximate spawning date and the corresponding month. Validation of ring counts were undertaken on a subsample of scallops from each region using different researchers and counts were found to be within 5-10 ring counts.

4.2 Gonad condition

Ballot's saucer scallop sexes are separate. The present study examined temporal variation in gonad development across the different commercial stocks in WA to help validate the spawning

cycles in these regions. A number of previous studies have used numerical indices derived from the external appearance of the gonad of male and female scallops, including a six stage scale used by Dredge (1981) for *Y. balloti* from Queensland. Similar to Dredge (1981), an arbitrary scale of gonad development (in freshly shucked scallops) was used to classify different stages of gonad development of male and female *Y. balloti* in WA. Scallops were differentiated into stages of immature (undifferentiated) gonads, developing (after differentiation of the sexes), mature, pre-spawning and spent (post-spawned) (Figure 15). Scallops are known to undergo partial spawning events where sperm and eggs are released gradually over a period of months (Joll & Caputi 1995b). This was evident where the gonads appeared granulated but flaccid and smaller than pre-spawned scallops. This created an issue when three stages of spent scallops were observed; i) partially spent, ii) fully spent but sexes discernible and iii) fully spent where there were no residual gonads visible. These observations made it difficult to differentiate between immature and fully spent scallops. Thus, the immature classification was combined with fully spent scallops. Validation of these stages using microscopic histological examinations may be necessary in the future to provide greater certainty in the observations of gonad development. In Shark Bay, scallops were sampled from DS and NSB during February, April, June and November 2016 and in February and June 2017. Size of scallops ranged between 84 to 120 mm SH. In the AI, sufficient numbers of scallops were collected during December 2016 and February 2017 as there were insufficient scallops available until November 2016, post heatwave.

Scallops assessed for their gonad condition were also used for maturity analyses for NSB, DS and AI. Individual scallops of both sexes were classified as being mature or immature based on the five gonad stages, however, the difficulty in separating the immature scallops from fully spent scallops presented a challenge. Therefore, one set of analyses were done on the data where all immature/ fully spent scallops were considered immature while all other stages were considered mature. Given the high likelihood of scallops greater than 70 mm being fully spent rather than immature, a separate set of analyses were undertaken where scallops greater than 70 mm SH in the immature fully/spent category were changed to a mature status.

Logistic regression was used to determine the shell height (SH) at which 50% (SH_{50}) and 95% (SH_{95}) of scallops were mature. The logistic equation used to relate the probability, P, of individuals being mature given its SH was

$$P = 1/(1+\exp\{-\ln[(19)(SH-SH_{50})/(SH_{95}-SH_{50})]\}$$

On the basis of its SH, the likelihood of the jth scallop being mature or immature was calculated as Pj or $1 - Pj$, respectively. Setting $Xj = 0$ if the jth scallop was immature and $Xj = 1$ if the scallop was mature, the overall log-likelihood, λ , was calculated as

$$\lambda = \sum_j \{X_j \ln P_j + (1- X_j) \ln (1- P_j)\}$$

The logistic equation was fitted by maximizing this log-likelihood and the data were randomly resampled and analysed to create 500 sets of bootstrap estimates of the parameters of the logistic equation.

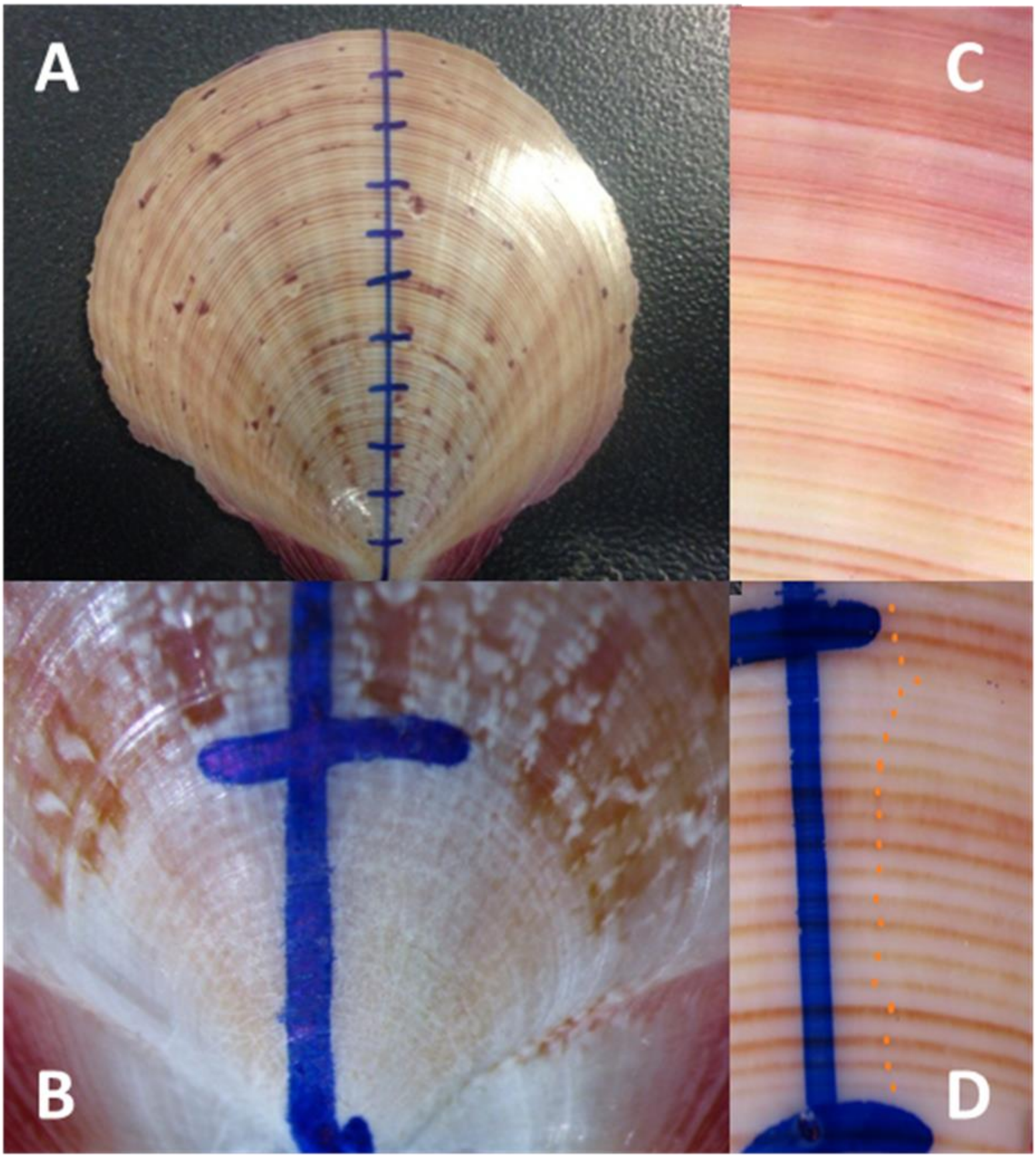

Figure 14. (A) Ventral value of a scallop marked (5 mm intervals) for ring counting (B) The umbo region of a scallop shell marked to be counted (C) Growth rings on a scallop from Rottnest Island showing compacted rings closer to the shell edge (D) Abrolhos Islands. Example of ring counts (20 rings) in a 5mm interval.

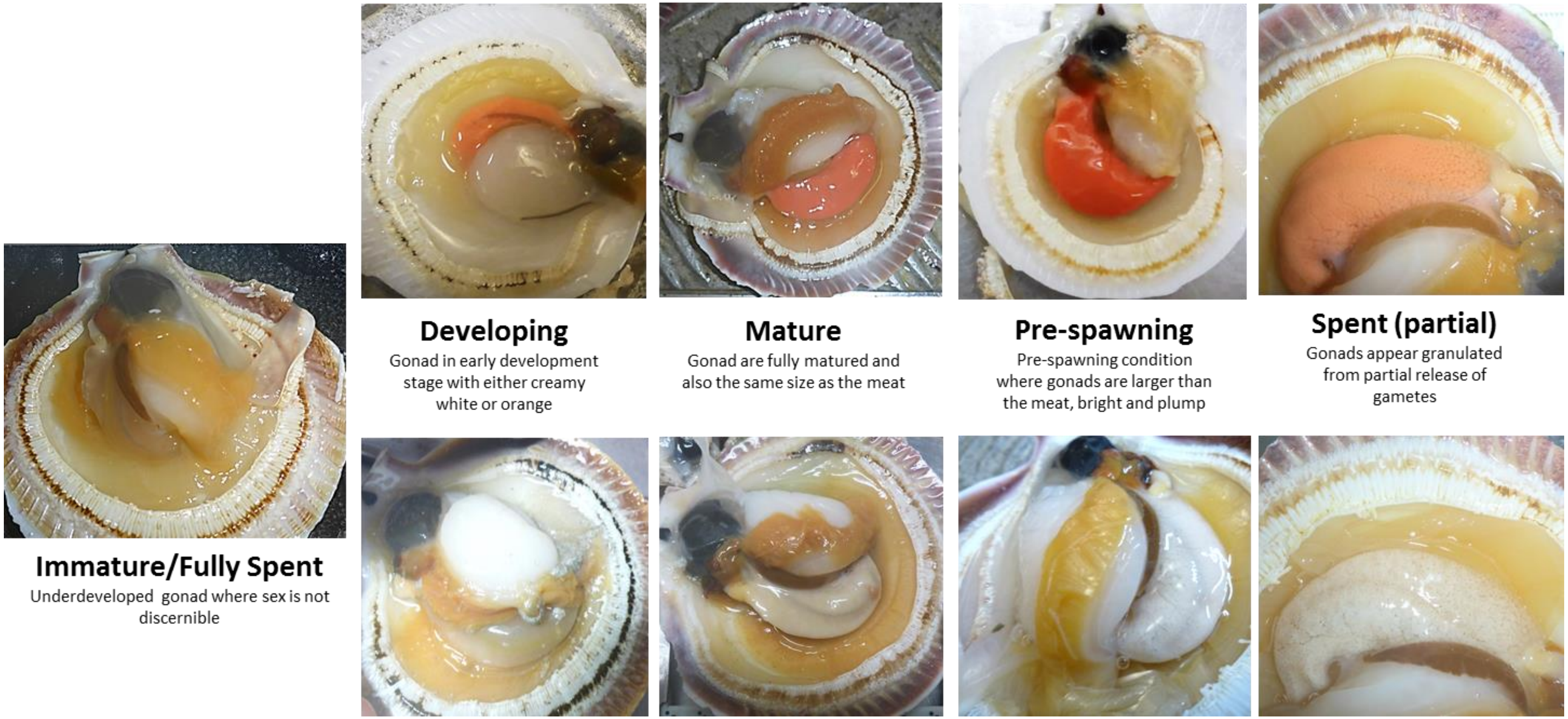

Figure 15. Gonad stage index used to categorise the development of male (bottom row) and female (top row) *Y. balloti* in this study.

4.3 Satellite and meteorological data

NOAA High Resolution SST (1/4 degree daily sea surface temperature) data was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at https://www.esrl.noaa.gov/psd/. Locations used to calculate mean monthly SSTs for each of the four regions are shown on Figures 1, 3, 4 and 7. Fremantle Sea Level (FSL) measurements were used as a proxy for the strength of the LC. Monthly mean sea level data was obtained from the Bureau of Meteorology (BOM) website, http://www.bom.gov.au/ntc/IDO70000/IDO70000_62230_SLD.shtml. The SOI is calculated from the monthly air pressure difference between Tahiti and Darwin and is an indicator of El Niño events. The mean monthly data was obtained from the BOM website; http://www.bom.gov.au/climate/current/soi2.shtml.

Seasonal and regional wind regimes may drive variations in coastal current systems and potentially influence the passive movement patterns and distances of scallop larvae during the spawning period and in turn influence settlement success. Thus wind strength and direction was examined in this study. Wind data was obtained from the BOM from four stations that were considered most representative of the four scallop regions; Esperance (009789) on the South Coast (1969 – 2017), Rottnest Island (009193) (1987 – 2017), North Island (008290) in the Abrolhos Is. (1990 – 2017), Carnarvon Airport (006011) in Shark Bay (1945 – 2017). Average wind speed (km/hr) was calculated based on 9am and 3pm daily observations. Monthly average of the Northward and Eastward wind components were also calculated, based on 9am and 3pm daily observations. In meteorological convention, winds are described by the direction "from" which they blow while currents are described as the direction "towards" which they are flowing, thus southerly winds generate northward currents. Average monthly values were derived for each of the available time series for each of the four regions.

We hypothesised that environmental conditions during spawning/settlement and early juvenile phases were likely to be of critical importance for successful scallop recruitment in all five scallop stocks. Relationships between individual environmental parameters (LC, SST, wind speed and direction) and scallop catch and catch rates were investigated for each of the stocks using the Pearson Product-Moment Correlation (r). Lags up to 24 months were examined to encompass conditions prior and during the spawning period and also during the post settlement/ juvenile phase of scallop development. After preliminary data inspection, step-wise multiple regression analysis was undertaken of months or periods that were identified as being significant ($p < 0.05$). For the AI, DS and NSB stocks, further analysis was undertaken to determine possible stock–recruitment-environment relationships where indices of direct or proxy spawning stock levels were incorporated in the correlation analyses. All analyses were done using R (version 3.0.2; R Development Core Team 2013).

4.4 Fishery-independent surveys (FIS)

Annual fishery-independent scallop surveys are undertaken in Shark Bay and at the Abrolhos Islands regions during November/December. Surveys were conducted on the Research Vessel (RV) Flinders until 2000, then on the RV Naturaliste from 2001 onwards in Shark Bay and using commercial trawlers in the AI until 2010 after which the RV Naturaliste has been used. Twin six-fathom head rope length flat nets with 50 mm mesh in the panels and 45 mm in the cod-end were used on all surveys. A number of standardised sites covering known scallop distribution are surveyed at night, commencing approximately at dusk and the duration of each trawl shot is 20 minutes. The trawl period begins when the trawl gear starts to fish i.e. winches cease paying out until the commencement of retrieving the trawl gear.

Processing of catch from each shot involves recording of the total number of recruit (scallops < 86 mm SH, 0+ year class) and residual (scallops ≥ 86mm SH, 1+ year class) scallops from the port and starboard codends by visual assessment. A subsample (approximately 200 scallops) of randomly selected scallops from one side or both sides are then measured (using Vernier calipers) to obtain shell height (SH) frequency distribution information and the proportion of recruits and residual scallops from each shot. Therefore, from each trawl site a total catch per unit effort (CPUE), recruit CPUE and residual CPUE are calculated. As these are standardised surveys with a consistent gear configuration, nominal (non-standardised) catch rates were used for all data analyses. For the AI, DS and NSB stocks, indices of recruits (scallops < 86 mm SH) and residual (scallops > 86 mm SH) adult scallop abundance are used to determine a catch prediction range for the following fishing season (Joll and Caputi 1995a, Caputi et al. 2014).

4.5 Translocation of scallops in the Abrolhos Islands

4.5.1 Pre-translocation stock survey

The December 2016 survey of Abrolhos Islands resulted in the highest scallop abundance and overall survey catch rate (988 scallops/nm) since the stock decline in 2012 (0.3 scallops/nm). Majority of the abundance was highly localised in the Hummocks region (25,626 individuals of the 29,469 sampled in total), while all other regions had a much lower abundance. The abundance was also dominated (88%) by adult (1+) scallops (> 83 mm SH).

The March 2017 survey indicated increased catch rates compared to December 2016 with a total of 41,627 scallops sampled and a catch rate of 1476 scallops/nm. There were widespread juvenile recruits (< 83 mm SH) observed at almost all sites and island groups although the highest abundances were at the Hummocks region. Scallops therefore could be sourced for the pilot translocation experiment from this area with the Easter Group region the release location due to persistent low scallop abundance in this region (Figure 16).

As the target size range of scallops for the experiment was 50-70 mm SH (i.e. less than size of maturity), the overall low abundance of these sized scallops only permitted one translocation trial. Furthermore, since only one survey site in the Easter Group was able to be properly sampled (due to excessive algae clogging nets in other areas), the experiment could not test releases at differing densities. Therefore, only one control site (close to Hummocks) and one translocation site was used (Table 1). Translocated (and control) scallops ranged in size from 50 - 80 mm SH.

Scallops for the "Control" experiment were collected at Site 5 in the Hummocks region (Figure 16) and these scallops were held in a recirculating water tank, measured and tagged (with individually identifiable glue-on shellfish tags (Hallprint, FPN tags) attached with cyanoacrylate adhesive) and released by tipping baskets of tagged scallops directly overboard at the release site without extensive holding and transport durations. The translocated scallops were caught at the adjacent, Site 6 in the Southern Group (Figure 16), held in a recirculating seawater tank, measured and tagged whilst the boat travelled slowly to the release site and all scallops were released at the Easter Group after approximately 3.5 hours. No mortality of tagged scallops were observed for either treatment.

4.5.2 Post-translocation survey

A post translocation survey of the release sites was undertaken during the November 2017 survey. To account for any small scale scallop movement at or since the time of release, the

control and translocated sites were trawled 5 - 6 times (20 minutes each), to maximise the recapture rate of tagged scallops over a wider area of distribution.

Commercial fishing resumed in May 2017 due to moderate stock recovery, confirmed by increased scallop abundance in the December 2016 and March 2017 surveys. This presented an opportunity for further recaptures of tagged scallops, thus, commercial fishers were provided with location of the release sites. The ventral valve of any recaptured tagged scallops were returned to the Department for recording of size and ring count information.

Table 1. Experimental design for pilot translocation in the Abrolhos Islands during March 2017.

Hummocks	**Easter Group**
Control Site	**Release site**
• 1000 tagged scallops (orange coloured tags) • 50 -70 mm size range • Tags 001-999	• 1500 scallops (purple and tan coloured tags) • 50 – 80mm size range • Tags W000-W999 • Tags X000-W500

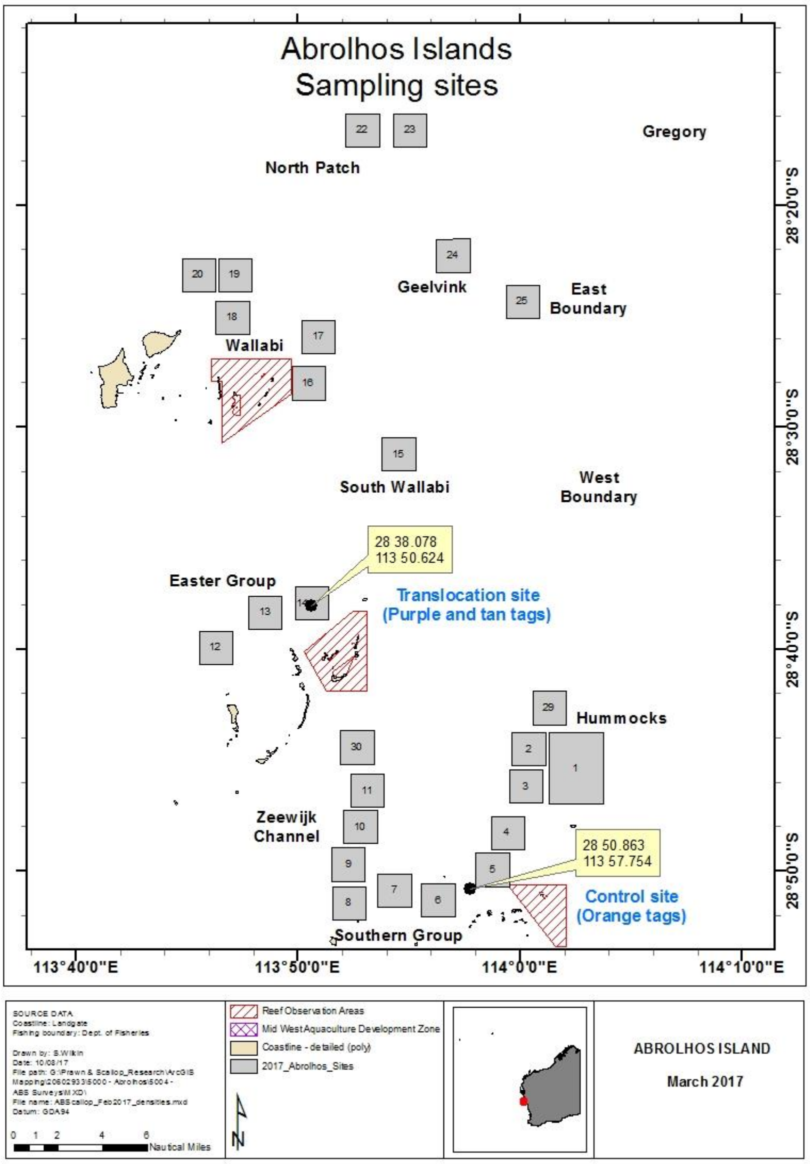

Figure 16. Standardised scallop trawl survey sites at the Abrolhos Islands during March 2017 and the release sites of the translocated scallops in the Easter Group (Site 14) and the control site (corner of site 5). The scallops for the control and translocation releases were collected in sites 5 and 6, respectively.

5. Results

5.1 Spawning periods (ring counts)

On the SC, spawning months identified from ring counts were November to February with peak spawning during December. Similarly, at RI, spawning was slightly extended from October to March with peak spawning during November/December (Figure 17). Further north, spawning was estimated for all months of the year in AI and SB. At AI, the peak spawning month was October with June recording the lowest level of spawning and some spawning activity observed during other months. In DS, spawning activity was estimated to occur between February and October with an early peak during March and a late higher peak during July/August. In NSB, increased spawning activity was estimated to occur between May and

December, with a peak during June (Figure 17). In summary *Y. balloti* spawning was restricted to the summer months along the cooler south and south west coast locations and becomes more protracted with increasing warmer latitudes and peaks towards the cooler winter months.

5.2 Gonad development

The differentiation of gonad stages was generally visually possible except for the scallops that were fully spent (scallops enter a quiescent period before redevelopment) where the gonad was so reduced that it was difficult to separate them from immature scallops with an absence of gonad development. However, partially spent scallops (where some of the gametes are released) were discernible.

In NSB, scallops were generally either mature or in pre-spawning stage from April to June. During November and February, scallops had transitioned to exhibit a mixture of all gonad stages suggesting that spawning began around June and continued into the summer months. The resulting recruitment from this spawning period is evident in the proportion of immature scallops increasing from 40% during November to 70 % by February (Figure 18). Detection of spent scallops during November and February further confirms the end of the peak spawning period by November/December. The seasonal trend in gonadal development is similar to scallops from DS although slight variations in the proportions were observed. For example, there were a high proportion of developing and mature gonads in February which reflects the early spawning peak observed in DS compared to NSB. With only two sampling periods available from the Abrolhos Islands, the seasonal trend was less pronounced, nonetheless the highest proportion of scallops were estimated to be spawning in October, majority in pre-spawning stage during November and by February 40% of scallops were immature, 15 % spent and 20% mature. This confirms a spring/summer spawning period with new recruits resulting from this spawning detected as early as February, 3-4 months later.

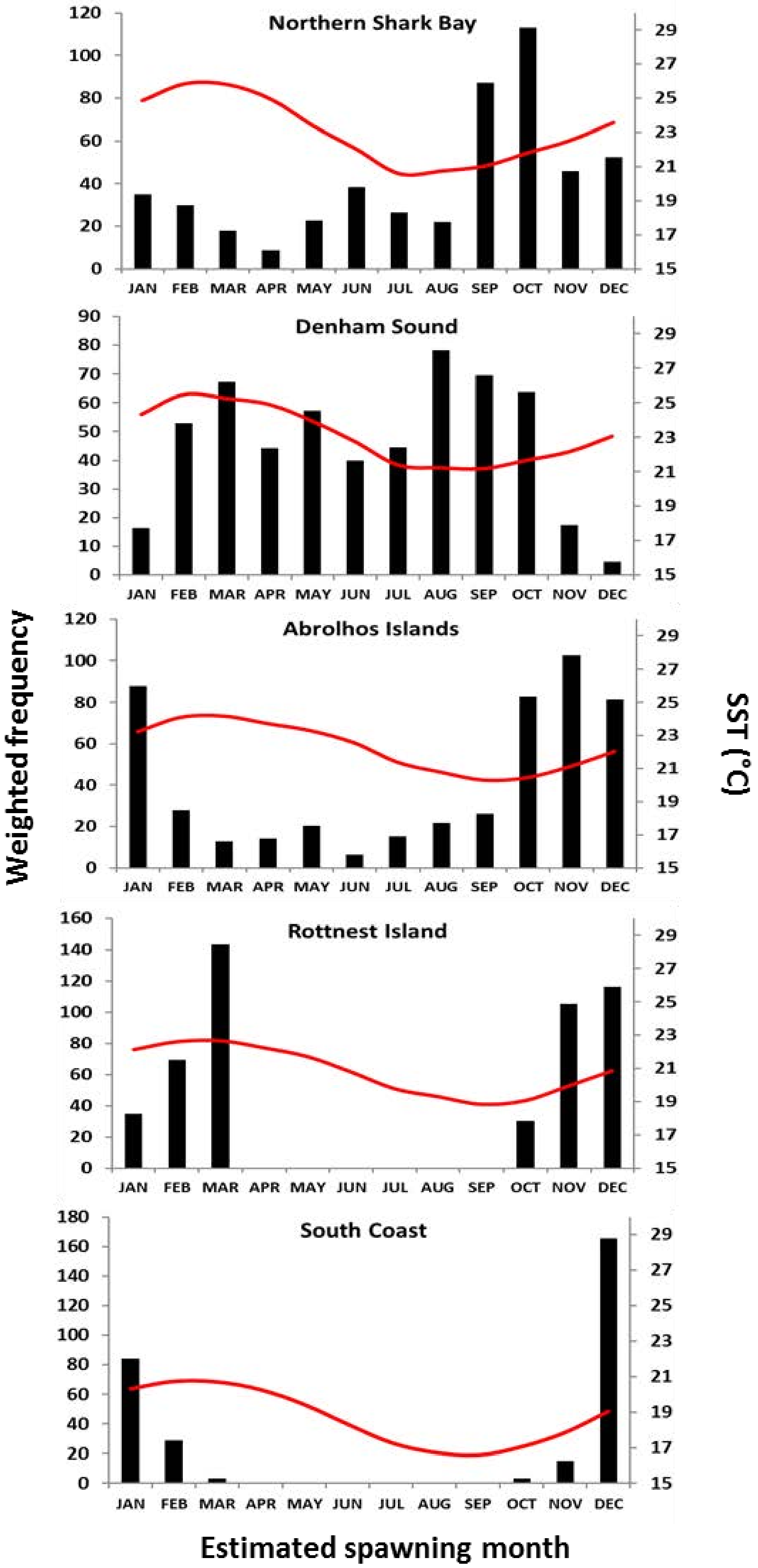

Figure 17. Estimated spawning month frequency in Shark Bay North (n = 358), Denham Sound (n =248), Abrolhos Islands (n =165), Rottnest Island (n=67) and the South Coast (n =135) collected between 2010 and 2017. The mean monthly SST between 2010 and 2017 is overlayed (red line) for each region.

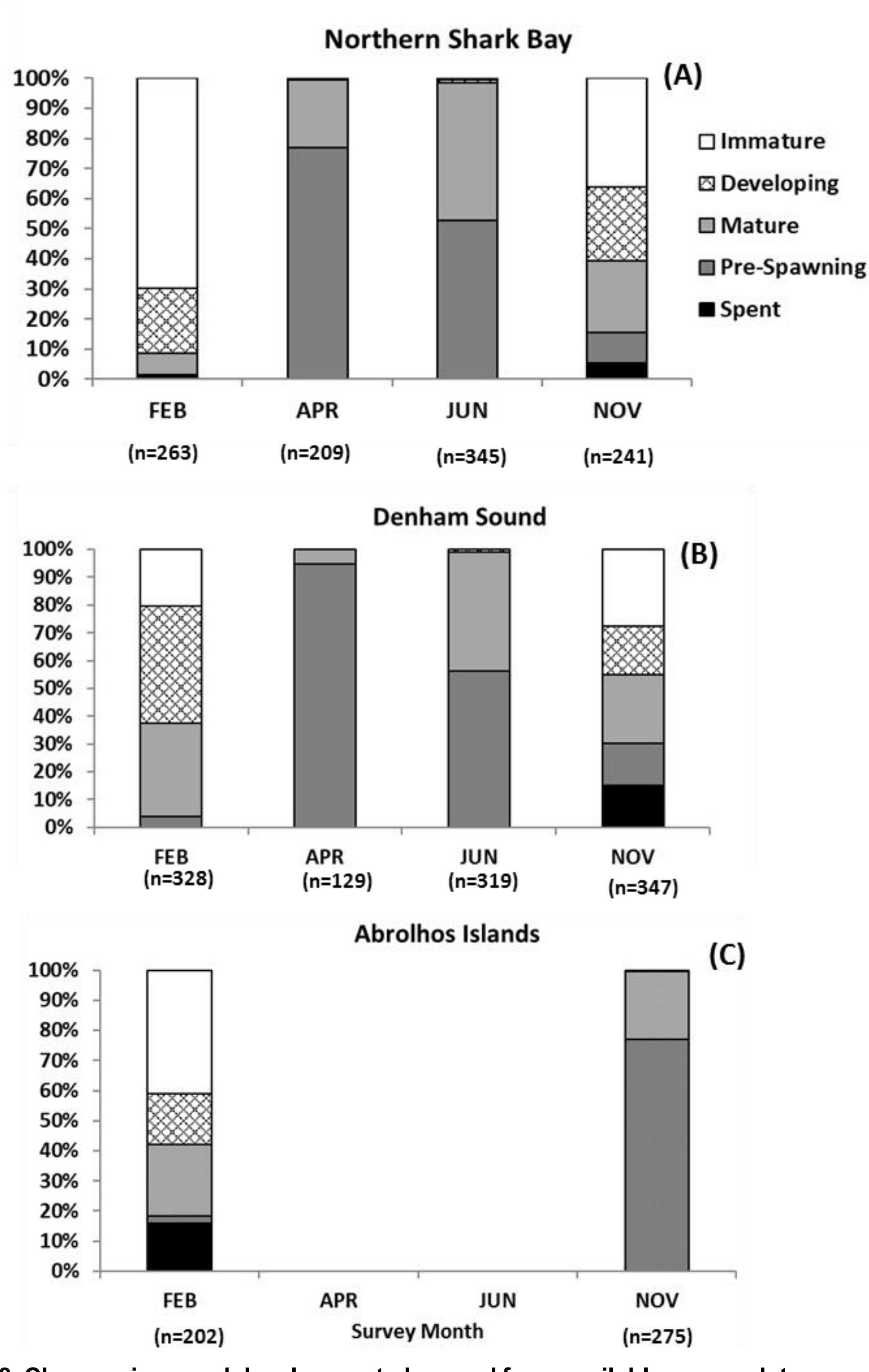

Figure 18. Changes in gonad development observed from available survey data sampled in 2016 and 2017 in (A) Northern Shark Bay (B) Denham Sound and the (C) Abrolhos Islands.

5.3 Size of Maturity (SOM) estimates

The relationship between gonad development and size of scallops was explored to determine if size at onset of sexual maturity estimates were possible for *Y. balloti*. Using the combined data from both sexes, the SH distributions of various gonad stages were similar between NSB and DS where majority of the developing and mature stages were recorded in scallops in the

70-80 mm SH size range (Figure 19). However, in the AI, majority of mature scallops were recorded from a size range of 55-60 mm SH. The smallest scallop of pre-spawning condition in the AI was 51 mm SH, while the smallest in NSB and DS were 74 and 81 mm SH respectively.

Mean estimates of L_{50} for Shark Bay scallops differed by 6.7 mm between the original (69.3 mm SH) and modified (62.6 mm SH) data sets (Figure 20b,d). Similarly mean estimates of L_{50} for AI scallops differed by 7.6 mm between the original (46.3 mm SH) and modified data (53.9 mm SH) sets (Figure 20a,c). Both data sets indicated scallops in the AI matured at a smaller size to scallops from Shark Bay.

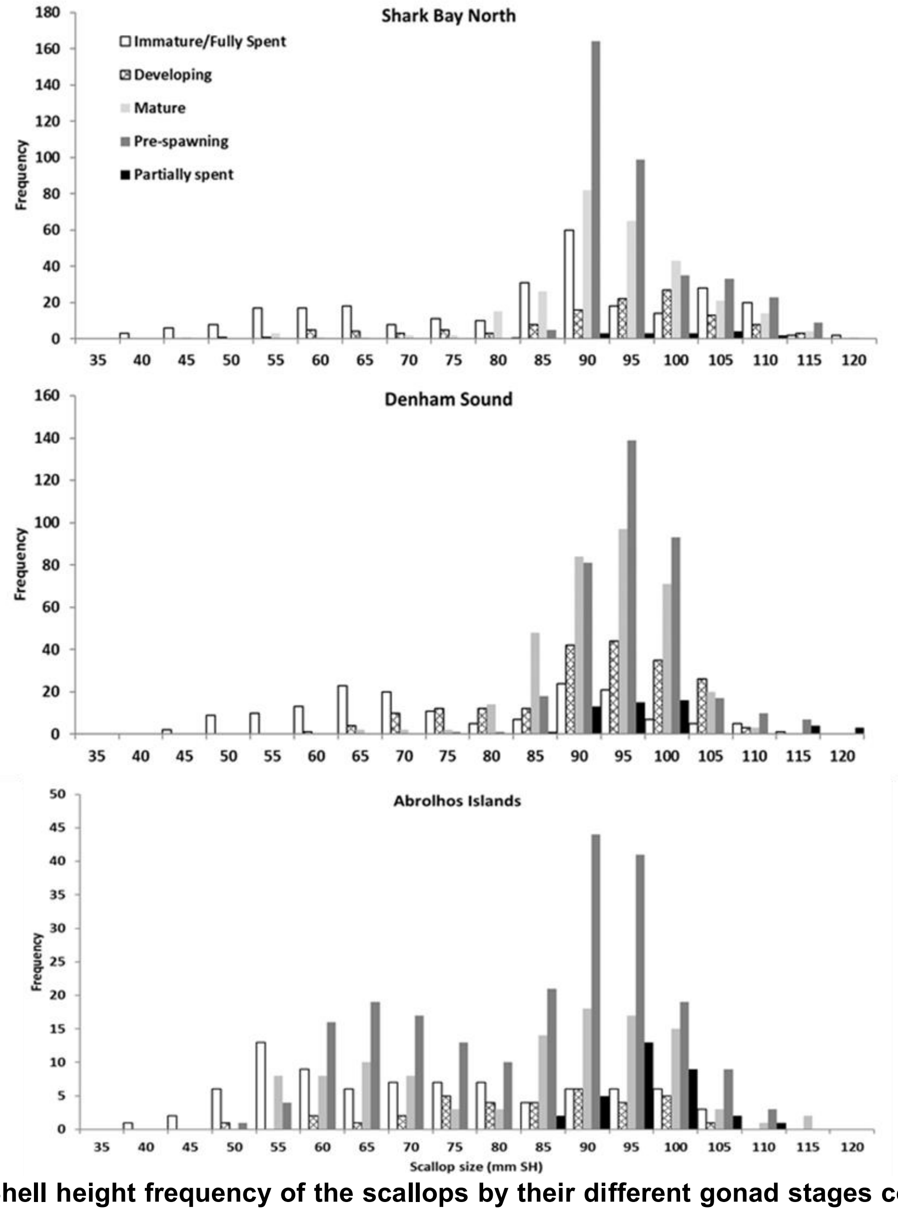

Figure 19. Shell height frequency of the scallops by their different gonad stages combined for all the months and years sampled in NSB, DS and AI.

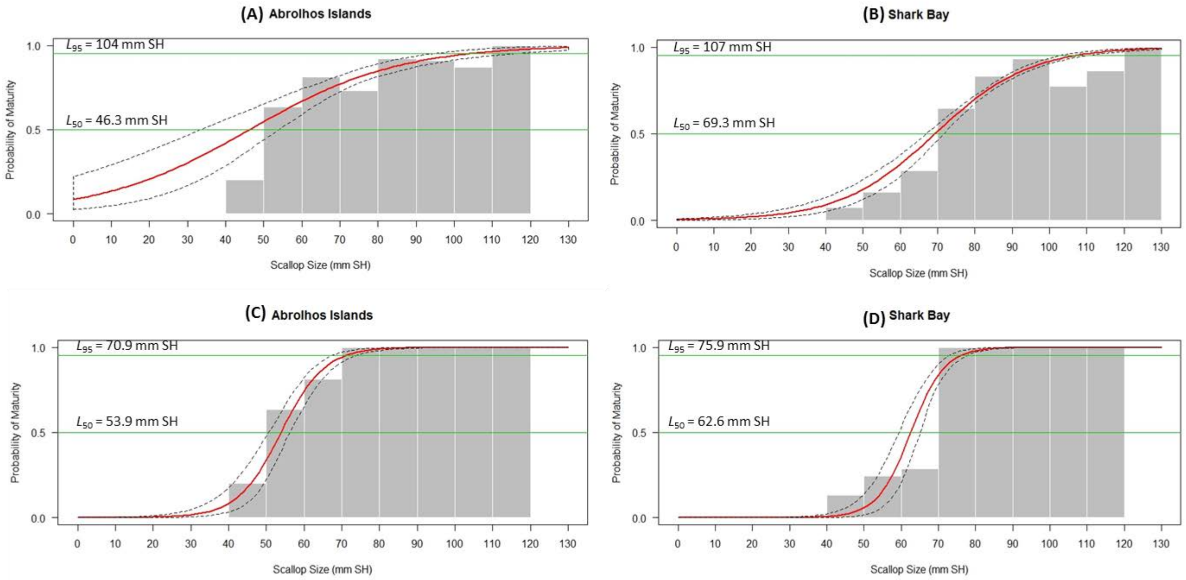

Figure 20. Logistic regression showing SOM estimates for Shark Bay and Abrolhos Island scallops with (C) and (D) assuming all SH above 70 mm being mature.

5.4 Environmental drivers of recruitment

5.4.1 South Coast

Along the SC, the austral summer months (November to February) are characterised by strong mean monthly wind speeds of up to 20 km/hr largely generated by southerlies (northward wind components) and to a lesser extent by easterlies (westwards wind components) (Figure 21a). Along this coastal region, the sea breeze appears to blow from the south east along the coast. Wind strength decreases from February to June which are largely driven by strong northerly and westerly winds which are characteristic of strong winter cold fronts that impact the south-west region of WA. From September onwards the southerlies return to sustain wind speeds above 19 km/hr into the spring summer months.

The warmest SST months defining the austral summer along the SC are between January and March when it is between ~18 - 21°C and winter temperatures are between 16 - 17°C during July to October. Decadal SST trends show increasing mean temperatures for all months along this region (Figure 21b) with average summer and winter temperatures since 2005 being generally warmer than historical years (Figure 21d). The 1999 and 2011 MHWs occurred during different seasons, however both events caused similar elevated SSTs between March and October, peaking in May where for both periods it was ~ 2°C above the historical range (Figure 21c).

In the absence of fishery-independent data, commercial catch data was used as the measure of recruitment. Thus the relationship between log-transformed annual catch in a given year (y) and mean monthly SST, FSL, wind speed, northing and easting components in the previous 24 months were examined. This assessment identified three significant time periods that were positively correlated with SST and two periods with FSL; SST Apr-Nov (y-1), SST Nov-Dec (y-2), SST January-May (y-2), FSL Jan-May (y-1) and FSL Oct-Jan (y-1/y) (Figure 22). Only a few individual months were identified to be significant with wind speed and northing component. A step-wise regression model of these significant variables provided a model fit of $r^2 = 0.43$ ($p < 0.05$) and revealed SST (Apr-Nov)(y-1) as the most significant contributor explaining 28% ($r^2 = 0.284$) of catch variability (Figure 23a) whilst SST (Jan-May) (y-2) explained a further 15% (Figure 23b). This relationship is described as;

$$\ln Catch_{(y)} = 2.21\ SST\ (Apr\text{-}Nov)_{(y-1)} + 1.02\ SST\ (Jan\text{-}May)_{(y-2)} - 56.95$$

Therefore, warmer winter to spring water temperatures are positively associated with higher scallop catches the following year. The highest catch on record during 2000 corresponds with the 1999 MHW which raised the water temperatures over the autumn/winter months. Likewise, higher than average scallop landings between 2012 and 2015 are also associated with the 2011 MHW and the 2010-12 La Niña event. The analysis was extended to examine possible spawning stock-recruitment-environment (SRE) relationship for the SC stock by using catch lagged by one year as a proxy for spawning stock. The addition of spawning stock however did not improve the model further and spawning stock was not a significant factor contributing to catch variability.

5.4.2 Rottnest Island

Wind strength is strongest between November and March (26–30 km/hr), with winds blowing predominantly from south to north (Figure 24a). Average monthly wind speed decreases to 23 km/hour during May before increasing to 20 - 22 km/hour between June and July from strong northerlies. Mean monthly differences in SST around RI is relatively small with a SST range between 19 - 22°C (Figure 24b). The warmest months at RI are between February and March when SSTs are currently (2010-17) at an average of 20.9°C, 0.4°C warmer than during the 1980’s (Figure 24b). Mean winter temperatures between August and October are ~19°C with June and July temperatures currently slightly cooler than during the 1980’s. The 1999 MHW increased water temperatures between February and August, peaking at 24.8°C during April which was 2.7°C warmer than the historical average (Figure 24c). The 2011 MHW caused elevated water temperatures between December and May peaking during February at 24.5°C when the SSTs were 2.4°C warmer the historical range (Figure 24c). Above average summer temperatures persisted into 2012 and 2013 with below average summer temperatures observed since 2016 (Figure 24d).

The relationship between log-transformed annual catch in a given year (y) and mean monthly SST, FSL, wind speed, and northing and easting components in the previous 24 months were examined. This assessment found individual months that produced significant correlations but no time series of months (Figure 25). Therefore, based on the spawning period inferred from ring count data, a step-wise regression model analysis was undertaken on log transformed catch (y) with mean SST during the spawning period October and March (y-2/y-1) and mean SST between April and August (y-1) that represents the juvenile phase. This multiple regression model was not significant (p = 0. 29) and fitted poorly to the data, $r^2 = 0.08$.

In examining possible SRE relationship for the RI stock (using catch lagged by one year to represent spawning stock), the output revealed a significant model fit of $r^2 = 0.45$ ($p < 0.005$) with only the catch harvested the previous year (as a proxy for spawning stock) explaining 45 % of catch variability and no environmental variables.

$$\ln Catch_{(y)} = 0.67 \ln Catch_{(y-1)} + 0.36$$

The positive linear relationship shows spawning stock levels greater than ~ 6 t (log 2.5) produced catches above 10 t and vice versa (Figure 26). The exception being 1987, 1990 and 2010 which were the three highest catch years from this fishery resulting from low to average spawning stock levels.

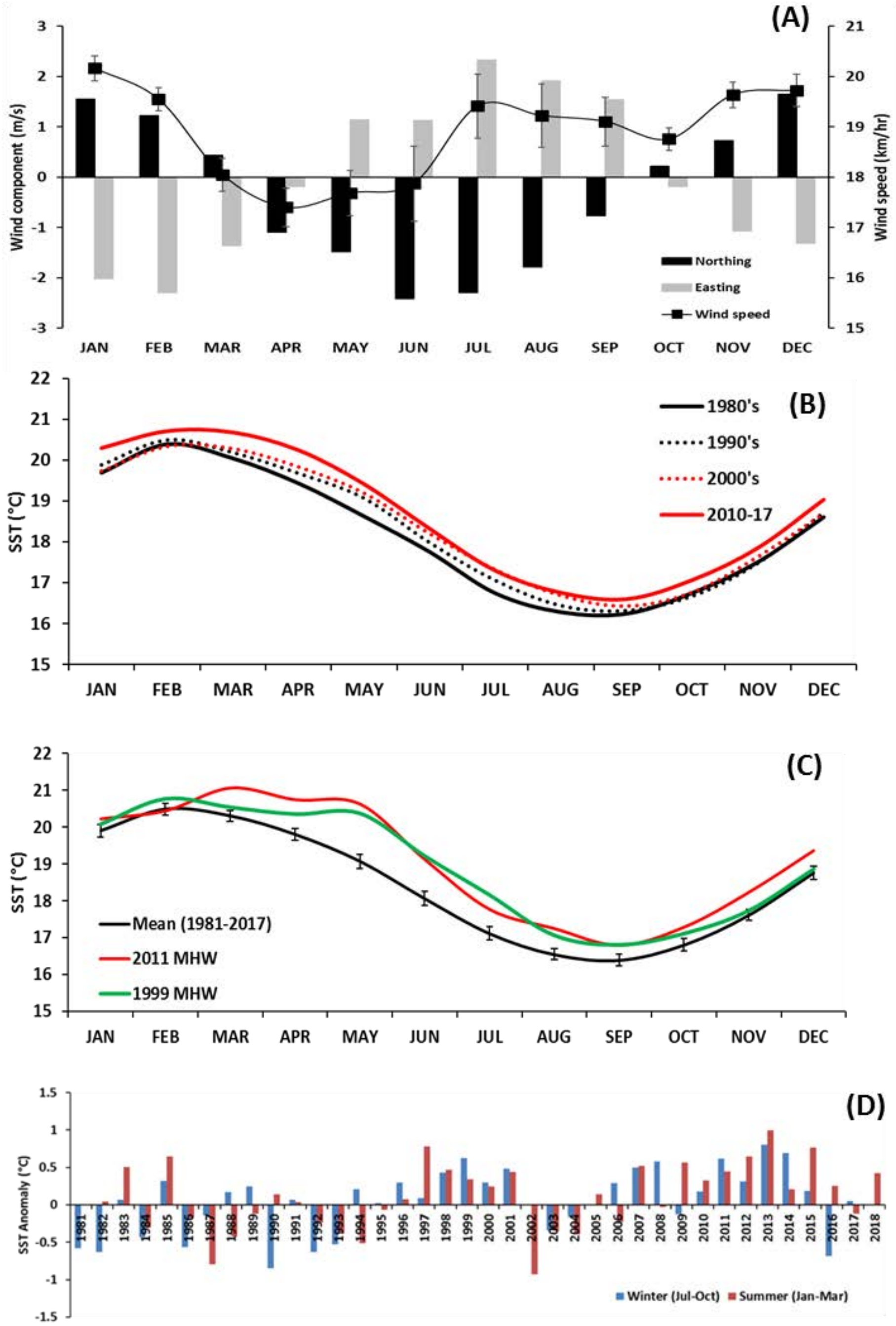

Figure 21. (A) Mean monthly wind speed (km/hr ±S E) (1969-2017) and directional wind components recorded at Esperance weather station (B) Decadal trends in mean monthly SST (C) Monthly mean SST during the 1999 and 2011 MHWs relative to historical monthly mean SSTs (D) Winter and summer SST anomalies for the SC with a reference period 1981-2009.

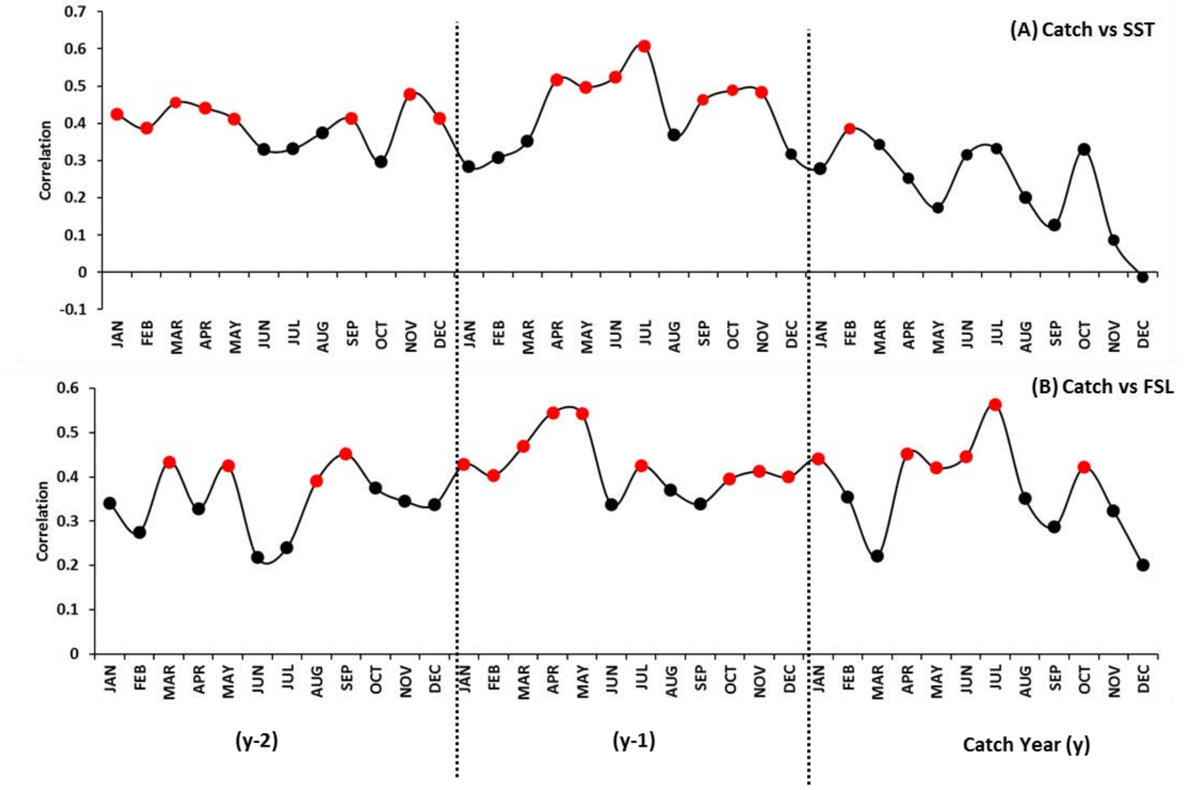

Figure 22. Correlations of log-transformed annual commercial catch with mean monthly (A) SST and (B) FSL in the current and previous two years for the period 1988 to 2016 from the SCTF. Red data points indicate significant correlation (*p* < 0.05).

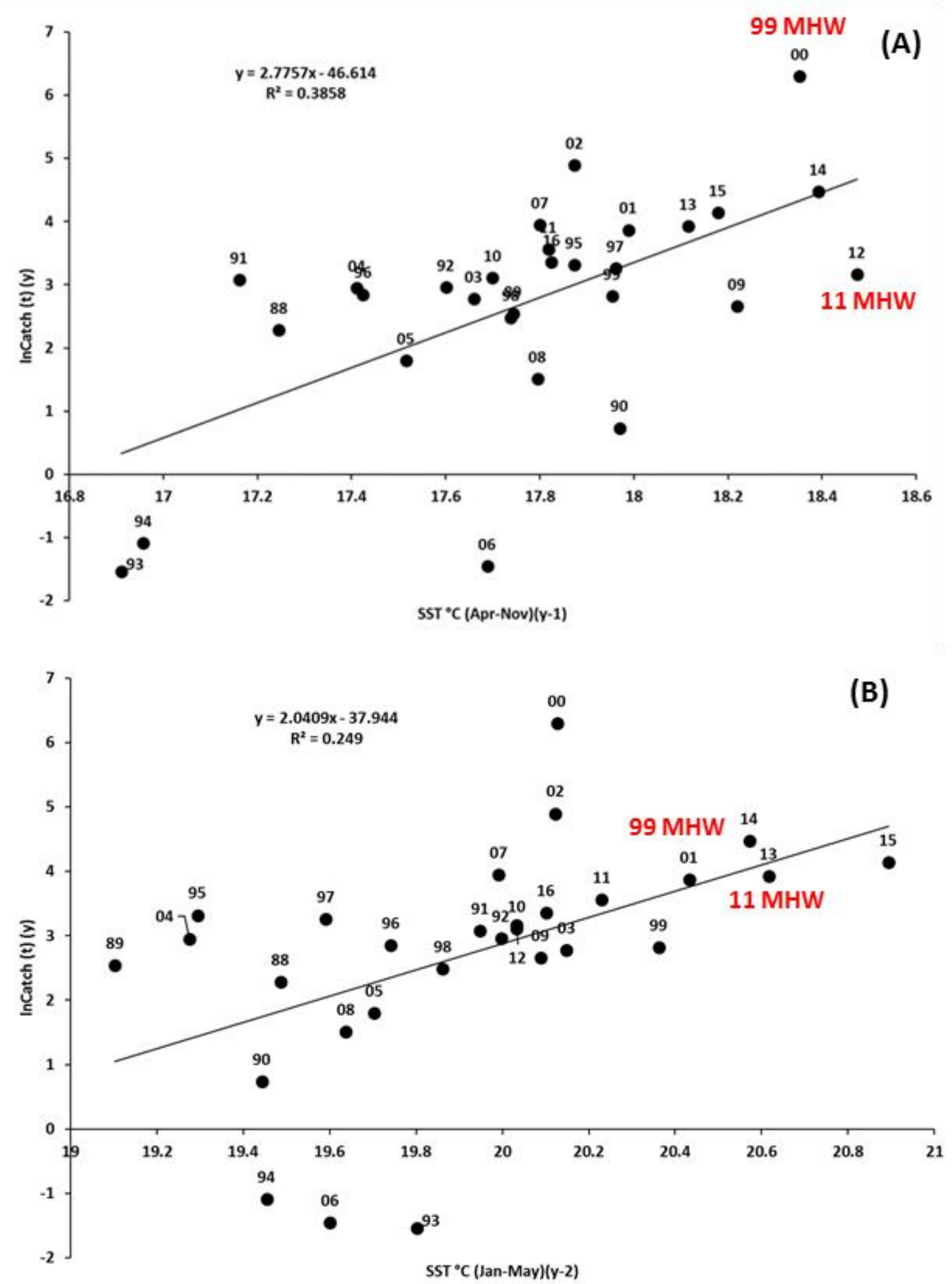

Figure 23. Relationship between log-transformed annual commercial catch from the SCTF and mean (A) SST between April and November (y-1) and (B) SST between January and May (y-2) for the period 1988 to 2016. Data labels indicate catch year, and years corresponding with the 1999 and 2011 MHW are also indicated.

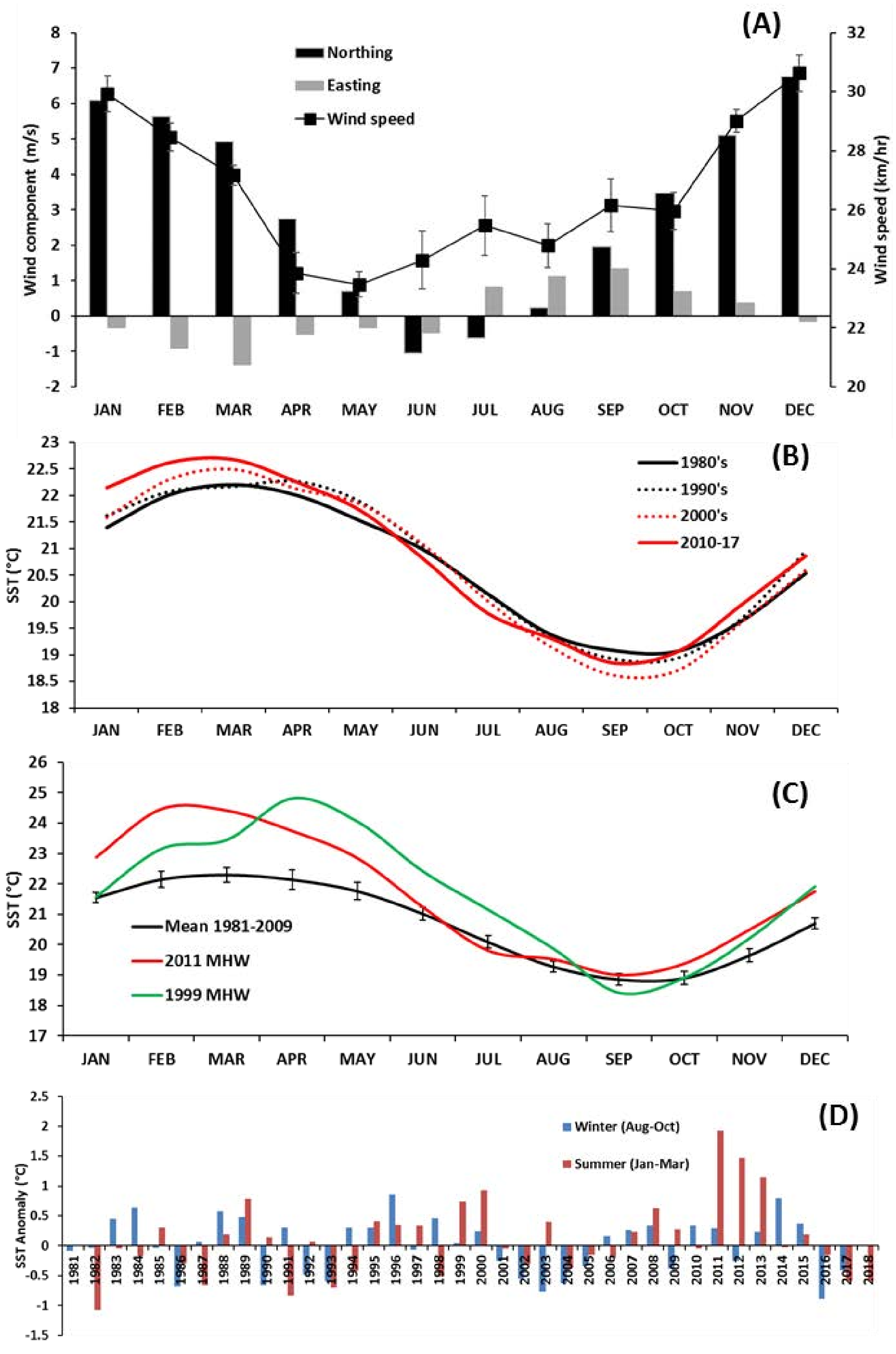

Figure 24. (A) Mean monthly wind speed (km/hr±SE) (1988-2017) and directional wind components recorded at Rottnest Island weather station (B) Decadal trends in mean monthly SST (C) Monthly mean SST during the 1999 and 2011 MHWs relative to historical monthly mean SSTs (D) Winter and summer SST anomalies for RI with a reference period 1981-2009.

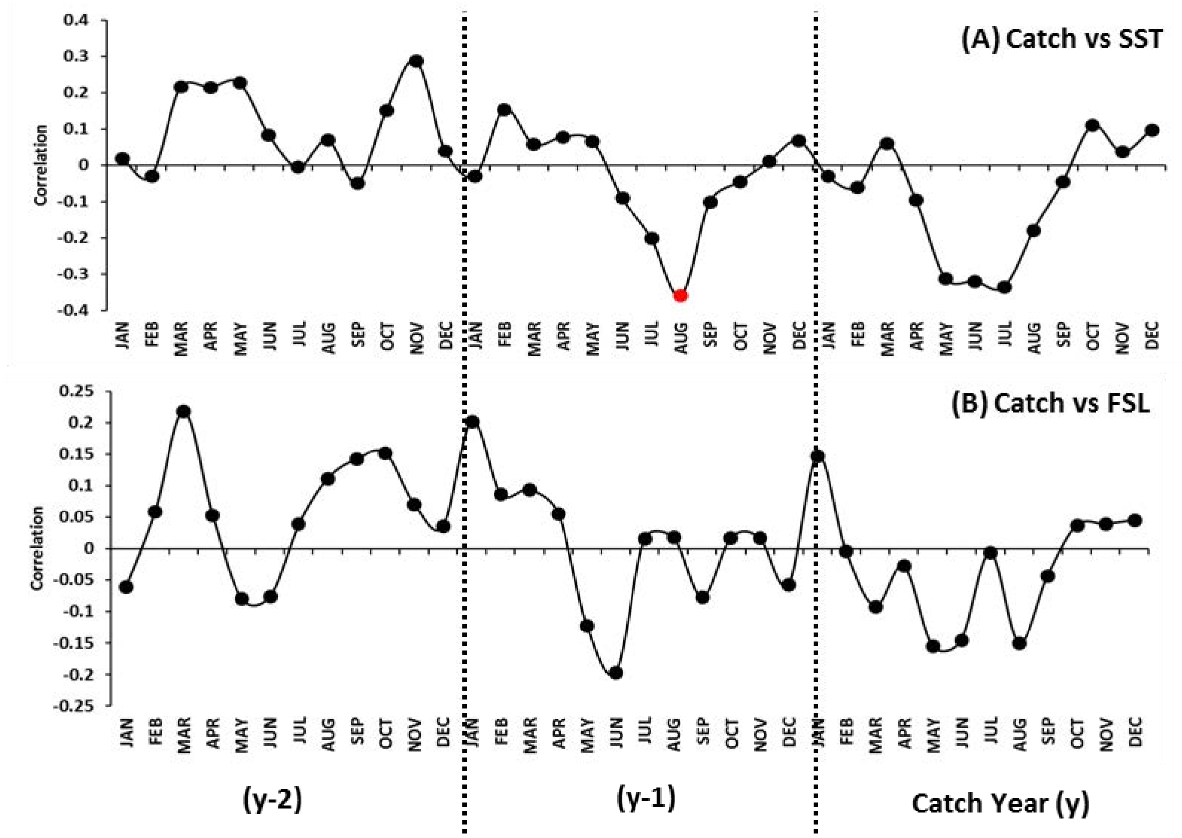

Figure 25. Correlations of log-transformed annual commercial catch with mean monthly (A) SST and (B) FSL in the previous two years for the period 1983 to 2013 from the SWCTF. Red data points indicate significant correlation ($p < 0.05$).

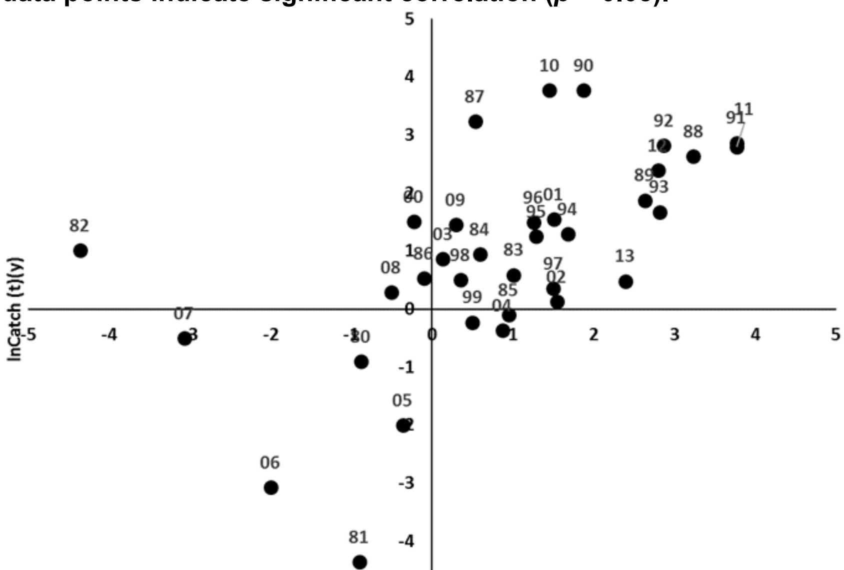

Figure 26. Relationship between log transformed catch as a proxy for recruitment in year (y) with log transformed catch in the previous year (y-1) as a proxy for spawning stock. Data labels refer to recruitment year (y).

5.4.3 Abrolhos Islands

At AI, winds are strongest between October and March (28–31 km/hr) driven by the dominant southerlies (Figure 27a). Average wind speed decreases to 24 km/hr between April and September. Seasonal differences in SST at AI range between 20 and 24°C with the warmest

months between February and March with current SST at an average of 24°C, 0.6°C warmer than during the 1980’s (Figure 27b). Average winter temperatures are around 20°C between September and October and the mean minimum temperature month shifting slightly from October to September in recent years. During the 1999 MHW, water temperatures were above the historical average between February and August, peaking in April with a monthly mean temperature of 26.1°C degrees that was 2.5°C above the historical average (Figure 27c). The 2011 MHW elevated water temperatures between November 2010 and May 2011, peaking during February/March at 26.7°C when the SSTs were 3°C warmer the historical average (Figure 27c). Above average summer temperatures persisted into 2012 and 2013 with average to below average summer temperatures since 2014 (Figure 27d).

The annual FIS provides a measure of total abundance and size composition of scallops across the main fishing grounds in the AI. Majority of these scallops represent the new recruitment from the spring/summer spawning period and can be represented by one or two cohorts. The relationship between log-transformed annual total CPUE during November/December in a given year and monthly SST, FSL, wind speed and northing and easting components in the previous 24 months were examined. This analysis excluded the time series 2012 to 2015 to remove the effects of very low spawning stock levels that persisted after the 2011 MHW.

Lagged correlations were not significant for any months or environmental variables (Figure 28). The SST analysis did however show that March to June (y) was negatively correlated with catch rates which provided a weak model fit of $r^2 = 0.17$ ($p = 0.109$).

$$\text{lnRecruitmentCPUE}_{(y)} = -0.46 \text{ SST (Mar-Jun)}_{(y)} + 17.7$$

Scallop catch rates during November appear to be negatively associated with winter temperatures, where mean SSTs > 24.5°C have resulted in very poor recruitment while SSTs < 24.5°C have resulted in both good and poor recruitment with the highest catch rates associated with the coolest SSTs < 23°C (Figure 29). The warmest winters are associated with the 1999 and 2011 MHW events. The inclusion of spawning stock into the model resulted in a significant model fit of $r^2 = 0.58$ ($p < 0.005$). Spawning stock was the main contributor to recruitment explaining 45% of variability ($p = 0.0002$) and the remaining 13% by the winter SST ($p = 0.013$).

$$\text{lnRecruitmentCPUE}_{(y)} = 0.72 \text{ lnSpawningCPUE}_{(y-1)} - 1.7 \text{ SST (Mar-Jun)}_{(y)} + 41.44$$

In AI, the current stock-recruitment-environment (SRE) relationship suggests spawning stock levels greater than 420 scallops/nm (log 6) have generally led to recruitment levels greater than 280 scallops/nm (log 5.5) that have allowed the fishery to operate (Figure 30). When sufficient spawning stock levels are available, cooler SSTs < 23 °C have produced recruitment levels above 1800 scallop/nm (e.g. 2002, 2004, 2007, 2010, 2018 and 2016), while warmer SSTs > 23 °C have produced average to poor recruitment which have generally resulted in catches being < 50 t or the fishery being closed. The recruitment failure during 2012 is associated with the warmest SST during May – June 2011 at 25°C, the tail end of the temperature signal from the 2011 MHW event. Subsequent recruitment was likely impaired by low spawning stock levels from 2012 to 2015, while the recovery in 2016 can be attributed to the return of cooler winter SST of 22.2°C during 2015. This was associated with one of the strongest recorded El Niño events. The improved recruitment observed during 2016 indicates spawning stock levels as low as 29 scallops/nm can produce above average recruitment level of 988 scallops/nm under conducive environmental conditions.

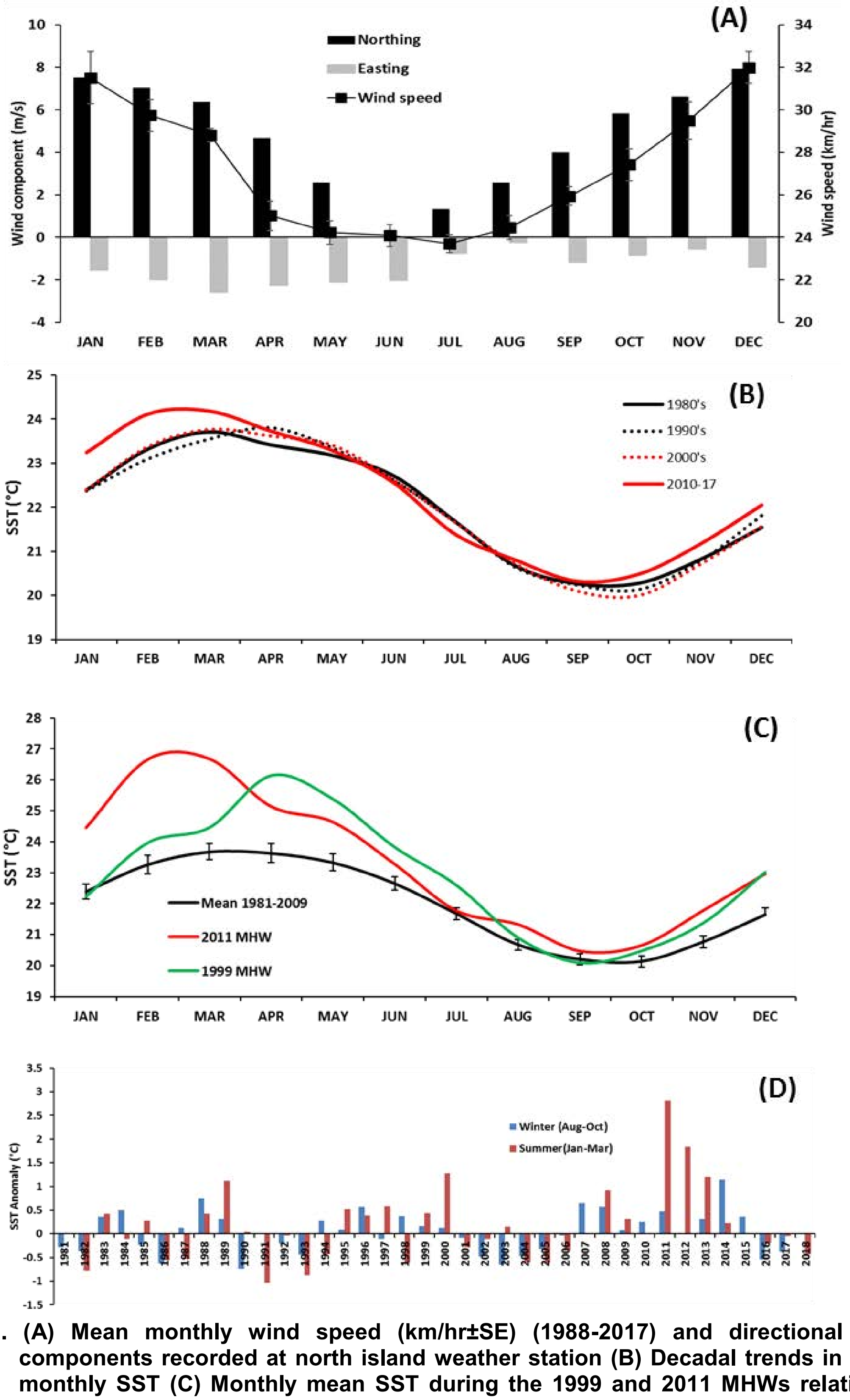

Figure 27. (A) Mean monthly wind speed (km/hr±SE) (1988-2017) and directional wind components recorded at north island weather station (B) Decadal trends in mean monthly SST (C) Monthly mean SST during the 1999 and 2011 MHWs relative to historical monthly mean SSTs (D) Winter and summer SST anomalies for AI with a reference period 1981-2009.

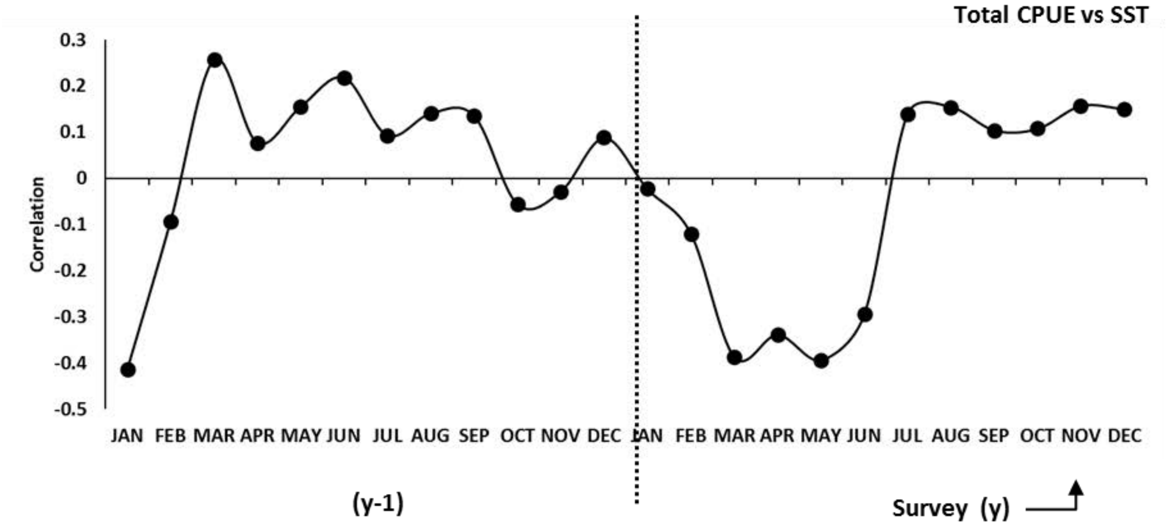

Figure 28. Correlations of log-transformed total CPUE from annual November survey with mean monthly SST in the previous 2 years at AI.

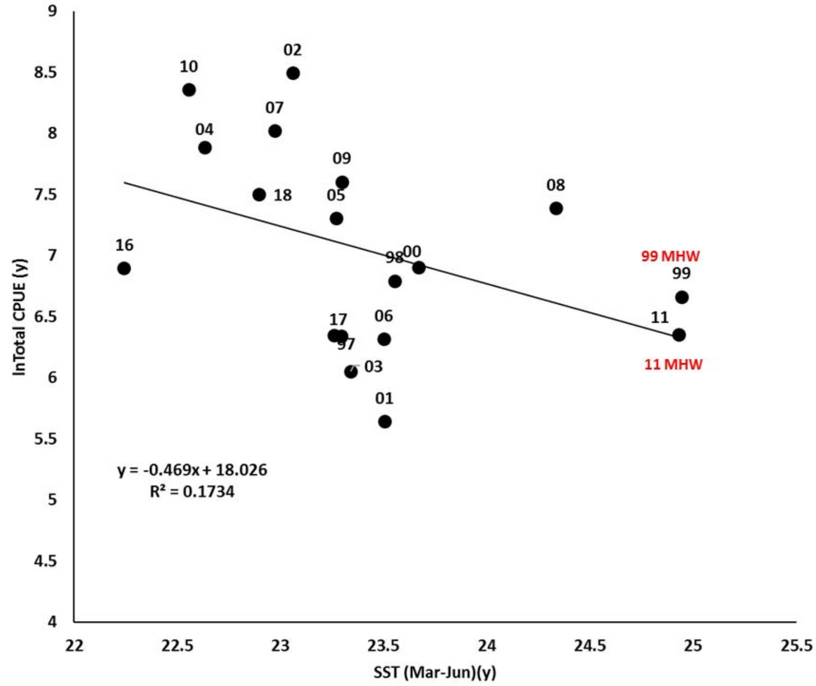

Figure 29. Relationship between log-transformed annual total catch rate during November (y) and mean (A) SST (Mar-Jun) (y) for the period 1997 to 2018 (excluding 2012-2015). Data point labels indicate survey year and years corresponding with the 1999 and 2011 MHW are also indicated.

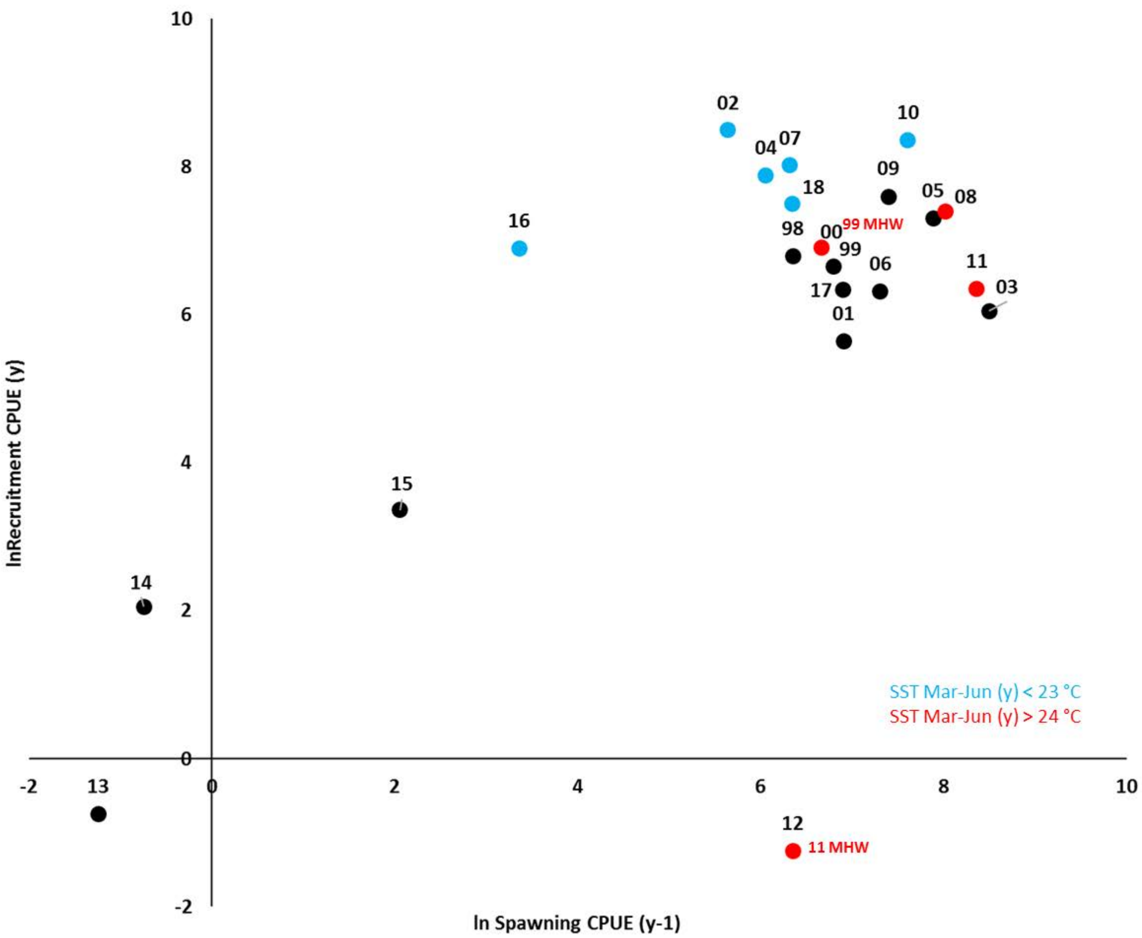

Figure 30. Relationship between log transformed recruitment CPUE (total CPUE) during November (y) with log transformed spawning stock CPUE during November (y-1) in the previous year at the AI. Data labels refer to recruitment year with mean SST (March – June) > 24°C (red) and < 23°C (blue).

5.4.4 Shark Bay

Seasonal wind patterns inside Shark Bay are similar to AI where monthly mean wind strength is strongest between October and March (22 – 27 km/hr) over the summer months and decreases to around 14 km/hr during June/July (Figure 31a). The Bay is predominantly impacted by southerlies throughout the year while easterlies are the second strongest winds over the winter period.

Seasonal differences in mean SST inside and outside Shark Bay range between 20-26°C with the warmest months generally between February and April (Figure 32). Between October and March, mean SSTs outside and inside the Bay are currently warmer than the 1980’s. The warmest month, February is now 0.5 to 1°C warmer than during the 1980’s. Conversely, the autumn/winter SSTs inside the Bay is showing a dramatic decrease since the 1980’s as well a shift in the minima from September to July (Figure 32b,c) which is not evident in the water body outside the Bay. Average July SSTs are currently 1.2°C and 1.6°C cooler than the 1980’s in DS and NSB respectively.

The 1999 MHW increased the average April SST by 2.3°C outside Shark Bay, 2.2°C in DS and 2°C in NSB (Figure 32d-f). The 2011 MHW raised the mean SSTs much higher between January and March where it peaked at ~29°C during February 2011, ~ 4-5°C warmer the historical range. Average summer SSTs remained 1-2°C warmer during 2012 and 2013 inside

Shark Bay which was also attributed to the extended La-Niña event. Both DS and NSB winter SSTs have been average to below average since 2001 with the coldest winters occurring during 2016 and 2018 (Figure 31b.c).

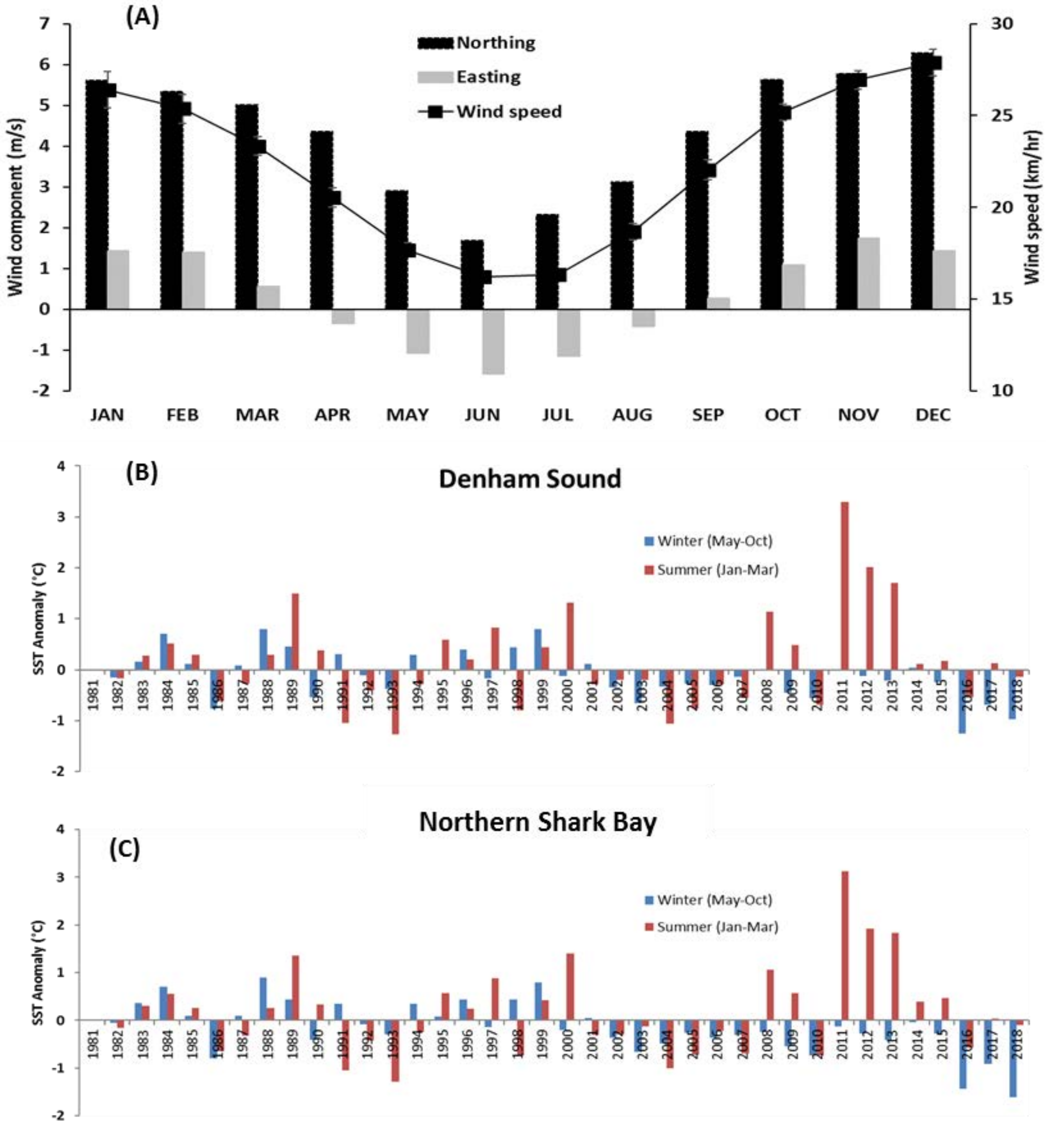

Figure 31. (A) Mean monthly wind speed (km/hr±SE) (1945-2017) and directional wind components recorded at Carnarvon Airport weather station. Winter and summer SST anomalies for (B) Denham Sound and (C) Northern Shark Bay with a reference period 1981-2009.

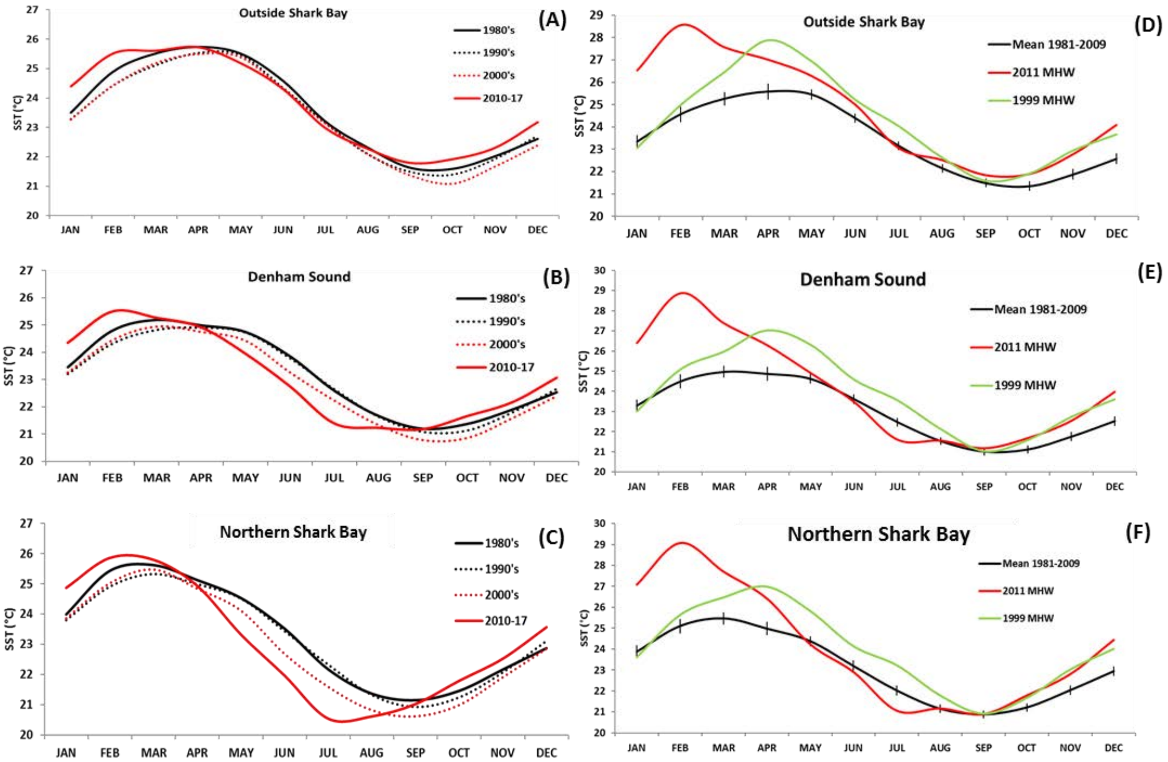

Figure 32. Decadal trends in mean monthly SST (left column) and monthly mean SST during the 1999 and 2011 MHWs relative to historical monthly mean SSTs (right column) for the Outside Shark Bay, Denham Sound and Northern Shark Bay regions.

5.4.4.1 Denham Sound

The annual FIS during November/December provides a measure of total abundance and size composition of scallops across a number of standardised sites within DS. Majority of these scallops represent the new recruitment from the summer/autumn spawning period which can be represented by up to three cohorts (0+ age class) but also the older adult scallops (1+ age class). The relationship between log transformed recruitment CPUE in a given year and monthly SST, FSL, wind speed and southerly wind components in the previous 24 months were examined. Since DS has historically been less productive than NSB and characterised by a large number of low abundance years (e.g. 1984-88, 1996-2000), all years were included between 1983 and 2018 in the correlation analyses.

Lagged correlation analysis identified SST April to August (y), wind speed November to December (y-1), and northing wind component September to November (y-1) as significant time periods (Figure 33). A step wise regression model of these variables provided a model fit of $r^2 = 0.57$ ($p < 0.001$) with SST explaining 30% ($p = 0.0003$) of the variation in CPUE, and 27% by the northing wind component ($p = 0.0005$). The relationship between these factors are shown by;

$$\text{LnRecruitment}(0+)_{(y)} = -1.16\ \text{SST (Apr-Aug)}_{(y)} + 0.19\ \text{Northing (Sep-Nov)}_{(y-1)} + 22.59$$

Recruitment is shown to be negatively associated with winter SSTs April to August during the spawning period (Figure 34a) and positively associated with southerly winds September to November (y-1) (Figure 34b). Higher recruitment levels were generally associated with mean SSTs < 23 °C and the warmest mean SSTs > 24°C were associated with the lower recruitment levels. The warmest winter SST at 24.7°C occurred during the 1999 MHW event. The model also revealed a positive relationship with the southerly wind where the number of southerly

components > 43 was associated with good and poor recruitment but < 43 producing the lower range of recruitment levels.

Inclusion of spawning stock (Total $CPUE_{y-1}$) into the above model did improve the model fit $r^2 = 0.64$ ($p < 0.001$), where SST contributed 24% ($p < 0.001$), southerly wind component explaining 23 % ($p < 0.001$), and spawning stock explaining 17% of recruitment variability ($p = 0.037$).

$$LnRecruitment_{(y)} = 0.25\ lnSpawning_{(y-1)} - 0.88\ SST\ (Apr\text{-}Aug)_{(y)} + 0.18\ Northing(Sep\text{-}Nov)_{(y-1)} + 15.41$$

In DS, the stock-recruitment-environment relationship is largely driven by the environmental conditions with winter water temperatures and spring southerlies equally influencing recruitment strength. Since 1983 there has been 12 separate years in total where no fishing had taken place due to low stock abundance which includes the four years after the 2011 MHW. These low stock abundance years occurred when spawning stock levels were < 150 scallops/nm (log 5) and recruitment < 55 scallops/nm (log 4) and being associated with winter SSTs > 23.5°C and weaker (< 5) spring time southerlies (Figure 35a and b). Among these low recruitment years are those that are impacted by the 1999 and 2011 MHW events where winter SSTs were > 23.5°C. The stock did recover after both MHWs as SSTs decreased and the southerlies increased. For example, recruitment levels increased from 2013 to 2014, despite lower than average spawning stock levels, and this may be due to cooler water temperatures and stronger southerlies. A similar stock improvement can be seen between 1989 and 1990 where a marked increase in recruitment occurred despite little change in spawning biomass. Therefore, with the exception of 2014 and 1990, spawning stock levels > 150 scallops/nm (log 5) have generally produced higher recruitment and these are associated with cooler winter SSTs < 23.5°C and stronger southerlies. The spawning stock level in 1992 had been the highest on record due to an exceptional recruitment that year, however recruitment during 1993 was considered poor despite cooler winter SST. One school of thought being the lack of available settlement grounds for new recruits in years of very high adult stock abundance. Juvenile scallops require sandy bottom for successful settlement and dense scallop beds could be an inhibiting factor.

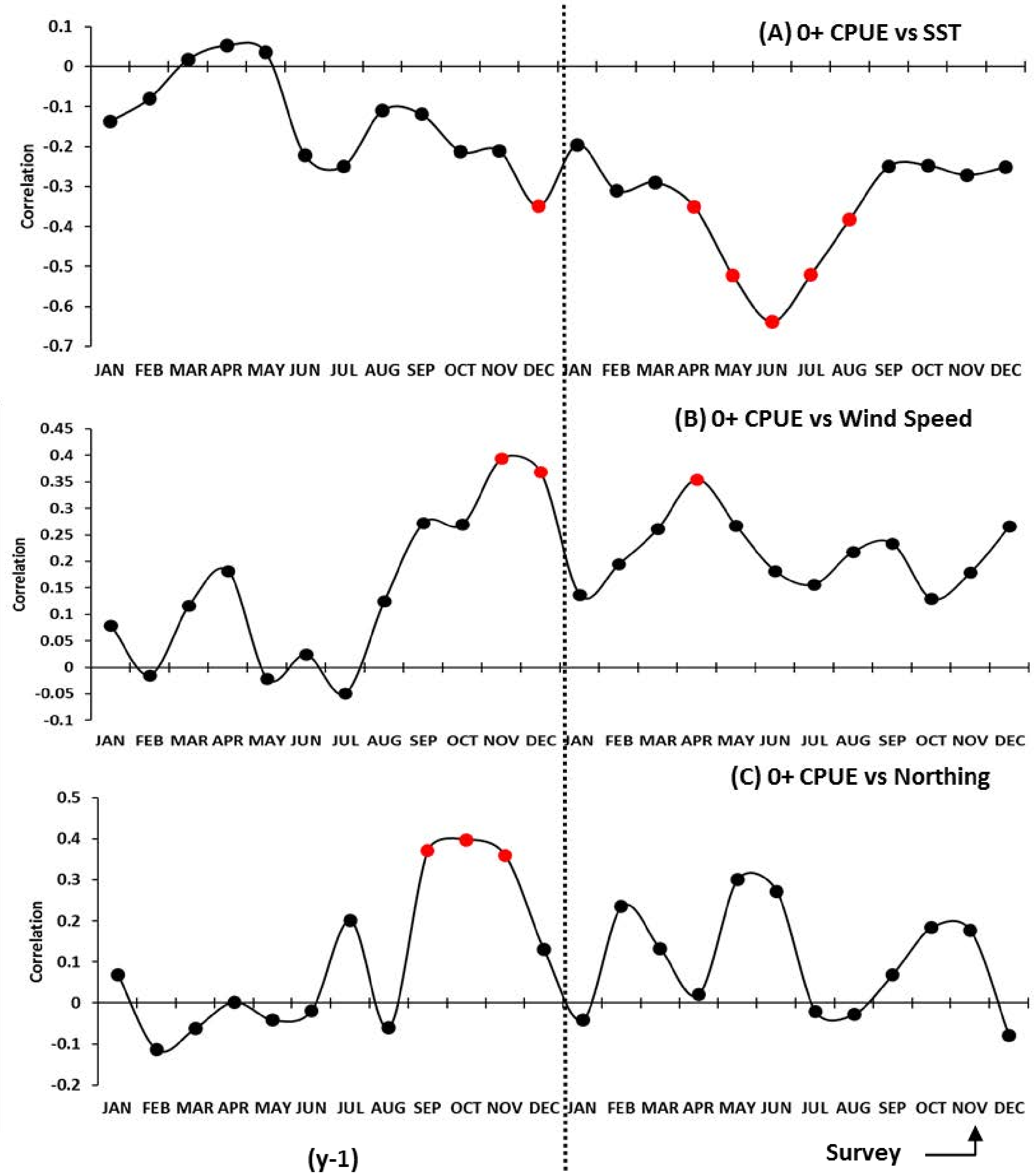

Figure 33. Correlations of mean monthly (A) SST (B) Wind Speed and (C) Northing wind component with log-transformed annual 0+catch rate (scallops/nm) in the previous 24 months for the period 1983 to 2018 in Denham Sound. Red data points indicate significant correlation ($p < 0.05$).

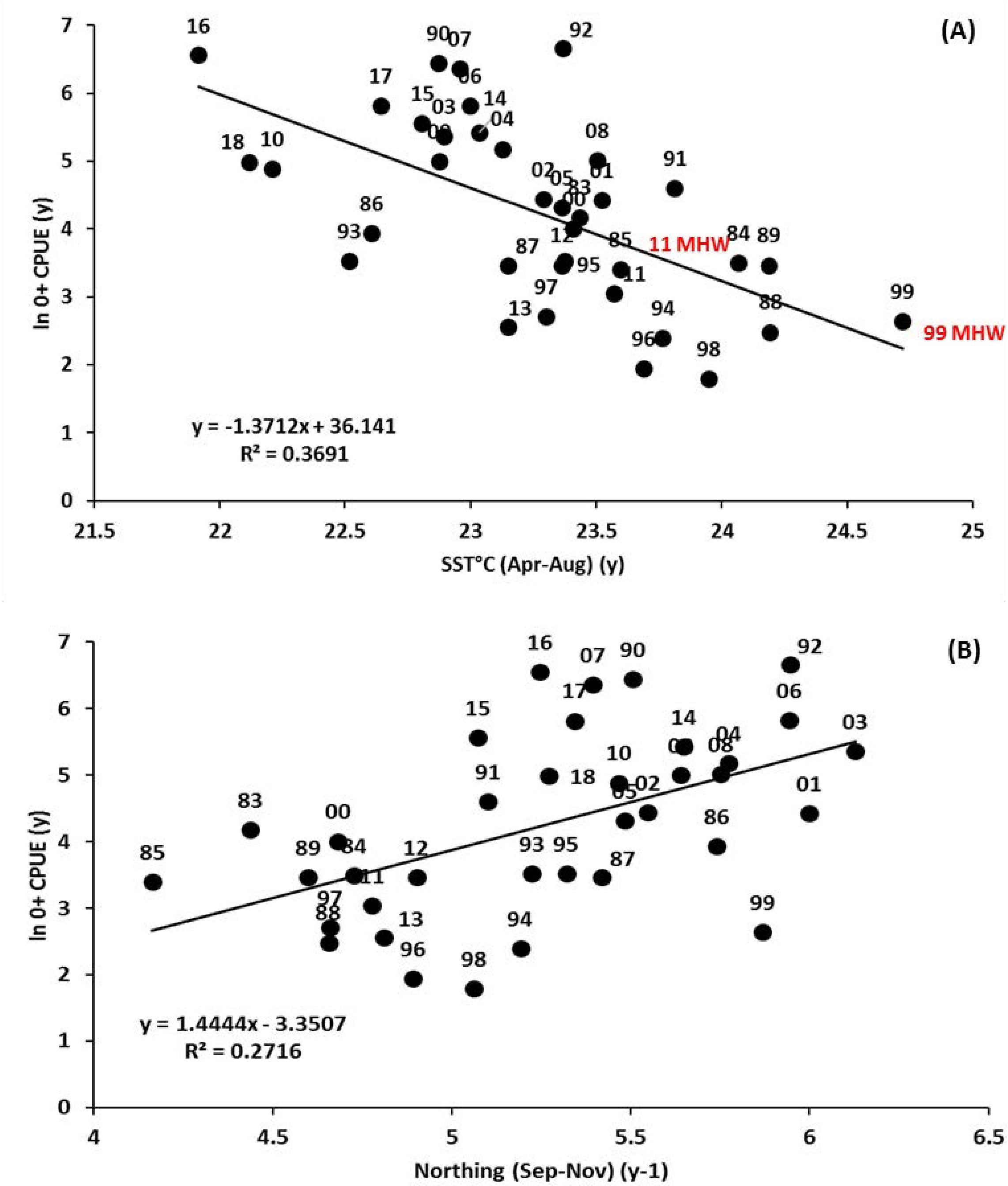

Figure 34. Relationship between log-transformed annual recruitment (0+) catch rate during November (year y) and mean (A) SST (Apr-Aug) (y) and (B) Southerly components (Sep-Nov) (y-1) in Denham Sound. All data point labels indicate survey year.

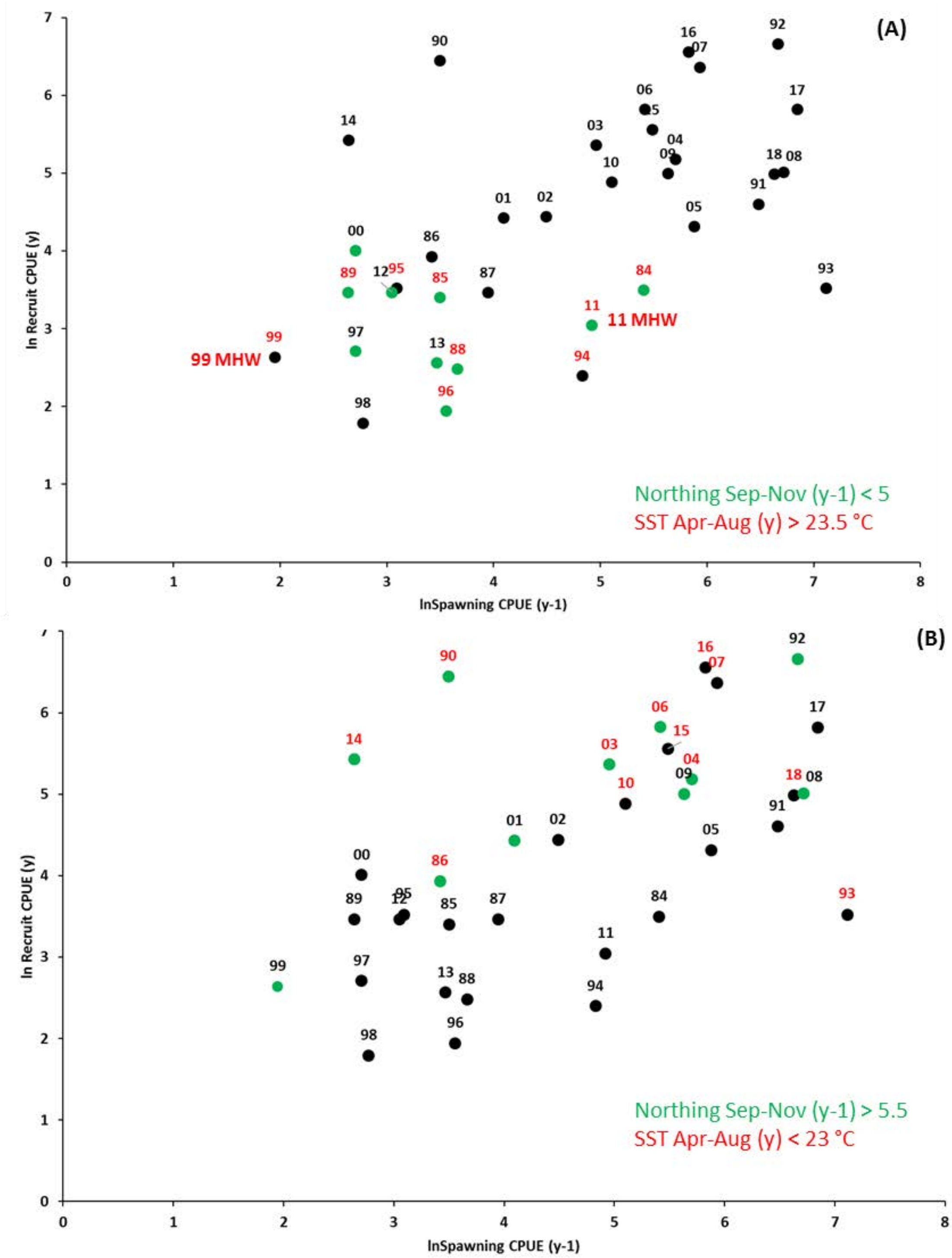

Figure 35. Relationship between log transformed recruitment CPUE (0+) during November (y) with log transformed spawning stock (total CPUE) during November (y-1) in the previous year with data labels referring to the recruitment year. (A) Recruitment years where the mean SST (Apr – Aug) > 23.5°C are indicated by red labels, recruitment years where the Northing wind component (Sep-Nov) (y-1) < 5 (green) are indicated by green dots. (B) Recruitment years where the mean SST (Apr – Aug) < 23°C are indicated by red labels, recruitment years where the Northing wind component (Sep-Nov) (y-1) > 5.5 (green) are indicated by green dots.

5.4.4.2 Northern Shark Bay

Prior to 2011, NSB had been the most productive scallop stock in WA and low stock levels had only been experienced after the 2011 MHW. To exclude the effects of very low spawning stock levels on recruitment, survey catch rates from 2013 were excluded from the correlation analyses with environmental variables as they were the lowest on record. All other years between 1983 and 2018 were used to determine the relationship between log transformed recruitment CPUE in a given year and monthly SST, FSL, wind speed and southerly wind components in the previous 24 months for NSB.

The correlation analysis identified SST December - January (y-1/y), FSL May-June (y) as significant time periods (Figure 36). A step-wise regression model of these variables provided a model of $r^2 = 0.25$ ($p < 0.01$) identifying SST Dec-Jan (y-1/y) as the only significant contributor. The relationship is shown as;

$$\ln Recruitment_{(y)} = -0.81\ SST\ (Dec\text{-}Jan)_{(y-1/y)} + 23.8$$

Recruitment in NSB appears to be negatively associated with the previous summer temperatures which would impact on the condition of the spawning stock. Low to high recruitment levels are observed when mean SSTs are < 24°C, while average to very low recruitment levels when SSTs were > 24°C (Figure 37).

Incorporating spawning stock into the model did not improve the model and thus stock-recruitment model was not significant (Figure 38). This may be due to the low number of points with low spawning stock. Both recruitment and spawning stock levels declined from 2010 to its lowest levels in 2013. Recruitment levels improved despite low spawning biomass during 2014 and progressively improved until 2017. The most recent recruitment level in 2018 is the lowest since the recovery despite average spawning biomass levels and average SST levels (Figure 38).

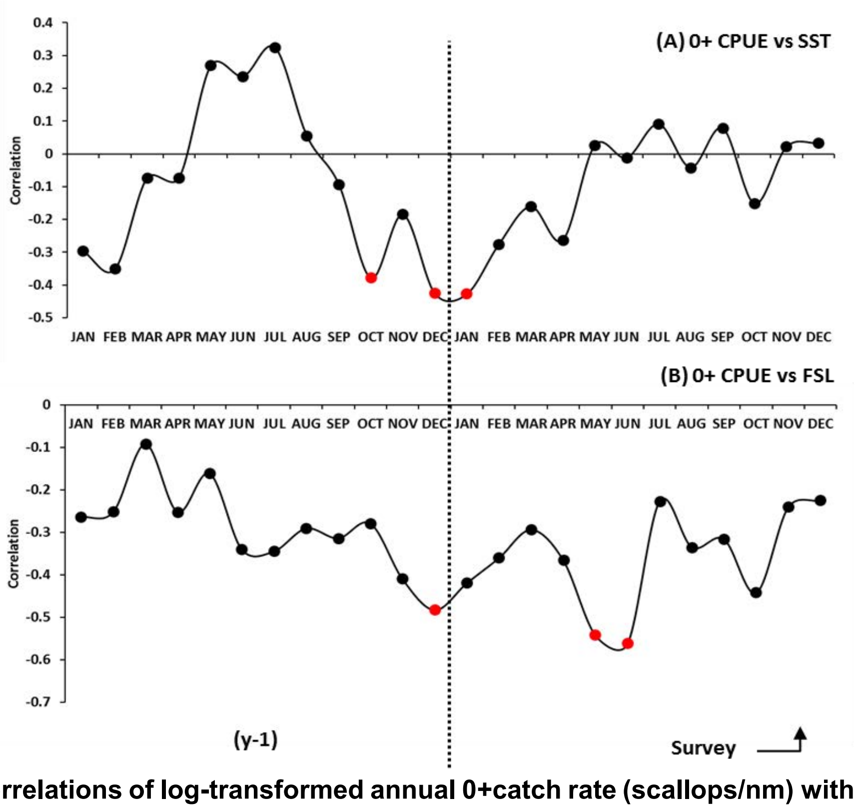

Figure 36. Correlations of log-transformed annual 0+catch rate (scallops/nm) with mean monthly (A) SST (B) FSL in the previous 24 months for the period 1983 to 2018 (2013-16 excluded) in Northern Shark Bay. Red data points indicate significant correlation (*p*

< 0.05).

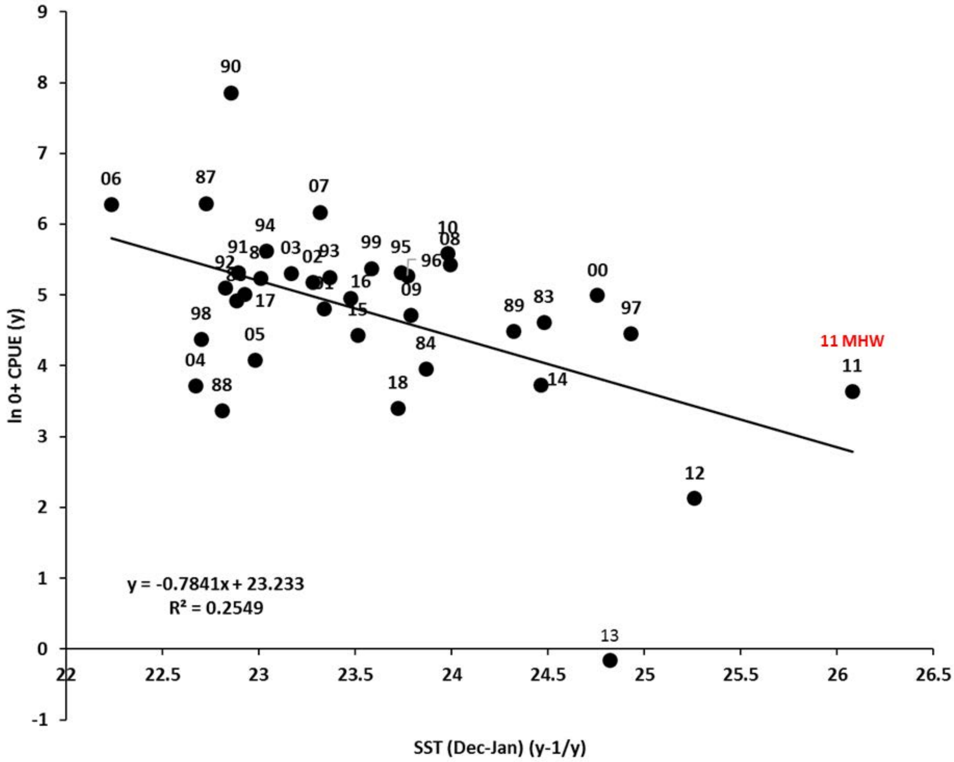

Figure 37. Relationship between log-transformed annual recruitment catch rate during November (y) and mean SST (Dec-Jan) (y-1/y) in Northern Shark Bay. All data point labels indicate survey year.

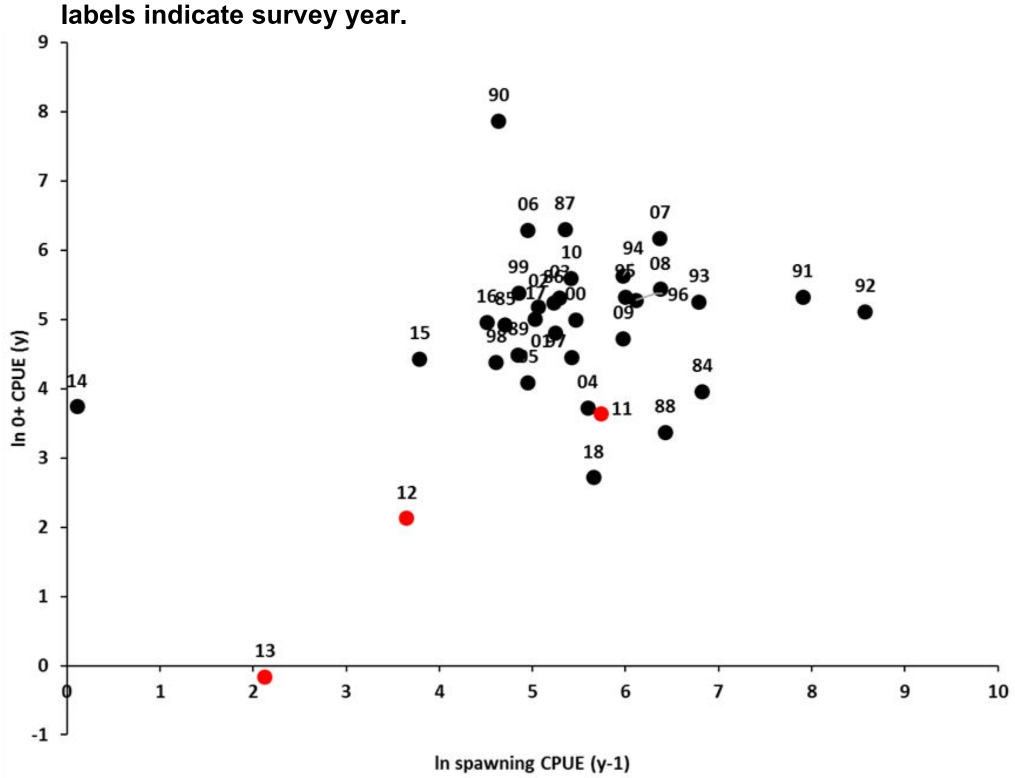

Figure 38. Relationship between log transformed recruitment CPUE (0+) during November (y) with log transformed spawning stock CPUE during November (y-1) in the previous year in Northern Shark Bay. Data labels refer to recruitment year with mean SST (Oct – Jan) > 25°C indicated by red dots.

5.5 Translocation pilot study

The overall recapture rate of tagged scallops was very low at < 1% at both the control and translocated sites. Commercial fishers recaptured eight tagged scallops from the control site and six tagged scallops from the translocated site during July 2017. The mean growth increment of recaptured scallops was 30 mm and 27 mm at the control and translocated sites respectively after 122 days at liberty (Figure 39). From the November 2017 survey, a further seven tagged scallops at the control site and none from the translocated site were recaptured. The mean growth increment of these recaptured scallops was 33 mm after 262 days at liberty (Figure 39). All of the recaptured scallops from the control site were used to determine the number of rings over the growth increment region while none from the translocated site were available for ring counts. The relationship between the number of rings in the growth increment and the days at liberty was very close to 1:1 at 122 days at liberty but very much below this line of equality for the 262 days at liberty (Figure 40). This supports the growth increments being similar between July and November recaptured scallops, suggesting little to no shell growth during this post-spawning period. Many recaptured scallops showed trawl damage scaring and fragmentary remnants of new shell formation from the time they were captured for tagging (see Figure 41 as an example). It does appear that the trauma to shell margin from the trawling is visible by the change in shell thickness, pigmentation flaring and the obvious disruption to the ring formation.

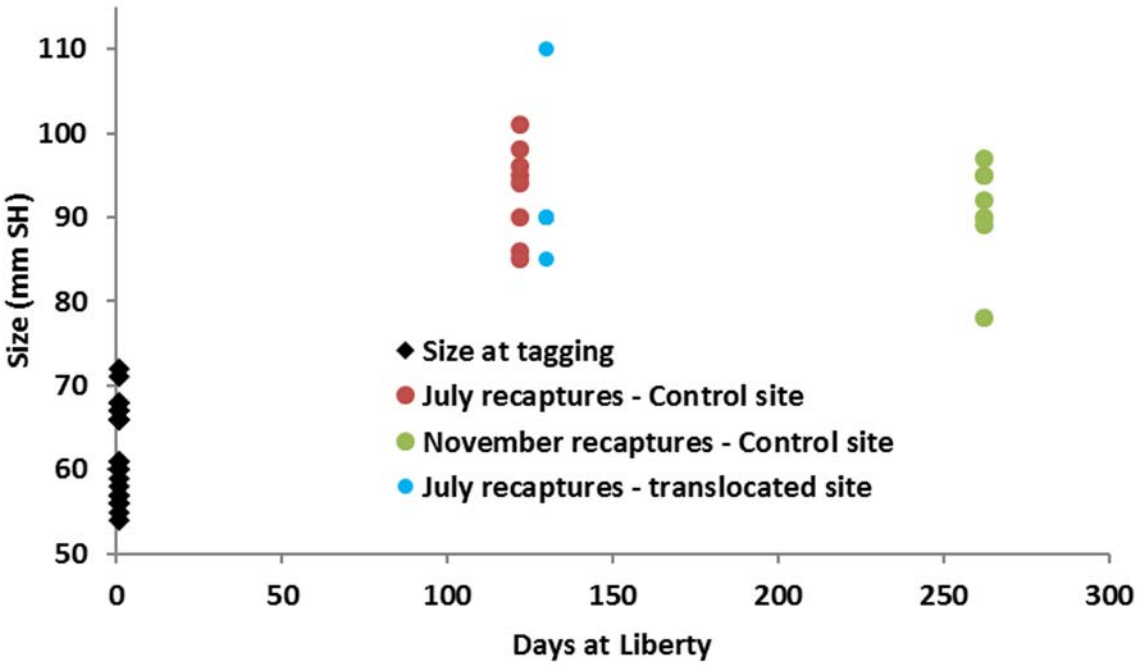

Figure 39. Size range of tagged and recaptured scallops at the control and translocated sites.

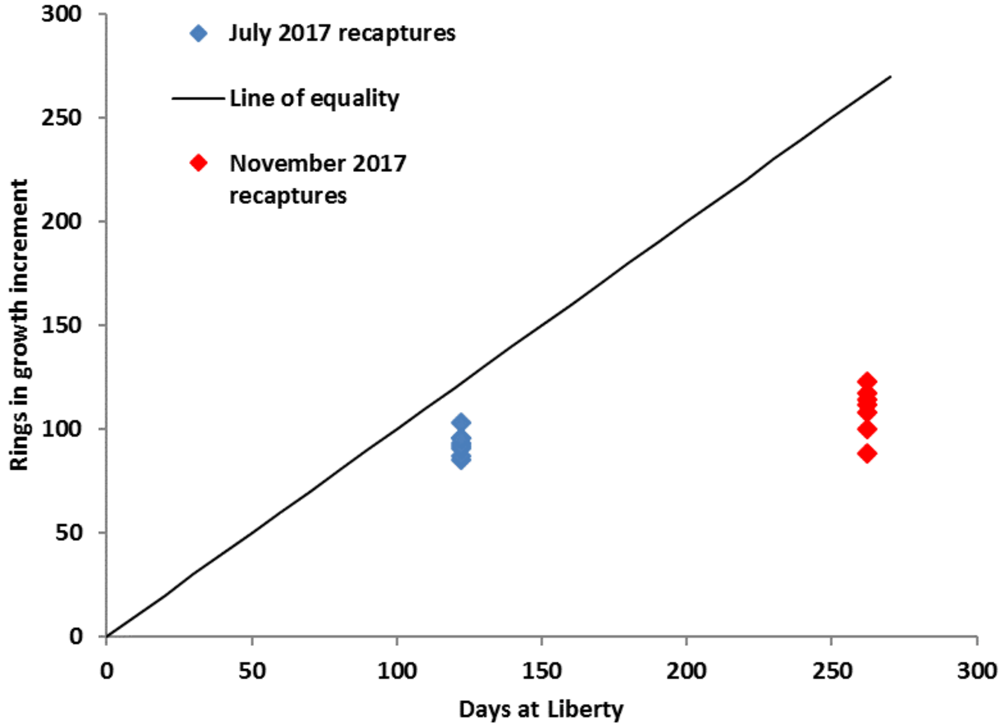

Figure 40. Number of rings in the growth increment of recaptured tagged scallops during July and November 2017. Line of equality indicates daily growth rings.

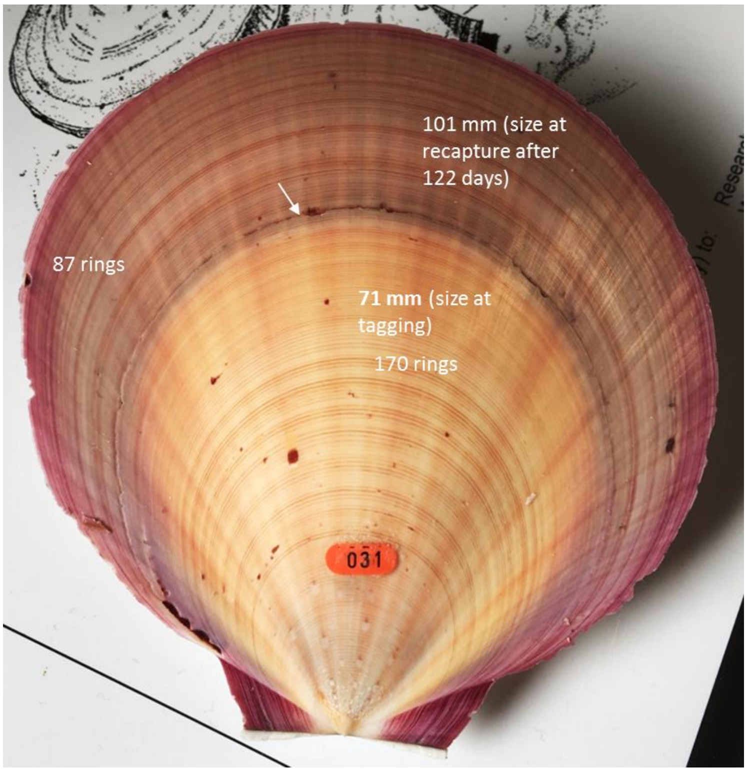

Figure 41. Image of a recaptured tagged scallop (031) from the control site in July 2017. Trawl scarring during initial capture is indicated by arrow.

6. Discussion

6.1 Recruitment dynamics of *Y. balloti*

6.1.1 South Coast and Rottnest Island

For the two most southern scallop stocks in WA, spawning was constricted to the summer months between October and March when mean water temperatures increase from 17 to 23 °C. Juveniles grow and mature in the following autumn/winter months and undertake their first spawning over the following summer when they are approximately 70 - 80 mm SH. This post-spawned adult cohort are then commercially harvested during the following year when they are approximately 12-18 months old and range between 90 and 120 mm SH (Figure 42). Factors influencing spawning success, larval retention/drift, growth and settlement are then largely related to the summer environmental conditions. The current systems impacting these shallow inner shelf waters during the summer period are driven by local wind forcing rather than the dominant LC which is usually weaker and its position further offshore during the summer months, the exception being the 2010-12 La Niña event and 2011 MHW.

On the SC, passive state drifting larvae is likely transported in a north westerly direction (driven by southerlies and easterlies) alongshore where geographical barriers such as embayments and lee of islands (eg. Israelite Bay, Doubtful Island and Cheynes Beach) promote larval entrapment and induce settlement. At RI, the main fishing grounds for scallops lies to the north of the island in the passage along the 20-40 m depth range off the Perth coastline. RI lies on the edge of the Perth canyon, and in the absence of any large embayments, the shallow inner shelf slope may act as a topographical barrier to encourage larval retention and settlement. The summer wind regime at RI is dominated by southerlies which can create cross-shelf oceanographic processes such as localised eddies, upwelling events and an offshore near-surface Ekman transport of equal current strength (Pearce & Hutchins 2009). Therefore, larvae can be transported offshore or onshore depending on its position in the water column. Patchy settlements of scallop aggregations which periodically occur all the way down to Geographe Bay further suggests localised currents play a crucial role in larval dispersal. The low and highly variable productivity of this stock also reflects the dynamic coastal oceanography in this region.

For the SC stock, summer water temperatures during the spawning and juvenile phase of the parental stock and winter temperatures during the juvenile phase of the harvested cohort explained approximately 43% of recruitment variability. Both these relationships show higher recruitment associated with warmer than average temperatures for this coastline. As a tropical species, *Y. balloti* is likely to thrive in warmer temperatures ≥ 18 °C where improved growth and maturation is likely to increase survival and overall condition as they become adults. The extended southern range of *Y. balloti* along the WA coastline compared to the east coast of Australia (as far south as Moreton Bay) has been attributed to the warming influence of the LC (Lenanton et al. 1991). Along the SC, the LC travels eastwards and meanders on and off the continental shelf and diverted out to sea around cyclonic eddies (Cresswell & Domingues 2009). Its influence may be reduced at shallower depths closer to the coast except during strong La Niña years where it can potentially move further inshore. Both MHWs resulted in the water temperatures along the SC to be elevated by 1°C between March and August and these events were responsible for the warmest winters during 1999 and 2011-12. These warmer temperatures likely contributed to the SCTF producing its highest scallop catch on record during 2000 (544 t) and above average catches between 2013-15 (51-87 t).

A slightly extended summer spawning period for RI scallops compared to SC, but no significant environmental drivers of recruitment were identified in this study. Neither MHWs appear to have adversely or positively impacted on catches with the highest catch landings during 1987, 1990 and 2010 are not associated with any significant periods of water temperatures or wind patterns. Productivity at RI is the lowest across all of the regions and this is likely due to limited habitat, greater flushing and/or limited retention from other oceanographic factors such as inshore currents not considered in this study. However, a significant stock-recruitment relationship was established for this fishery which suggests that maintaining a level of spawning stock is still important to enhance recruitment when favourable environmental conditions do occur.

The stock-recruitment relationship for the SC was not significant. Accurate assessment of spawning stock is difficult for this fishery given the large expanse of coastline that needs to be assessed and commercial catch data as a proxy for spawning stock may not be ideal as its often confounded by fishing effort and other operational factors. Average catch landings during 2016 and no fishing during 2017 was due to low abundance from poor recruitment. This is likely associated with well below average winter temperatures from the strong 2016 El-Niño event and subsequent years of average to cooler than average winter SSTs.

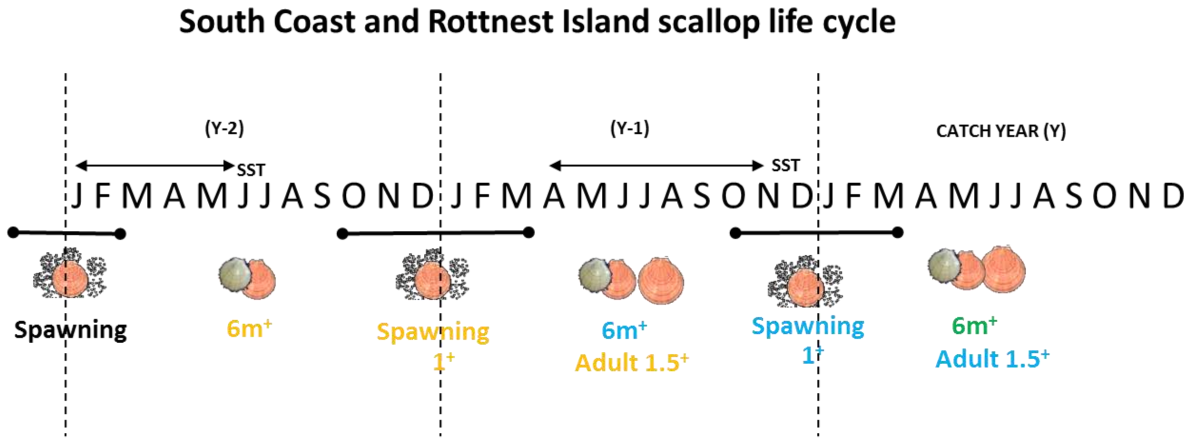

Figure 42. Life cycle diagram of *Y. balloti* along the South Coast and at Rottnest Island. Spawning over the summer months gives rise to recruits that grow and mature over the following 12 months and enter their first spawning event by the following summer. Post-spawned adults are then commercial targeted the following year when they are 12-18 months old. Also indicated are the months of significant environmental correlations for the SC population.

6.1.2 Abrolhos Islands

The peak spawning period at the AI extends into spring with spawning occurring from September through to March. Majority of scallops were in pre-spawning gonad developmental stage during November followed by spent and immature scallop stages detected during February. The spring/summer water temperatures at the AI currently ranges from 20 – 24 °C and the area is protected from the peak strength of the LC which usually strengthens from March onwards after the settlement of scallops has taken place. The exception being the summer of 2010/11 when the LC unseasonably flowed at record strength over the summer months. Despite the stock collapse after the 2011 MHW, no significant environmental correlations with summer months were identified from this study. Spawning biomass and winter water temperatures explained 58% of the recruitment variability which did identify low recruitment in 2011 and 1999 associated with the warmest winter years from the 2011 and 1999 MHWs. After the 1999 MHW, there were no significant decline to the spawning stock. Low recruitment levels continued into 2001 and higher recruitment levels returned as winter SSTs

dropped below 23°C. However, after 2011 MHW, a progressive decline in stock abundance and lack of recovery and recruitment was observed between 2012 and 2015.

During the 2011 MHW, AI was in the direct pathway of a very strong and warm LC. Water temperatures until January remained below 24°C which may have allowed some successful early season spawning to occur. Water temperatures further increased to 27 °C in the following months, likely above the physiological tolerance threshold for spat and juveniles and inducing a state of thermal stress for the remaining spawning adult scallops. Apparent low survival of larvae and juveniles resulted in only the surviving adult stock contributing to the low catches during 2011. Recruitment impairment and probable mortality of adults can be inferred from the significant stock decline during the November 2011 and subsequent low abundance in the following years. The 2010-2012 La Niña event kept water SSTs warmer than average for several years. The very low spawning stock years coincided with the warmest summer temperatures (2011-13) and so by omitting these years in the correlation analyses, the peak summer spawning months were not identified as being significant to recruitment. The inclusion of these years did however show December to January SSTs being significant.

Similar to SC, juveniles recruiting from the summer spawning enter their early growth and maturation life stage over the autumn/winter months and reach sexual maturity from 50 mm SH onwards and undertaking their first spawning event in the summer months that follow. Annual November surveys usually detects a single cohort of scallops between 60 and 110 mm SH size range (Figure 43). During this period, the south-flowing LC moves further onto the continental shelf and flooding the AI with warm, nutrient rich waters that is likely to enhance growth and development of juveniles over the winter months (Koslow et al. 2008). Previous studies have suggested that cooler SSTs associated with weaker LC being necessary for good recruitment (Lenanton et al. 2009, Joll and Caputi 1995b) and this is supported by the current study which identified mean water temperatures between March and June as a driver of recruitment as long as sufficient spawning stock was available.

The circulation patterns in the AI are complex and considered responsible for the triangular evolution of the Pelsaert and Easter Group Islands (Wells 1997). The formation and elevation of reefs and islands both above and below sea level essentially trap larvae from being flushed through the channels which are created by the cross-shore currents and to some extent the northward moving Capes Current (Maslin 2005). During the summer months, the prevailing southerly winds induce a northerly wind stress which in turn is forced to the left at the surface, under the influence of the Coriolis force, creating a predominantly westerly current pattern in the channels between the island groups. This creates vertical mixing and the transport of passive particles such as planktonic larvae to move down the water column. The circulation pattern near the bottom is largely channel-centric where particles are likely to be retained within the system for periods of time (Maslin 2005).

The importance of these wind-driven hydrodynamics on scallop recruitment was not explored in this study due to its complexity. These small scale hydrodynamic processes may play a critical role in the larval settlement distribution across the islands groups that are highly variable year to year. For example, a genetic study of the scallops within one area over two years indicated different source populations in each year (Puslednik, *pers. comm*).

Generally, the most productive scallop fishing grounds are the Pelsaert group where settlement is more consistent but scallop density can vary significantly from 239 to 7497 scallops/nm. Successful recruitment at the Easter and Wallabi groups are more annually variable and overall

the area is less productive. It is plausible that some recruitment in the northern island groups are from larvae originating from the Pelsaert group where the largest concentrations and catch rates of scallops are usually found.

Since the 2011 MHW, an additional FIS during February (and sometimes in March) has been established within the stock monitoring program at the AI. The February survey provides an additional index of early 0+ recruitment (30 – 70 mm SH) and serves to provide any early signal of stock abundance following the summer spawning period. Since 2016, both summer and winter temperatures have been cooler than average which has likely enhanced stock recovery and improved the strength of subsequent recruitment events. The AI commercial fishery re-opened in May 2017 with a catch of 130 t but this dropped to a below average catch of 30 t during 2018. The catch forecast for 2019 is expected to be 150-200 t. based on the November 2018 survey. Recruitment levels during February 2019 has been one of the highest on record and this will be fished in 2020.

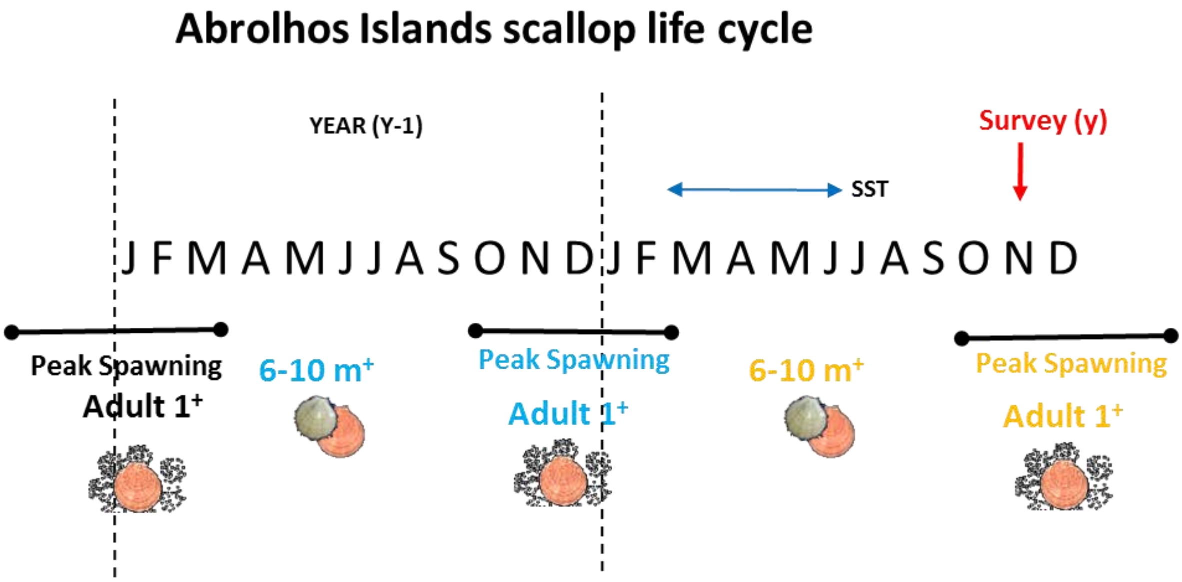

Figure 43. Life cycle diagram of *Y. balloti* along the Abrolhos Islands. Peak spawning between September and March gives rise to recruits that grow and mature over the following 12 months and enter their first spawning event by the following spring/summer. Post spawned adults are then commercial targeted the following year when they are 12-18 months old. Also indicated are the months of significant environmental correlations for the AI population.

6.1.3 Denham Sound and northern Shark Bay

In Shark Bay the peak spawning period moves away from the spring/summer months as observed at the AI and towards the autumn/winter months when water temperatures start to cool down. Denham Sound scallops showed a slightly extended spawning period from as early as February/March (Figure 17), although the peak spawning period was towards July/August in line with the peak spawning by NSB scallops (Figure 44, Figure 45). A number of observations of partially spent gonad condition confirmed that *Y. balloti* was capable of extending their reproductive output through multiple spawning events. The annual November FIS surveys often show recruits ranging from 30 - 80 mm SH (3-10 months old) and consisting of two 0+ cohorts of variable strength year to year (Figure 46, Figure 47). These recruits grow into a single cohort by February/March the following year when they are sexually mature and ready to enter their first spawning.

The SRE relationship for the DS scallop stock indicated spawning stock, winter SSTs and the southerly wind stress to all contribute fairly evenly (approximately 30% each) to the recruitment variation of the population. However, none of these variables were significant for the NSB stock where the only significant variable contributing to recruitment was the summer SSTs between October and January. This may seem unusual given these two stocks occur in close proximity inside the same Bay region experiencing similar environmental conditions. The circulation of SB is strongly influenced by wind and tidal regimes that impact this region while also being influenced by the seasonal intrusions of the LC and Capes Current at the channel entrances. Hydrodynamic modelling of Shark Bay demonstrated the presence of a hydrodynamic barrier between DS and NSB which allowed only up to 5% larval dispersal between these regions (Hetzel et al. 2015). Therefore, similar to our findings at AI, RI and SC, the influence of local-regional scale oceanographic processors is the key to understanding recruitment dynamics.

Mean autumn SSTs between April and August was negatively correlated with recruitment 3 - 6 months later in the same year in DS where mean SSTs below 23.5°C were associated with higher recruitment events. Larval rearing experiments for *Y. balloti* had showed that 18°C supported the highest larval survival over other water temperatures tested and that larvae could not survive at 24°C and above (Wang 2007). The same study showed larval growth being restricted at lower water temperatures of 14 -18°C but improved at and above 20°C. Therefore, the optimal water temperatures for larval growth and survival is between 18 - 20°C for *Y. balloti* (Wang 2007). The peak of the 1999 MHW and the tail end of the 2011 MHW were directly in line with the spawning period in Shark Bay, thus a significant level of larval mortality is likely to have occurred when SSTs breached the optimal thermal range for larval survival. In general, DS experiences slightly warmer winter SSTs from the surface intrusions of the LC compared to NSB scallops that are further away from the channel entrances and towards the central regions of the Bay (Figure 48a). During both MHWs, the mean winter SSTs experienced by NSB scallops were slightly cooler than experienced by DS scallops (Figure 48b). For example, NSB had a mean winter SST of 24.4°C during 1999 and 23.1°C during 2011 while DS experienced 24.7°C and 23.6°C respectively. This may explain why winter SSTs were not identified as a significant period associated with recruitment for NSB scallops but they were for DS.

The strengthening of the LC during the winter spawning period has a two-fold impact on the larval dynamics inside SB. In addition to raising the water temperatures through the intrusions of the warmer LC, it also influences larval flushing dynamics depending on the position of the larvae in the water column. Hydrodynamic modelling of SB suggests larvae in the upper water column during the winter spawning period were much less likely to be flushed from the Bay as the circulation tended to cause them to converge in the middle of the Bay from the push-back of the incoming LC and through the relaxation of the southerly winds (Hetzel et al. 2015). However, larvae on the bottom layer of the water column were transported out of the Bay at a much faster rate from density driven bottom outflow currents, and especially near the channel entrances. Therefore, larvae from DS are more likely to be flushed outside through bottom outflows due to their closer proximity to the channel entrance, which may explain why DS has historically experienced more years of low to below average recruitment events than NSB.

The importance of the summer water temperatures for recruitment was only identified for the NSB scallop stock where mean summer SSTs between December and January explained 25% of recruitment variability. Mean SSTs greater than 25°C were associated with the 2011 MHW and the extended La Niña event. Satellite imagery shows the intrusions of the northward

flowing inshore Capes Current driven by strong southerlies over the summer months. The influence of the cooler surface water appears to be greater inside DS although it does extend further inside the Bay (Figure 49a). The intrusion of cooler water through the Naturaliste Channel may also explain why DS generally experiences slightly cooler summer SSTs than NSB (Figure 49b) and therefore the slightly extended spawning period observed for DS scallops which is not apparent in NSB.

The thermal tolerance range for juvenile and adult scallops in WA is not fully tested, however *Y. balloti* in Queensland are able to tolerate and thrive in summer water temperatures up to 27°C (Courtney et al. 2015). The recruitment failure of both NSB and DS stocks after the summer 2011 MHW and not after the winter 1999 MHW suggests that water temperatures up to 29°C had caused some degree of irreversible thermal stress leading to mortality. Otter trawl sampling requires scallops to be swimming within the water column to be captured, therefore dead scallops cannot be captured using trawl gear. So we rely on the index of juvenile recruits and adult abundances from our FIS to infer survival and larval retention rates. The significant and widespread decline in all sized scallops from November 2010 to 2011is therefore indicative of a significant mortality event.

In addition to water temperatures, DS scallops were also positively correlated with the southerly wind stress between September and November. This period is associated with the juvenile phase. The reason for this unexpected relationship requires further assessment and verification with more years of data. Hetzel et al. (2015) reported on the positive relationship between high recruitment years and strong southerlies during winter and hypothesised that stronger southerly winds could limit hydrodynamic flushing by acting against the formation of stratification needed for the development of density (gravity) driven outflows in Shark Bay. Furthermore, increased wind stress creates greater mixing of the water column which may provide greater accessibility of nutrients, phytoplankton and detritus to be available in the water column as a food source for juvenile scallops. Variability and seasonality in food source for scallops is poorly understood for *Y. balloti*. Juvenile scallops grow rapidly within the first 12 months to reach sexual maturity, therefore food quality and/or availability must also play a crucial role in their development in addition to environmental conditions.

Lack of hydrodynamic connectivity between DS and NSB suggests there two stocks are essentially self-seeding populations that require a certain level of spawning stock to ensure successful recruitment. While spawning stock was a significant contributing factor for recruitment of DS and AI stocks, it was not a significant driver of recruitment for the NSB stock. Prior to the 2011 MHW, the NSB stock had been the most productive in WA and the only stock that had not experienced significantly low spawning stock levels since FIS began in the 80s. Therefore, for this stock, it’s resilience to recover from low spawning levels had not been previously tested or observed. There is currently a number of uncertainties regarding the NSB stock largely arising from its ongoing poor recovery, despite spawning stock levels within the historical range and summer SSTs within the optimal range. November 2017 FIS results signaled a level of recovery but this did not flow through to expected harvests even though we set conservative TACCs on expected levels. Subsequently the February and June 2019 FIS results indicated low survival of scallops measured in November. This suggests other factors are impeding stock recovery as the stock was protected from harvest between 2012-2015. Between 2014 and 2016, a notable reduction of 1+ scallops (Figure 47) from November surveys seemed to suggest poor survival and/or growth of recruits into adults. A preliminary health condition screening of scallops in Shark Bay in early 2019 indicated greater prevalence of parasitic and bacterial infestations of NSB scallops compared to DS scallops (*unpub. data*).

Poor condition of scallops is either indicative of nutritional and/or physiological stress and further investigations are needed to understand the causal mechanisms for these observations. Shark Bay itself is also experiencing "atypical" environmental conditions with shifts in seasonal temperatures and wind patterns due to climate change impacts on this region (NESP 2018). As the northern end of its range distribution, recruitment dynamics of this stock may now be more vulnerable.

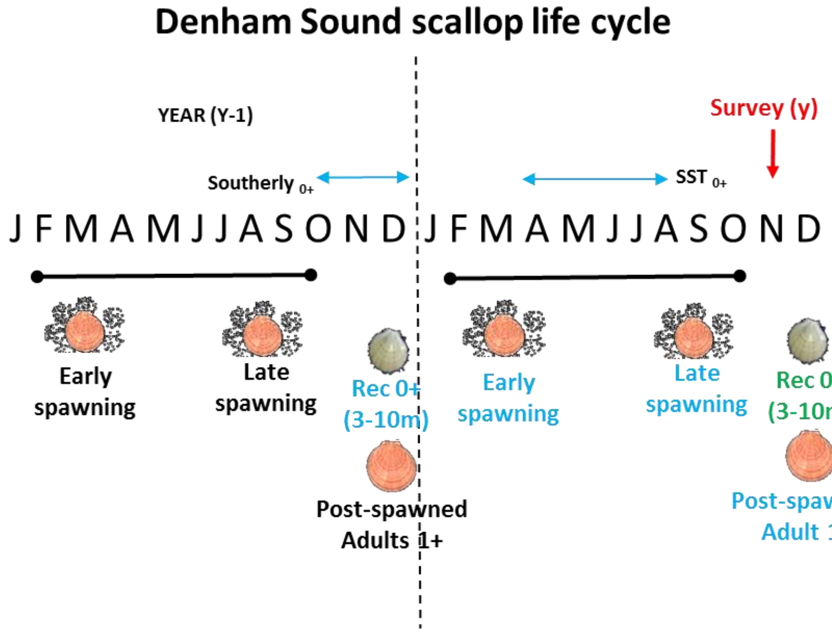

Figure 44. Life cycle diagram of *Y. balloti* in Denham Sound. An extended spawning period with an early peak around March and a late peak around August. Recruits range from 3 – 10 months old when sampled in November. Juveniles grow and mature over the following summer months and enter their first spawning event in the following year. Commercial fishing target a small proportion of pre-spawned scallops with majority of harvest targeting post spawned adults that are 12-18 months old. Also indicated are the months of significant environmental correlations for the DS population.

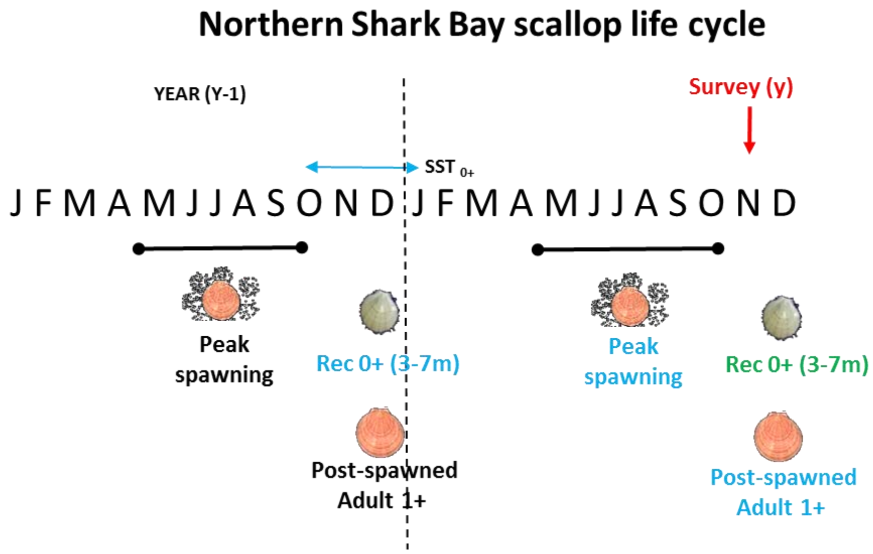

Figure 45. Life cycle diagram of *Y. balloti* in Northern Shark Bay. Peak spawning period between April and October with recruits ranging from 3 – 7 months old when sampled in November. Juveniles grow and mature over the following summer months and enter their first spawning event in the following year. Commercial fishing target a small proportion of pre-spawned scallops with majority of harvest targeting post spawned adults that are 12-18 months old. Also indicated are the months of significant environmental correlations for the NSB population.

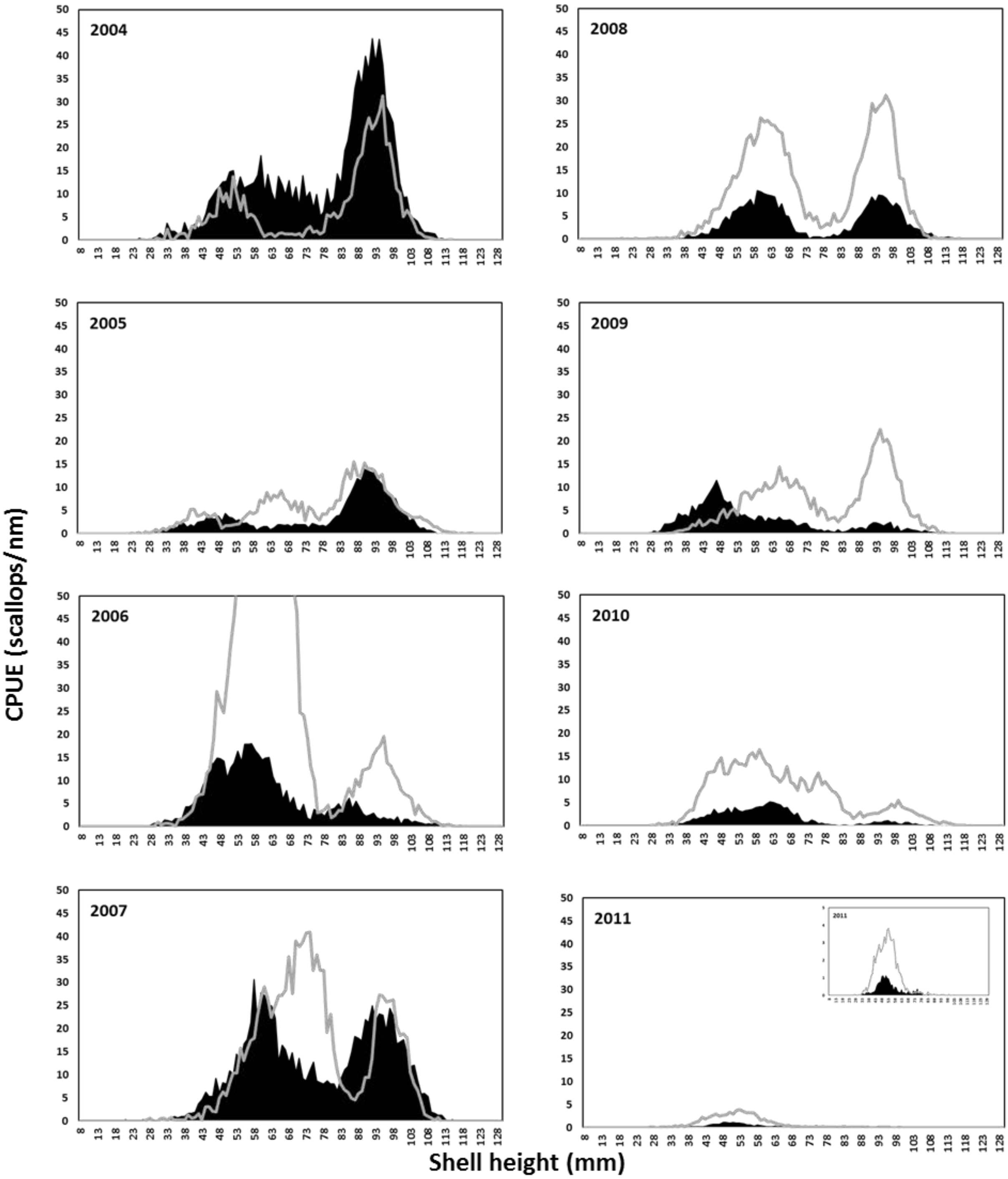

Figure 46. Length frequency of DS (solid black) and NSB (grey line) scallops during annual November FIS between 2004 and 2011. Inserts of magnified LFs are included for some years.

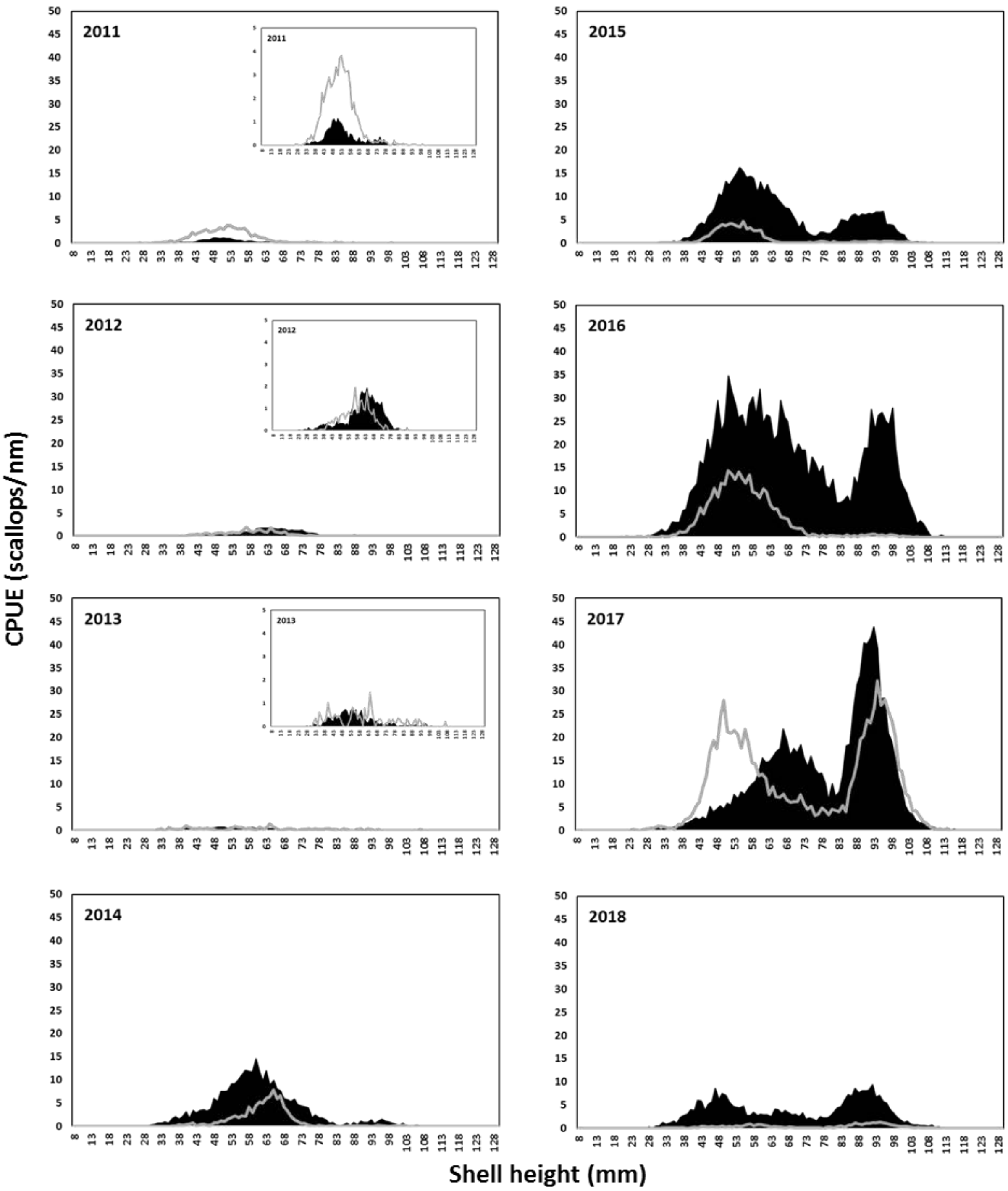

Figure 47. Length frequency of DS (solid black) and NSB (grey line) scallops during annual November FIS between 2005 and 2018. Inserts of magnified LFs are included for some years.

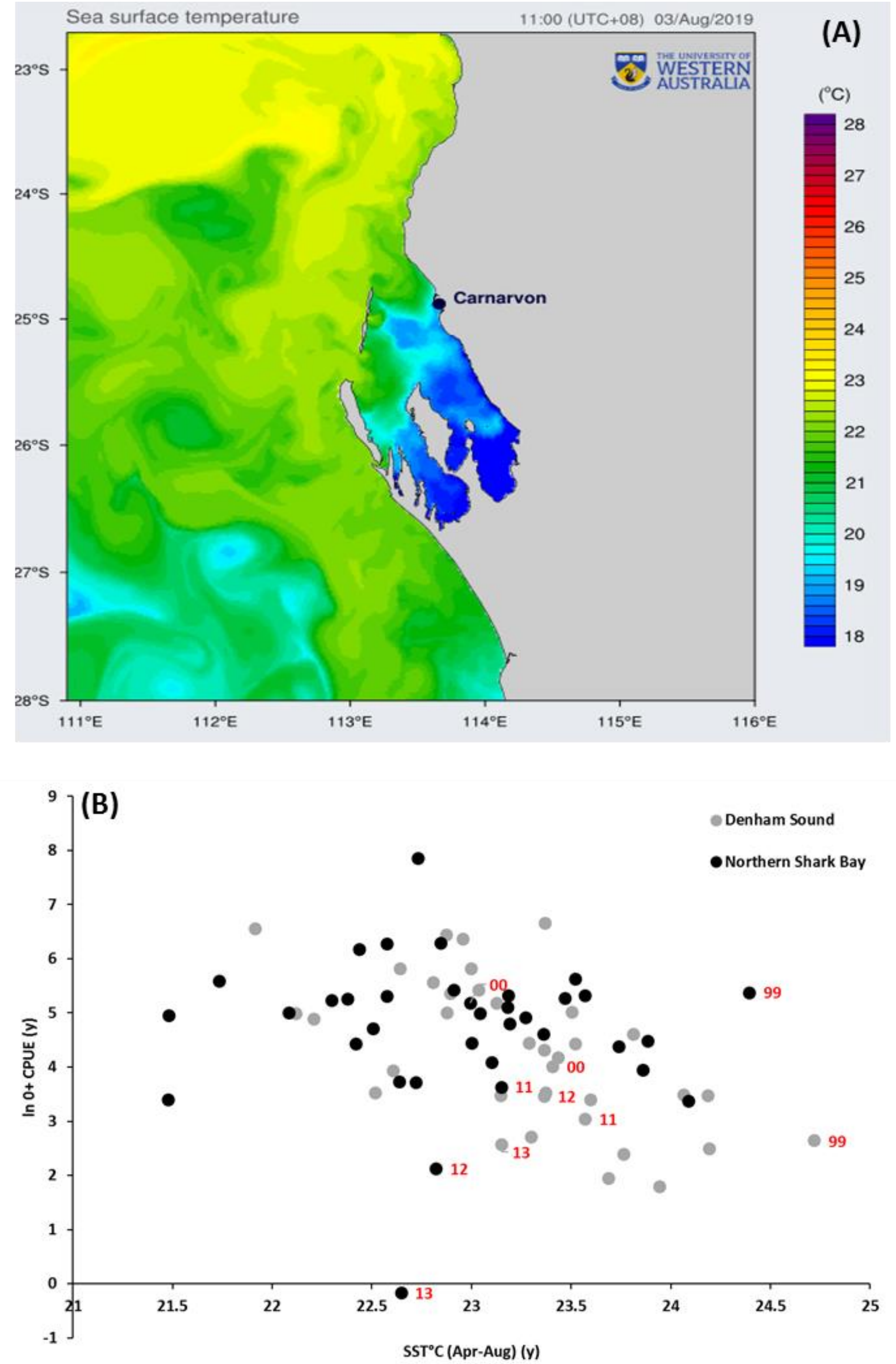

Figure 48. (A) Simulated SST map of the ocean conditions during August 2019 showing the warmer SST signature of the southward flowing LC intrusions at the channel entrances of Shark Bay (B) Relationship between log-transformed annual 0+ recruitment catch rate (log transformed) during November (year, y) and mean winter SST (Apr-Aug) (y) of NSB and DS stocks. Labels are shown for the survey years associated with the 1999 and 2011 MHWs.

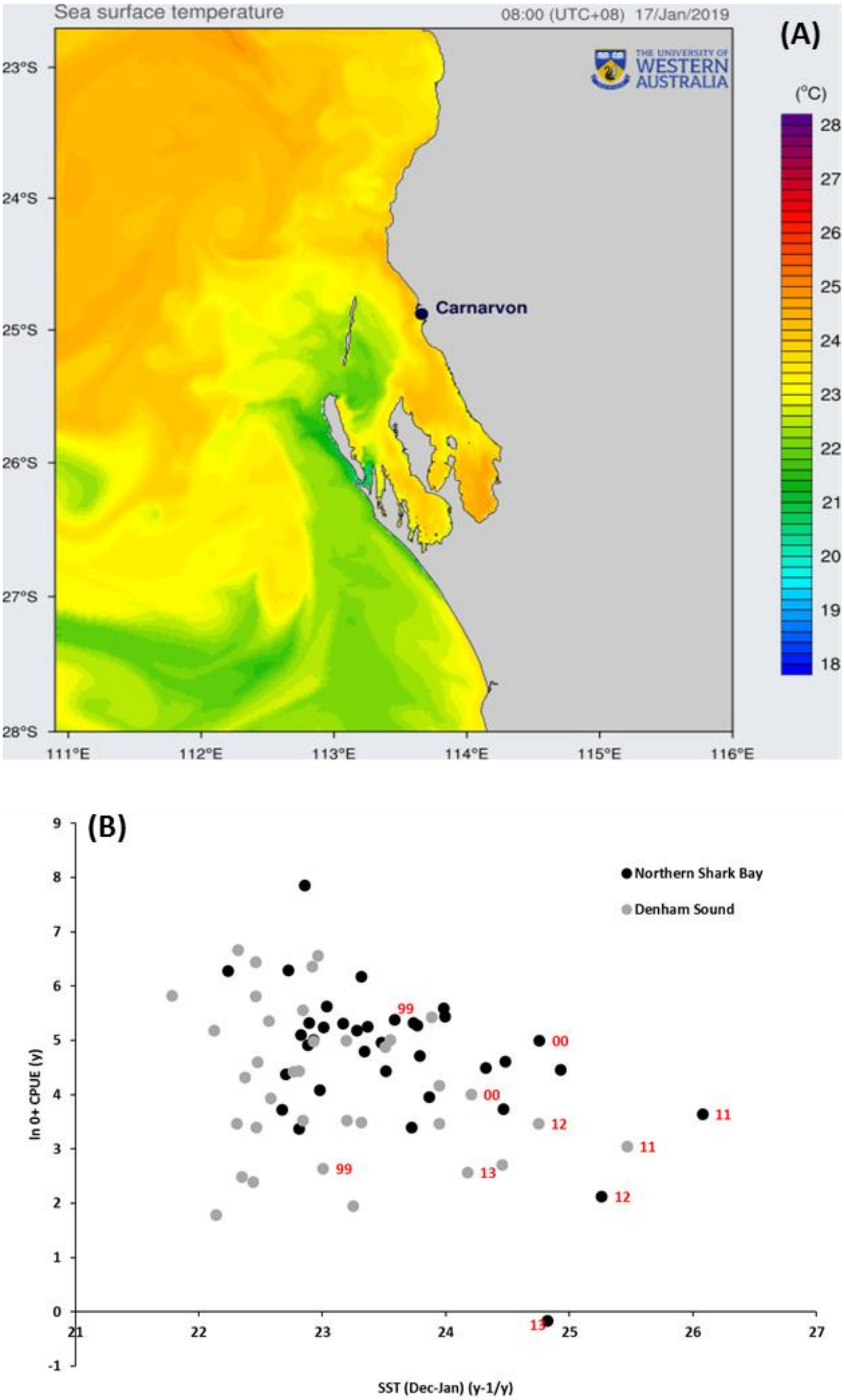

Figure 49. (A) Simulated SST map of the ocean conditions during January 2019 showing the cooler SST signature of the northward flowing CC intruding through the bottom channel entrance of Shark Bay. (B) Relationship between log-transformed annual 0+ recruitment catch rate (log transformed) during November (year y) and mean summer SST (Dec-Jan) (y-1/y) of NSB and DS stocks. Labels are shown for the survey years associated with the 1999 and 2011 MHWs.

6.1.4 Feasibility of assisted recovery measures

An objective of this study was to assess the feasibility of assisted recovery measures as a fisheries management tool to enhance local populations after stock collapses and/or recruitment failures from environmental perturbation. The first phase of this study was to examine the feasibility of producing robust larvae and juveniles which could be released to enhance the scallop spawning stock.

The hatchery facility was able to maintain live and feeding scallops and several feed and sediment trials were conducted to determine under which conditions adult scallops could be maintained in good condition. Immature scallops were also kept for 3-6 months and these developed into mature scallops with ripe gonads. However, when these individuals were spawned, their progeny were not robust and died within 15 days. The experiment was repeated with the resultant larvae again suffering high mortality within 2 weeks (DPIRD 2016, unpublished). Therefore, although the trials indicated an ability at a macro-level (i.e. in vivo) to condition non-mature scallops to maturity, they were presumably not healthy enough to produce viable offspring and their larvae were susceptible to high mortality. Non-optimal rearing conditions may have also contributed to poor larval survival.

Various attempts to transport mature females indicated that they were highly sensitive to transport and temperature fluctuations and they can either spawn prematurely and/or suffer high mortality during transport. Five transport trials were undertaken of mature scallops from Shark Bay to the Perth hatchery facility. Low mortality was experienced on two occasions while the other three trials resulted in all or the majority of scallops dying. The two successful transport trials were also different in that one involved transporting scallops in a circulating tank on the RV Naturaliste (3 days) from Shark Bay to Fremantle and then by car (45 minutes) to the hatchery facility. The second trial involved packing scallops in foam eskies (out of water) with ice packs and flying from Carnarvon to Perth (2 hours) and then by car (45 minutes) to the hatchery facility. These individuals were used in the feeding and substrate trials and the first conditioning experiment.

The three unsuccessful transport trials were due to i) high temperatures experienced before transport in Carnarvon and all scallops died ii) scallops were driven from Carnarvon to Hillarys (9 hours) and whilst on-route they spawned and died due to low oxygen levels in the containers, iii) scallops were packed in foam eskies and ice (as in the previously successful trial) and flown from Carnarvon to Perth but the majority of scallops died.

Due to these challenges, further transport trials of mature scallops from Shark Bay to Perth were discontinued and instead brood stock of mature females were sourced from the RI population, the closest scallop fishery to the Perth hatchery facility with only a 45-minute transport time from the harbor to the hatchery facility. However, due to very low stock levels during the study period, insufficient scallops were able to be sourced on any one sampling trip to complete rigorous experiments. Seven trips were made to source sufficient mature scallops without success.

The second phase of this project was to examine the feasibility of translocation of juvenile/sub-adults for stock enhancement and/or as a supplementary fisheries management tool. Initially, translocating scallops from RI to the AI were under consideration but due to continued low stock abundance this was not pursued. Consideration for moving scallops from the recovering Shark Bay stocks was also made, however, given the previous logistical challenges involved

in the hatchery rearing component and low probability of survival of a larger scale transport of scallops this was also discounted. Therefore, a decision was made to translocate scallops from high abundance areas within the AI to areas of lower abundance within the AI. The trial therefore only enabled a general assessment of feasibility of a short-distance translocation of juvenile scallops within a fishery. At the AI there was spatial disparity in stock recoveries and settlement between the island groups. The trial at the AI in March 2017 began at the time of natural stock recovery in the wild fishery being detected in some areas of the stock, after four years of poor recruitment and low stock abundance.

The results of the pilot translocation study in the AI indicated that, although it yielded poor recapture rates, given the scale of the project and limited post-release sampling, the tagged scallops that were recovered showed good post-release survival and growth rates that were comparable to the control site.

Attempts at spawning of *Y. balloti* from wild brood stock in a hatchery environment has been successful in previous enhancement projects both in Western Australia and Queensland, but rearing of larvae to settlement and beyond has been more challenging with little success (O'Brien 2005). Translocation of wild populations for stock enhancement purposes has not been attempted with *Y. balloti* and although the scale of the operation attempted in this study was small, the positive results do highlight its potential. What remains unknown and to some extent untested is the potential of translocation to enhance natural recruitment. The stock-recruitment relationships determined from this study provides guidelines for minimal spawning stock levels for successful recruitment, therefore translocation of spawning stock may still hold some promise when all other conditions are met. Secondly, given the climate shifts occurring on the WA coast with a warming trend on the SC, strategic consideration could be given to potentially translocating scallops to the SC to increase their population size which may improve frequency of higher recruitment events in that region.

6.1.5 Climate change impacts on scallop productivity in WA

In assessing the key drivers of scallop recruitment for the five WA *Y. balloti* populations, water temperature appears to be a key driver influencing recruitment dynamics and one that is impacted by climate change. Decadal trends in seasonal SSTs across all regions is showing a greater warming of the summer months in the recent decade (2010-present) compared to the previous three decades, despite the recent cooling trend since 2016.

On the SC, water temperatures are showing a warming trend across all the months of the year. Warmer winter and summer SSTs are positively associated with scallop recruitment on the SC with positive recruitment pulses associated with warm water spikes associated with La Niña events and MHW events. While this may suggest an increase in the productivity of the SCTF fishery into the future based on changes in water temperature alone, we need to be cautious in our limited understanding of the remaining factors that influence recruitment that were not identified in this study. There were no significant correlations with SST at RI so it is not clear what effect climate change may have on this stock. Also our poor understanding of the local oceanographic processes means there is greater uncertainty in the likely trend in scallop productivity in the future. RI appears to be the transition area for scallops between the cooler SC area which has a positive relationship with SST and the warmer AI which shows a negative relationship with SST.

For the northern scallop stocks which have suffered and recovered from recruitment failures, the lessons learned after the 2011 MHW have been valuable in the future management of these stocks. From this study we have learned that when mean winter SSTs exceed 23° C, there is a higher likelihood of below-average recruitment. Warmer winter SSTs are associated with mild to moderate La Niña events, while strong La Niña events can cause MHW conditions. The Bureau of Meteorology (BOM 2019b) provides ENSO forecasting which is now regularly reviewed prior to and during the scallop fishing in WA. Therefore, with further development of stock-recruitment-environment models, the capacity to act early to reduce fishing pressure ahead of catastrophic events may be possible. Increased stock monitoring alongside environmental monitoring is the key to ensuring early management interventions are implemented to protect remaining spawning stock.

7. Conclusions

Factors impacting scallop recruitment variability are complex and the specific environmental/habitat data series for scallop regions are limited. In addition, there is a paucity of detailed modelling of hydrodynamic processes post-heatwave. Regional oceanographic processes driven by tides, currents, and winds transport larvae away from their spawning grounds. The larval period is approximately two weeks during which time water temperatures play a critical role in terms of its larval survival and growth while geographical barriers enable larval entrapment and settlement. Recruit and adult scallops occupy the same spatial benthic habitat in all five regions along the WA coast. Therefore, recruitment variability is primarily dependent on the biophysical processes that retain larvae within the self-populating spawning grounds. Population structure evaluation of WA scallop stocks in 2015, undertaken to support decision making in any future translocation applications indicated that there was genetic variability between scallops from all five regions but they were not distinct populations. The genetic analysis separated the five scallop stocks into three clusters with NSB, DS and AI belonging to a northern cluster and a southern cluster encompassing RI and SC. A third cluster which was predominately represented by RI shared equal number of genetic markers with both northern and southern clusters. The cluster representations largely arose from the geographical distances and ecological barriers between these scallop stocks but they were not significant enough to show the five managed stocks as being distinct populations (*unpub. data*).

In this study we found seasonal water temperatures, wind strength and direction, the ENSO cycle, ocean currents and geographical barriers as important factors influencing recruitment of *Y. balloti* in WA. A number of these factors and/or the level of spawning stock was shown to account for more than 50% recruitment variability in the scallop stocks within WA (Table 2). However, these factors were not consistent between fisheries due to differences in how these environmental drivers influence the specific geographical location of scallops. A key stock-environment relationship across all stocks were associated with winter and/or summer water temperatures. Water temperature appear to play a crucial role in the timing of the spawning and the length of the spawning period. In general, positive and above average recruitment years were associated with an optimal water temperature range between 18 and 23 °C and below average recruitment associated with temperatures below or above this thermal range. Water temperatures are highly influenced by the ENSO cycle where strong and extended La Niña events have led to two MHWs. The timing, duration and intensity of MHWs are also important considerations when assessing their impact on scallop recruitment.

Ylistrum balloti at their most southern range distribution on the SC experienced positive recruitment events after both MHWs while scallops at their northern range distribution in Shark Bay suffered catastrophic recruitment and stock declines. Assisted recovery strategies has

shown limited potential through this and pilot phase study, however improved hatchery protocols and technological advancements may allow for greater successful scallop stock enhancement in future and the efficacy of translocation of scallops to increase breeding stock was not fully tested.

The WA coastline is a climate change hotspot (Hobday and Pecl. 2013) and therefore the trends documented in this report highlight the need to consider climate change in management, fishery harvest strategies and for reviewing collection of long-term data sets (both fishery dependent and independent) in order to be able to fully evaluate stock status and likely production trends in these fisheries. Both stock abundance, commercial catch and effort (catch rates) and size (and quality) composition monitoring will continue to be important alongside environmental monitoring to enable adaptive management of these stocks.

Table 2. Summary of key findings, relationships and stock status of the five scallop stocks in WA.

	Spawning Period	MHWs impact (strong La Niña events)	Recruitment-Environment Relationship	Stock-Recruitment-Environment Relationship	Stock status
Northern Shark Bay	Peak Jun-Oct	Negative Below average recruitment when SST(Dec-Jan) > 24 °C	Summer SST explained 25% of recruitment variability $lnRecruitment_{(y)} = -0.81\ SST\ (Dec\text{-}Jan)_{(y-1/y)} + 23.8$	Spawning stock not significant	**Stock under recovery**
Denham Sound	Summer/ Winter Feb-Oct	Negative Below average recruitment when SST(Apr-Aug) > 23.5°C and weak Southerlies (Sep-Nov)	Winter SST and Northing explained 57% of recruitment variability $LnRecruitment(0+)_{(y)} = -1.16\ SST\ (Apr\text{-}Aug)_{(y)} + 0.19\ Northing\ (Sep\text{-}Nov)_{(y-1)} + 22.59$	Spawning stock explained 17% of recruitment variability $LnRecruitment_{(y)} = 0.25\ lnSpawning_{(y-1)} - 0.88\ SST\ (Apr\text{-}Aug)_{(y)} + 0.18\ Northing(Sep\text{-}Nov)_{(y-1)} + 15.41$	**3-4 years of recovery**
Abrolhos Islands	Peak Oct-Feb	Negative Below average recruitment when SST(Mar-Jun) > 23 °C	Winter SST explained 17% of recruitment variability $lnRecruitmentCPUE_{(y)} = -0.46\ SST\ (Mar\text{-}Jun)_{(y)} + 17.7$	Spawning stock explained 45% of recruitment variability $lnRecruitmentCPUE_{(y)} = 0.72\ lnSpawningCPUE_{(y-1)} - 1.7\ SST\ (Mar\text{-}Jun)_{(y)} + 41.44$	**5 years of recovery**
Rottnest Island	Summer Nov-Mar	No impact detected	No Significant drivers	Spawning stock explained 45% of recruitment variability $lnCatch_{(y)} = 0.67\ lnCatch_{(y-1)} + 0.36$	
South Coast	Summer Dec-Feb	Positive Above average catches when SST(Apr-Nov) > 18 °C and SST (Jan-May) > 20 °C	Summer and winter SST explained 43% of recruitment variability $lnCatch_{(y)} = 2.21\ SST\ (Apr\text{-}Nov)_{(y-1)} + 1.02\ SST\ (Jan\text{-}May)_{(y-2)} - 56.95$	Spawning stock not significant	

8. Implications

- The project clearly provides justification for close management of scallop stocks within WA and reinforces the need for regular monitoring and application of this information in managing scallop stocks. The Shark Bay fishery has adopted a mid-year review of the management measures to ensure proper management of the stocks.
- The project provides guidance into the existing research gaps to further improve our understanding of scallop recruitment variability and the likely trajectory of key environmental factors that may allow consideration of strategic/medium term management measures.

- The project has been able to identify several environmental factors that explain more than 50% of the variability in scallop recruitment, recognizing that the underlying mechanisms are not clearly known.
- The project outcomes highlight the need for protection of a component of the spawning stock in each fishery region with a clear correlation of the spawning stock size and environmental factors contributing to the variability in scallop recruitment. This information enables the development of limit reference points in the harvest strategies for these fisheries.
- The project has clearly identified that the environmental changes observed to date are not stable and continue to cycle or trend up or down and behave differently between regions. This knowledge has management implications as to considerations on what will constitute fishing grounds/region and 'individual fisheries' in the medium to longer term.
- Ongoing poor recovery of the Northern Shark Bay scallop stock highlights the need to assess changes to habitat, trophic-dynamics, scallop nutrition and health condition and the potential impact of cumulative trawl effort over scallop recruitment areas.

9. Recommendations

1. Continue regular environmental monitoring as a high priority and collaborate with climate scientists in terms of future projections to improve management of the scallop stocks in WA.
2. Incorporate Chl-a and salinity monitoring to the water sampling programs in SB and AI.
3. Maintain fishery independent sampling within the two major scallop fisheries (SBSMF and AIMWTMF) to enable monitoring both 0+ and 1+ individuals and compare with commercial spatial and temporal catch rate information. Discuss with industry the potential to develop fishery-independent surveys in the SCTF and SWTMF
4. Repeat the larval advection modelling that was completed as part of (FRDC 2007/051) to determine any changes in circulation patterns and outflows within Shark Bay, particularly in northern Shark Bay.
5. Conduct larval advection modelling in the other fishery regions to improve understanding of scallop settlement patterns and processes.
6. Develop additional harvest control rules based on improved understanding of stock-recruitment-relationships combined with current measurable environmental factors influencing scallop recruitment.
7. Conduct ongoing scallop health condition sampling and analyses within Shark Bay to assist with understanding the disconnect between stock recovery in DS and lack of recovery in NSB.

10. Further Development

Monitoring medium term changes in growth and reproduction i.e. every 5 years to detect responses to further climate change/productivity between regions. This should include regular health/condition sampling.

To improve larval advection modelling, a better understanding of the diurnal and temporal behavior of larvae so this could be incorporated into the existing or updated model.

Improved monitoring of carbon cycling/chlorophyll/habitats in Shark Bay may also provide a better understanding of the lack of recovery within northern Shark Bay compared to Denham Sound.

Translocation experiments could be expanded to provide further information on transport and release mortality, growth and survival. These could be conducted within one fishery or between adjacent fisheries.

Improving hatchery techniques would require a comprehensive dedicated program to overcome the numerous challenges observed in this project as well as those undertaken in the past.

Investigating non environmental impacts associated with trawling and discarding scallops and the contrasting trawling management strategies between DS and NSB to assist with understanding the variation in recovery of scallops stocks in Shark Bay.

11. Extension and Adoption

Results of the project have been presented at Departmental and industry Annual Management meetings and during the Shark Bay Scallop Working Group meetings throughout the project timeline. The results were presented at a Department's Internal Science Day held in March 2019, and an external science review in April 2019. Details of these meetings have been provided to FRDC in Milestone reports.

Results were also presented at a FRDC (FRDC projects 2017-048 and 057) scallop steering group meeting held in Brisbane in December 2018, at the 22nd Pectinid Workshop in Santiago de Compostela, Spain in April 2019 and most recently at the 2019 Australian Marine Science Association conference in Fremantle in July 2019. Some results have been published in Caputi et al. (2016, 2019),

As part of the pilot translocation experiment and genetic analysis of each of the stocks in WA, DPIRD developed of a Translocation Protocol for Ballot's saucer scallops within WA.

Project findings will be incorporated into management discussions with the scallop working group and AMMs for each fishery with a clear emphasis on spawning stock protection during periods of low abundance. These discussions will assist with setting annual management arrangements and the development of fishery specific harvest strategies.

12. Project materials developed

The project developed, through the hatchery component, a key for the identification of reproductive condition of scallops which can be easily used in field programs.

The results of the reproductive biology and environmental factors and examination of the SRER and management changes in Shark Bay will be published as 2 scientific papers.

13. Appendix 1 Staff and Co-investigators

This project contained Phase 1 and 2 (as described in Section 6.1.4) and initially commenced as a Pilot Project – funded by the DPIRD and the WA scallop industry prior to receipt of the FRDC funding. Most of this pilot project focused on the hatchery component in Objective 2 and collection of small scallops for ring counts.
Staff involved with the FRDC project:

- Dr Arani Chandrapavan, Research Scientist (DPIRD)
- Dr Mervi Kangas, Principal Research Scientist, PI, (DPIRD)
- Dr Nick Caputi, Senior Principal Research Scientist (DPIRD)

- Mr Dean Meredith, Technical Officer (DPIRD)
- Mr Nick Breheny, Technical Officer (DPIRD)

The co- investigators of the pilot project were:

- Dr Sagiv Kolkovski, Principal Research Scientist (DPIRD)
- Mr Patrick Cavalli, Principal Management Officer (DPIRD)
- Dr Michael Snow, Supervising Research Scientist (DPIRD)
- Mr Simon Ch'ng, Far West Scallops Pty. Ltd.
- Mr. Phil Bruce, Shark Bay Prawn Trawler Operators Association

14. Appendix 2 Intellectual Property

No intellectual property has been generated by this project.

15. Appendix 3 Scallop collections for ring counts

	No. of scallops read	Collection Date
Northern	16	Nov 2010
Shark	12	Mar 2011
Bay	28	Feb 2012
	50	Apr 2012
	13	Jun 2012
	14	Oct 2013
	3	Feb 2014
	9	Nov 2014
	4	Apr 2015
	79	Nov 2015
	13	Feb 2016
	6	Apr 2016
	11	Jun 2016
	8	Jul 2016
	36	Nov 2016
	2	Feb 2017
	6	Jun 2017
	11	Nov 2017
Denham	20	Sep2008
Sound	48	Nov 2012
	7	Nov 2013
	28	Aug 2014
	12	Nov 2014
	15	Nov 2015
	45	Jan 2016
	27	Feb 2016
	46	Jun 2016
	35	Aug 2016
	86	Nov 2016
	19	Feb 2017

	21	Jun 2017
	14	Nov 2017

Abrolhos Islands	14	Apr 2011
	5	Apr 2015
	36	Nov 2015
	7	Feb 2016
	27	May 2016
	27	Dec 2016
	67	Mar 2017
	19	Jun 2017
	14	Nov 2017
Rottnest Island	19	Feb 2012
	2	Sep 2015
	5	Nov 2015
	15	Mar 2016
	13	Mar 2017
	13	Jun 2017
South Coast	46	May 2014
	32	Aug 2014
	57	Jun 2015

16. Appendix 4 References

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