THE SHY ALBATROSS (*THALASSARCHE CAUTA*):

Population Trends, Environmental and Anthropogenic Drivers, and the Future for Management and Conservation

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Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

University of Tasmania

(May, 2012)
Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government’s Office of the Gene and Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

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Authorship and Contributions

The candidate contributed between 70-90% to each of the four data chapters in this thesis, including primary design, data collection, data analysis and writing. The candidate has been responsible for the co-ordination of the annual DPIPWE shy albatross monitoring programme since June 2003 and has collected all field-data presented in this thesis from the 2003 breeding season to the present day. This includes multiple island visits each season to conduct banding and recapture programmes, deploy satellite transmitters and undertake ground counts and aerial photographic surveys. Data prior to the 2003 breeding season has been collected by a range of personnel and was made available for use in this thesis by the DPIPWE data custodian, Dr. Rosemary Gales.

Two chapters in this thesis (chapters two and three) have already been published as:


The candidate is the primary author on both publications. Supervisors (R. Gales, A. Hobday and G. Tuck) are included as co-authors on publications for the provision of data (shy albatross data, fisheries data and remotely sensed oceanographic data respectively), their contributions towards developing the idea and subsequent refinement and presentation of publication chapters. External co-authors, J.D. Lebreton and S. Candy, provided assistance with models (survivorship models and
linear mixed effects models respectively). Relative author contributions on each publication are indicated below.

i) R. Alderman (candidate) (80%), R. Gales (7.5%), A. J. Hobday (7.5%), S. Candy (5%)

ii) R. Alderman (candidate) (85%), R. Gales (5%), G. N. Tuck (5%), J. D Lebreton (5%)

We the undersigned agree with the above stated “proportion of work undertaken” for each of the above published peer-reviewed manuscripts contributing to this thesis:

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Thesis Abstract

Despite recent global conservation efforts, albatrosses remain amongst the most threatened groups of birds. Worldwide, they are affected on land and at sea by a range of processes, particularly fisheries bycatch. In spite of their high conservation profile, albatrosses present challenges for monitoring and recovery actions because they are long-lived, spend most of their life at sea and return to breed at colonies that are often located on remote, relatively inaccessible islands.

This thesis offers a comprehensive assessment of the population status and trends of Australia’s endemic shy albatross, *Thalassarche cauta*, which breeds exclusively on three Tasmanian offshore islands. The main anthropogenic, physical and environmental processes that influence each of the three breeding populations are examined and the processes that shape key demographic parameters and trends are assessed in four analytical chapters which follow the introductory chapter.

Chapter two compiles and analyses available population and demographic data to provide the first comprehensive assessment of the status and trends of the three individual shy albatross colonies and of the species as a whole. This chapter shows that the Albatross Island population has recently stabilised following a period of sustained increase post-harvest and that this change in trajectory appears driven by a decrease in juvenile survival. The small Pedra Branca population is declining, likely due to reduced breeding success associated with the increasing population of Australasian gannets on the island. While trends for Mewstone, the largest breeding population, are unknown, it is shown that birds from this colony have greater exposure to commercial fisheries, are therefore at higher risk of fishing-related mortality and, consequently, survival rates for this population are likely lower than their Albatross Island counterparts. Collectively, these results suggest the current status of the shy albatross is likely to be stable at best and quite possibly decreasing.
The third chapter uses satellite tracking data to investigate the at-sea distribution of post-fledging shy albatrosses. Data show colony-specific dispersal behaviour and subsequent post-fledging range. Accordingly, the three populations differ in the extent to which juveniles overlap with commercial fisheries and their consequent risk of by-catch. The satellite data and supporting evidence from band recoveries also show that juvenile mortality is highest in the period immediately after fledging, with population differences in the frequency of mortality also apparent. Post-fledging mortality is likely related to foraging failure of naive birds and the observed population differences may be related to proximity of colonies to food resources. Considering the combined impact of environmental and fisheries influences, it is probable that the juvenile survival rates for the two southern populations, and for Mewstone in particular, are lower than the northern, well-studied, Albatross Island population.

In line with the increasing focus of managers and researchers on understanding climate impacts on threatened species, chapter four assesses the efficacy of existing long term monitoring on Albatross Island in detecting the influence of climate change on the breeding performance of this population. This study shows that the current sampling design is biased towards older, more experienced breeding individuals, which are better able to buffer the effects of climate variability and thereby obscure climate signals. Modifications to the monitoring protocols are suggested, including the deliberate sampling of younger birds to provide a more sensitive and effective ecological indicator of the effects of climate variability and climate change on this population.

The fifth chapter takes the existing breeding-success time-series and investigates the relationship of this important life-history parameter with a range of local and regional environmental variables. The strongest relationships were found with environmental conditions during chick-rearing, including rainfall and maximum temperature during this period at the breeding site, and with sea-surface height anomalies associated with increased upwelling in the primary foraging areas during both
incubation and the chick-rearing phases. The population implications of these climate-biology relationships given future predictions for climate change are considered.

These findings are synthesised to produce the first comprehensive report of the overall conservation status of the shy albatross and a key conclusion of this research is that the species is not as secure as previously believed. In addition to contributing to our understanding of the status of the species, this thesis highlights a range of threatening processes and their underlying mechanisms and provides clear guidance for future management and monitoring of this species, findings that can be extended to other threatened seabird species.
Acknowledgements

Many people have contributed to the monitoring and conservation of shy albatrosses over the years – particular acknowledgement must go to Nigel Brothers, Rosemary Gales, April Hedd and Sheryl Hamilton. I am privileged to have had the opportunity to build upon their dedicated efforts.

Ian Hay (DSWEPaC) has been steadfast in his support and funding for the shy albatross monitoring programme.

I thank my fabulous team of supervisors – Alistair Hobday, Rosemary Gales, Geoff Tuck and Stewart Nicol – for their input and support, my friends in team marine for their assistance and good times in the field and Michael Berry for his help and encouragement across the finish line.
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<th>Description</th>
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<tbody>
<tr>
<td>ACAP</td>
<td>Agreement on the Conservation of Albatrosses and Petrels</td>
</tr>
<tr>
<td>AFMA</td>
<td>Australian Fisheries Management Authority</td>
</tr>
<tr>
<td>AVISO</td>
<td>Archiving, Validation and Interpretation of Satellite Oceanographic data</td>
</tr>
<tr>
<td>BSP</td>
<td>Breeding Success Plot</td>
</tr>
<tr>
<td>CCSBT</td>
<td>Commission for the Conservation of Southern Bluefin Tuna</td>
</tr>
<tr>
<td>Chl a</td>
<td>Chlorophyll a concentration</td>
</tr>
<tr>
<td>DSEWPaC</td>
<td>Department of Sustainability, Environment, Water, Population and Communities</td>
</tr>
<tr>
<td>DPPIPWE</td>
<td>Department of Primary Industries, Parks, Water and Environment</td>
</tr>
<tr>
<td>DSF</td>
<td>Days Since Fledging</td>
</tr>
<tr>
<td>EEZ</td>
<td>Exclusive Economic Zone</td>
</tr>
<tr>
<td>GOF</td>
<td>Goodness-of-fit</td>
</tr>
<tr>
<td>IOTC</td>
<td>Indian Ocean Tuna Commission</td>
</tr>
<tr>
<td>LMM</td>
<td>Linear Mixed-effects Models</td>
</tr>
<tr>
<td>MaxT</td>
<td>Maximum Temperature</td>
</tr>
<tr>
<td>MSMR</td>
<td>Multi-State Mark-Recapture</td>
</tr>
<tr>
<td>PTT</td>
<td>Platform Terminal Transmitter</td>
</tr>
<tr>
<td>QAIC</td>
<td>Quasi Akaike Information Criterion</td>
</tr>
<tr>
<td>SOI</td>
<td>Southern Oscillation Index</td>
</tr>
<tr>
<td>SSH</td>
<td>Sea-Surface Height</td>
</tr>
<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
</tr>
<tr>
<td>ZWW</td>
<td>Zonal Westerly Wind</td>
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1. Introduction

Albatrosses (family Diomedeidae) are a high profile marine taxon of significant global conservation concern. Albatrosses spend most of their life at sea, typically returning to land only to breed. Of 22 currently recognised albatross species, 17 are classified as threatened under IUCN criteria (see Table 1.1, IUCN 2010). The majority of albatrosses breed on remote oceanic islands in the Southern Ocean, resulting in a comparative paucity of reliable recent data on status and trends for many populations. Twenty-one percent of the approximately 290 substantive breeding populations (distributed across 36 island groups) have never been counted. Recent population trends from 2000 onwards are confidently known for only 13% of all breeding sites and of these more than 30% are in decline (ACAP 2011a).

Albatrosses have “K-selected” life histories, with a long life-span, delayed onset of breeding, a low reproductive output of one egg per breeding attempt, and a typically monogamous, obligate dual-care breeding strategy (Warham 1990). Albatrosses show a high degree of natal philopatry with limited interchange between populations (but see, for example, Inchausti and Weimerskirch (2002) who detected non-negligible rates of juvenile dispersal amongst populations of Wandering Albatrosses, Diomedea exulans). These characteristics make albatrosses sensitive to even slight changes in survival or breeding parameters. Individual albatross colonies may be subject to a variety of localised land-based threats. Within their oceanic realm, albatrosses face two pervasive anthropogenic threats: mortality associated with commercial fishing operations; and accelerated rates of climate change. The two key areas of research for conservation and management of these threats are population monitoring and foraging studies. Long-term and continuous demographic monitoring of albatross colonies is required to sensitively detect population changes and to identify which aspect of life-history is driving observed trends. A comprehensive understanding of the at-sea distribution allows the ultimate causes of demographic change to be investigated.
Table 1.1: IUCN conservation status of the 22 albatross species, family Diomedeidae.

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Species Name</th>
<th>IUCN</th>
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<tbody>
<tr>
<td>Amsterdam albatross</td>
<td>(Diomedea amsterdamensis)</td>
<td>Cr</td>
</tr>
<tr>
<td>Antipodean albatross</td>
<td>(Diomedea antipodensis)</td>
<td>Vu</td>
</tr>
<tr>
<td>Tristan albatross</td>
<td>(Diomedea dabbenena)</td>
<td>Cr</td>
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<td>Southern royal albatross</td>
<td>(Diomedea epomophora)</td>
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<tr>
<td>Wandering albatross</td>
<td>(Diomedea exulans)</td>
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</tr>
<tr>
<td>Northern royal albatross</td>
<td>(Diomedea sanfordi)</td>
<td>En</td>
</tr>
<tr>
<td>Short-tailed albatross</td>
<td>(Phoebastria albatrus)</td>
<td>Vu</td>
</tr>
<tr>
<td>Laysan albatross</td>
<td>(Phoebastria immutabilis)</td>
<td>NT</td>
</tr>
<tr>
<td>Waved albatross</td>
<td>(Phoebastria irrorata)</td>
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<td>Black-footed albatross</td>
<td>(Phoebastria nigripes)</td>
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<tr>
<td>Buller’s albatross</td>
<td>(Thalassarche bulleri)</td>
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<td>(Thalassarche corteri)</td>
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<td>(Thalassarche cauta)</td>
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<td>Vu</td>
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<td>(Thalassarche eremita)</td>
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<td>(Phoebetria fusca)</td>
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<tr>
<td>Light-mantled albatross</td>
<td>(Phoebetria palpebrata)</td>
<td>NT</td>
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Cr=Critically Endangered, En=Endangered, Vu=Vulnerable, NT=Near Threatened

Threats to albatross populations

A diverse range of processes threaten albatrosses. Some are local in scale and specific to individual breeding populations, such as disturbance from research activities (Moore 2003; Phillips et al. 2003) and other human visitation (Higham 1998; Villiers et al. 2005), poisoning (Finkelstein et al. 2003),
predation (for example, mice predating upon the Tristan albatross, on Tristan Da Cuhna, Wanless et al. 2009), deliberate catch (Awkerman et al. 2006) and parasites or pathogens (for example, avian cholera in Indian yellow-nosed albatrosses, Rolland et al. 2009a). These threats occur typically at the breeding site, resulting in different populations experiencing different threat frequency and severity.

Responsibility for management of these localised threats is clear and the approaches, such as feral pest and predator eradication (Nogales et al. 2004) and follow up habitat restoration (Micol & Jouventin 1995) programmes, relatively straightforward. However, the most pervasive threats to albatrosses operate on a much broader scale and occur primarily at sea through habitat and resource modification associated with climate change, and fatal interactions with commercial fishing operations. The scale and influence of these two processes vary with the biology and geography of individual populations, and there are regional differences that are linked to colony location and foraging areas.

**Fishing bycatch**

Commercial fishing, specifically the unintended capture of albatrosses on fishing gear or other incidental mortality associated with the fishing process (“bycatch”), is heavily implicated in the decline of albatross populations worldwide (for example, Nel et al. 2002a; Rolland et al. 2010). Albatrosses and fishing fleets often target similar prey species and often co-occur in oceanic regions with high productivity. Well known for their ship following habits, albatrosses are highly attracted to the bait and the discarded by-products of many fishing fleets. Interactions with seabirds were first identified in pelagic longline fisheries targeting tuna, mackerel and swordfish (Brothers 1991). The longline fishing method involves setting a line of up to 50 km in length with as many as 15,000 baited hooks from the stern of the vessel (Barnes et al. 1997). Albatrosses seize the bait as the line is being set and are subsequently hooked and drown as the line sinks below the water. This is a relatively rare event for an individual fishing vessel, but when multiplied across the entire fleet, the realisation
that hundreds of thousands of albatrosses were being killed each year quickly drew the focus of global conservation efforts.

Seabird fatalities on commercial trawl vessels were first documented around the same time as in the longline fishery (Bartle 1991), but whereas the threat from longlining was soon widely acknowledged, the potential scale and conservation consequences of trawl related mortality took longer to gain broad recognition. There is little or reference to trawl mortality in the albatross conservation literature until around 2000 (but see Prince et al. 1994) from which time trawl mortality rapidly became a global concern (Weimerskirch et al. 2000b; Sullivan et al. 2006b; Baird 2008; Watkins et al. 2008). Most likely, it is the way in which birds are killed that contributed to the delayed understanding of the impact. On longline fisheries, seabird deaths are usually obvious because most carcasses are retained on the hook and discovered when the line is retrieved. Mortality on trawl fisheries is largely cryptic. Although individuals are killed when caught in the trawl net itself and their bodies may subsequently be recovered (for example, Baird 2008), the majority of albatross deaths are through collision with high tension operational cables (net sonde (Bartle 1991) and trawl warp (Sullivan et al. 2006b)). These collisions occur when albatrosses come close to the stern of the vessel in pursuit of fishing discards. If the net is under tow, squabbling birds become tangled on the warp cable. They need only be caught for a moment and are dragged down the wire by the forward momentum of the vessel and subsequently drowned. In most cases, the carcass is not retrieved and potentially high rates of mortality go undetected unless there is specific and dedicated observation of interactions around the warp wires.

Irrespective of the operational method, commercial fisheries are the most important global threat to albatrosses. All sectors of the ocean are fished, from territorial waters to the high seas. Albatrosses disperse widely across the oceans, particularly during non-breeding phases of their life-cycle, and they encounter fisheries operating far from their breeding sites and outside any territorial jurisdiction. Other potential impacts of commercial fisheries on albatross populations include
competition (Crawford 2004) or augmentation of prey (Bunce et al. 2002), however populations are less sensitive to these processes than the effect of elevated mortality.

**Climate change**

Climate change and increasing climate variability are now recognised as anthropogenic in origin (IPPC 2007) and may influence seabird populations through a range of direct and indirect processes. Direct impacts include changes to prey abundance and distribution, indirectly leading to changes in albatross demographic parameters such as reproductive success and survival. In seabirds, climate variation has been associated with changes, including increased variability, to key demographic parameters such as breeding success (Barbraud & Weimerskirch 2001) and survival (Barbraud & Weimerskirch 2001; Nevoux et al.), to breeding phenology (for example, Barbraud & Weimerskirch 2006), foraging success and consequent provisioning ability (Smithers et al. 2003; Pinaud et al. 2005), and to breeding and foraging distribution (Veit et al. 1997; Olson & Hearty 2003).

Extending the detection of a relationship between climate variation and albatross ecology to the identification of the underlying mechanism and, consequently, the prediction of population consequences of change is more difficult. Strong causal relationships between a given environmental change and a population response need to be found. These relationships can be straightforward to detect for some seabird species, such as those reliant on ice extent to forage or breed, thereby enabling useful predictions of population consequences (Le Bohec et al. 2008). For species such as albatrosses, however, which interact in more complex spatial and temporal environments, relationships can be difficult to identify and define. Many of the responses may be non linear, or have contrasting and opposing effects (Barbraud et al. 2011). How individual populations respond to climate variation may depend on population density (Barbraud & Weimerskirch 2003), regional differences (for example, Wolf et al. 2009), or the plasticity of the species or population (for example, Lescroel & Bost 2005).
The impacts of climate change on albatross populations, and the consequent ability to manage them, is less understood in comparison to the issues related to fisheries bycatch. Clear, mechanistic relationships can be demonstrated between aspects of fishery operation and albatross demography and the conservation consequences can, accordingly, be reliably estimated under different scenarios, with individual fisheries or regions thus targeted for effective management action. In contrast, research and conservation efforts with regard to climate change remain largely focused on the detection of climate-biology relationships with the result that quantitative predictions of population consequences and the identification of possible management actions are limited.

*The importance of demographic monitoring and at-sea research*

Regardless of the threat, the ability to relate a given process to an observed impact on an albatross population requires robust demographic data. Demographic studies rely heavily on following individually marked animals through time. For albatrosses, with their long life-span and low reproductive output, this means decades of continuous longitudinal data must be collected in order to detect trends. Since most albatross populations nest on remote oceanic islands, such studies are logistically difficult, resource intensive and consequently limited. These studies must be comprehensive and collect data on a broad range of breeding and survival parameters because the impact of a threatening process may be experienced only by a specific subset of the population or a discrete life-history stage (for example, the decline in the Macquarie Island population of wandering albatross driven by elevated mortality during the juvenile stage, Terauds et al. 2006b).

Although very different in nature, both climate change and fisheries bycatch are threats in the marine realm. For both of these processes, the effective conservation and management of albatross populations requires an understanding of at-sea distribution. This area of research has been facilitated by the rapid development of remote tracking techniques in recent decades (Burger & Shaffer 2008) and has direct application to the investigation of fisheries and climate change impacts. These studies have shown substantial inter and intra-population variation in foraging behaviour,
with distribution varying with gender, age and reproductive status (Weimerskirch 1995; Weimerskirch et al. 2006), resulting in pronounced differences in the exposure to at-sea threats. Beyond the identification of key foraging areas and migration pathways, remote tracking studies provide an understanding of how albatrosses perceive their environment (Frederiksen et al. 2004a), their foraging habitat requirements (Suryan et al. 2006), and even fine scale analyses of how individuals respond to ships (Torres et al. 2011). These are all important considerations in the identification of areas of risk and appropriate management responsibilities, including planning and assessment of the efficacy of marine protected areas (Hyrenbach et al. 2006; Trebilco et al. 2008; Game et al. 2009) and the identification of fisheries and management agencies to be targeted (Small & Taylor 2006).

Conservation and mitigation

Examples of studies conclusively linking observed population trends to particular fisheries or climate fluctuations are rare. Clarifying these relationships may be difficult for many reasons, including the required sensitivity of analyses of demographic parameters and the complex and non-linear responses that can be displayed (Delord et al. 2008), the lack of reliable information of rates of by-catch for a candidate fishery (Gilman et al. 2005), and the difficulty in relating observed changes to climate variation due to lagged (Thompson & Ollason 2001) or competing effects. Regardless of the difficulties however, these studies help focus management upon key areas. In relation to fisheries, practical management may include the quantification of rates of bycatch (Gales et al. 1998; Lawrence et al. 2009), the investigation of factors influencing these rates (Klaer & Polacheck 1998) and the development of effective mitigation methods (Lokkeborg 2003; Sullivan et al. 2006a; Bull 2009). In terms of climate change, there is less scope for practical mitigation, with management mostly focussed upon increasing resilience through the reduction of non-climate stressors, such as bycatch, impacts of feral animals and accounting for food requirements in fisheries management.
The shy albatross

The focus of this thesis is the influence of environmental and anthropogenic processes, particularly climate change and fisheries, upon the shy albatross, *Thalassarche cauta* (Figure 1.1). The species is endemic to Tasmania, Australia, where it breeds on three offshore islands: Albatross Island; Pedra Branca and Mewstone (Figure 1.2). Originally part of the polytypic species *Diomedea cauta* (Gould 1841), the proposal to recognise four distinct species within this group, including the shy albatross (Robertson & Nunn 1998), was relatively controversial (for example, Penhallurick & Wink 2004). However, the separation has largely been accepted within the seabird community (Abbott & Double 2003b; Abbott & Double 2003a; Taxonomy working group of the ACAP 2006). The species is classified as *Near Threatened* under IUCN criteria (IUCN 2010) and considered *Vulnerable* under National (Australian Government Environment Protection and Biodiversity Conservation Act (EPBC Act) 1999) and State (Tasmanian Government Threatened Species Protection Act 1995) legislation.
Figure 1.1: The shy albatross (Thalassarche cauta – “cautious ruler of the sea”). Named by Gould who observed that the species was impossible to catch using the methods that worked for other albatross species, namely a long line baited with fat, and only managed to get close enough to shoot birds because they were feeding on the remnants of whales from the nearby whaling industry (Gould 1865).
Most of the existing data on shy albatross biology, ecology and population trends has been obtained from the Albatross Island population (Figure 1.3), largely because this is the most accessible of the three islands and has been monitored consistently since 1980. Data collected from Albatross Island include population size (Johnstone et al. 1975), foraging and distribution information (Brothers et al. 1997; Brothers et al. 1998; Hedd et al. 2001), diet (Hedd & Gales 2001) and chick provisioning (Hedd et al. 2002a), and behavioural observations (Hedd et al. 1997; Abbott et al. 2006b). Pedra Branca and Mewstone (Figures 1.4 and 1.5) have been represented in molecular and foraging studies (Brothers et al. 1998; Abbott & Double 2003b; Hedd & Gales 2005).
Figure 1.3: Albatross Island. Relatively easily accessible by sea and with hospitable conditions for camping, this island is the site of the long-term shy albatross demographic and population monitoring programme.
Figure 1.4: Pedra Branca. This gannet dominated rock-stack is mostly monitored from the air, but is occasionally accessed by sea when the southern ocean swells abate.
Figure 1.5: Mewstone. The steep ridgelines and cliff areas of this imposing island mean much of the shy albatross nesting area is inaccessible and remote monitoring methods must be used.
Mature individuals typically breed annually. Eggs are laid throughout September, chicks hatch from late November through to December and fledging occurs in April through to May. Young birds are first resighted back at the colony as young as three years, however, the majority of individuals do not commence breeding until six years of age. The species has an unusually restricted foraging range in comparison to other albatrosses. Adult birds, breeding and non-breeding, remain within Australian waters and typically in proximity to breeding islands (Brothers et al. 1998; Hedd et al. 2001). Indeed, many adults birds maintain an almost year-round presence at the breeding colony, even during the non-breeding period (Hedd & Gales 2005). Banding and colour marking data show that although juvenile albatrosses forage more widely than adults, they have a similarly restricted foraging range largely confined to Australian waters (Brothers et al. 1997).

Because of the restricted breeding and foraging habitat, the shy albatross is one of the few albatross species that is managed almost wholly within one national jurisdiction. In theory, this means easier identification and quantification, and more straightforward management of processes that impact shy albatross populations. The most significant land-based threat today is human disturbance, such as researcher work and tourism, particularly for the easily accessible Albatross Island. Avian pox virus occurs in a localised area on Albatross Island with unknown demographic consequences for that population (Woods 2004) but has not been detected in either of the other two populations. The Pedra Branca population is at risk of habitat loss and inter-specific disturbance, but no land based threats to the Mewstone population have been identified.

Some of the same ocean-based threats identified for other albatross species also impact on this species. Pollutant and plastic ingestion is less of an issue for shy albatrosses than it is for other species (Hindell et al. 1999). Inter-specific competition for prey including human fisheries and expanding fur seal (Arctocephalus spp.) and Australasian gannet (Morus serrator) populations is a significant factor in the south-east Australian region (Bunce et al. 2002; Gibbens & Arnould 2009). Fisheries-related mortality, however, remains the most serious potential threat to shy albatross
populations, with the species recorded killed on longlines in large numbers (Gales et al. 1998; Abbott et al. 2006a) and known to interact with trawl vessels (DPIPWE unpublished). Given the restricted foraging range of the species, fisheries bycatch is almost wholly within Australian jurisdiction and so, quantification and management should be fairly straightforward. The impacts of climate change on the marine environment, and how these changes affect dependant species, remain a great unknown. Projected ocean warming in the southern Australian waters, especially those of the Tasman Sea, is among the greatest worldwide (Hobday et al. 2006; Hobday & Lough 2011). There is less certainty about the south coast, although some projections suggest upwelling may even intensify, leading to increased productivity and foraging (Hobday & Lough 2011).

Here, I investigate the population status and trends of the shy albatross and demonstrate that the three breeding colonies are both physically and geographically distinct. Accordingly, their populations are exposed to a variety of past, present and future anthropogenic and environmental processes. These findings are considered with respect to the future for monitoring, management and conservation of this iconic species.

The thesis is presented in four data chapters and a concluding synthesis. Each of the data chapters is prepared as a stand-alone journal article, two of which have already been published and two have been prepared for submission. As such, individual chapters have been formatted for the requirements of particular journals and there is some repetition, particularly in the introduction and methods sections.

Chapter 2. Global population status of the shy albatross and an assessment of colony-specific trends and drivers.

Existing information of shy albatross population trends, demography and ecology comes from the Albatross Island population. Trends and drivers of that population, however, may not be applicable to either Mewstone or Pedra Branca. In this section, population data from heterogeneous sources
are combined to provide the first reliable estimate of the global shy albatross population. Where possible, an assessment of demographic trends for each of the three populations is undertaken. The key drivers of each population trend, historical through to present day, are considered, with a particular focus on the role of fisheries by-catch.

Chapter 3. Post-fledging survival and dispersal of shy albatrosses from three breeding colonies in Tasmania.

A key gap in our understanding of shy albatross ecology is the at-sea distribution of juvenile birds. This chapter investigates the dispersal behaviour of shy albatross chicks fledging from each of the three populations, providing critical information on the spatial distribution and consequent overlap with fisheries and risk of mortality. This chapter also investigates how juvenile shy albatrosses utilise the marine environment; information that improves understanding of how climate change may affect this age class. This life history stage is hard to monitor and particularly so for the remote populations on Mewstone and Pedra Branca, where key demographic parameters, juvenile survival and rate of recruitment to the breeding population, are unknown. This comprehensive tracking study allows managers to make population specific conservation assessments through less direct means by comparing and contrasting fisheries overlap and foraging behaviours of juveniles from the three colonies and inferring the consequent demographic effects.

Chapter 4. Monitoring seabird populations to detect impacts of climate variability

Monitoring shy albatross populations to understand the possible effects of climate variation and climate change is important. The relevance of climate change for conservation and management will increase into the future, possibly outstripping fisheries influences for this species. This chapter investigates whether the existing long-term study of shy albatrosses on Albatross Island collects the necessary information to detect population responses to climate change. The chapter assesses age-specific trends and inter-annual variation in breeding success to investigate whether the experience
of breeding birds obscures the climate signal contained within this key demographic parameter. The aim of this study is to maximise the monitoring programme so that it more sensitively and reliably detects relationships between climate fluctuation and breeding success parameters, allowing improved insights into the future impact of climate change for this species.

Chapter 5. Shy albatross breeding success: trends and climate influences

One of most important unresolved questions for conservation and management is, how will climate change affect shy albatrosses in the future. Predicting how populations may respond to climate change firstly requires the identification and quantification of functional relationships between demographic parameters and environmental variables. Where Chapter four focusses on how to partition demographic data to find the most sensitive relationship between breeding biology and climate, this chapter seeks to describe that relationship. I test for the relationship between annual reproductive success of shy albatrosses on Albatross Island with a suite of oceanographic and environmental variables at a range of temporal and spatial scales and consider what population impacts may be expected based on regional climate predictions.

Synthesis: The future of shy albatross populations, monitoring and management

The final chapter is a synthesis of what is now known about the status and trends of the three populations. It compares and contrasts the influences of climate, fisheries and other land based processes on key demographic parameters and life-history stages of each population and considers actions to mitigate threats or build population resilience. Finally, this section identifies key gaps in our understanding and makes practical recommendations for future monitoring to enhance the management and conservation of this species.
Appendix: Interactions between seabirds and the Commonwealth trawl fishery: a preliminary investigation.

A report, outlining the results of a small project undertaken by DPIPWE and funded by DSEWPaC to investigate the interactions between seabirds and the Australian Commonwealth-managed trawl fishery, is included as an appendix. This report was prepared by the candidate and details evidence of the nature and scale of seabird bycatch in the Australian trawl fishery, and importantly, identifies the shy albatross as the species at highest risk of mortality.
These chapters have been removed for copyright or proprietary reasons

Two chapters in this thesis (chapters two and three) have already been published as:

**Chapter 2. Global population status of the shy albatross and an assessment of colony specific trends and drivers**


**Chapter 3 - Post-fledging survival and dispersal of shy albatrosses from three breeding colonies in Tasmania**

4. Monitoring seabird populations to detect impacts of climate variability

Abstract

Monitoring wildlife populations to understand the effects of climate variation and climate change is being recognised as increasingly important. Long-term studies are required, particularly for long-lived species such as seabirds and marine mammals. Many studies may be effectively collecting the key demographic information for which they were originally established, but not maximising information regarding responses to climate variation as they were created for another purpose. As the focus of managers and researchers shifts increasingly towards climate, the re-evaluation of existing data and monitoring approaches may identify modifications that would enhance the ability to detect the effects of climate variation. Here, we assess the long term monitoring programme of shy albatrosses on Tasmania’s Albatross Island as an example. We illustrate how the sampling design might obscure signals of climate variation in this case as contained in two measures of breeding performance, breeding success and chick weight. For this population, we demonstrate that breeding performance in younger birds with little breeding experience is more variable than older, more experienced birds. Younger, less experienced breeding birds have a reduced ability to buffer the effects of climate variation, and we suggest that this may provide a more apparent climate signal. As young birds are currently under-represented, modifying the existing monitoring programme to deliberately sample younger birds may help elucidate the climate-biology relationships for this population and provide a more sensitive and effective ecological indicator of climate change. Other long-term monitoring programmes may benefit from a similar assessment process and with such awareness be better placed to evaluate the effects of climate on populations.
Introduction

Populations of many iconic marine bird and mammal species have been affected by a range of anthropogenic stressors including pollution (for example, Eriksson & Burton 2003; Wiese & Robertson 2004), legal and illegal harvesting (for example, Awkerman et al. 2006), habitat loss (for example, destruction, Micol & Jouventin 2001) and fishery bycatch (Julian & Beeson 1998; Baker et al. 2007). National legislation and international conventions charge governments with monitoring the status of these threatened species and mitigating the threats to population viability where they exist (DSEWPaC 2011; Durant et al. 2009; ACAP 2010b). As a result, many long-term programmes have been implemented to address a specific conservation or research goal, with a particular focus on monitoring population trajectories and identifying the demographic drivers of those trends.

Seabirds, particularly colonial nesters such as penguins, shearwaters and albatrosses, now represent some of the longest continuous population monitoring programmes in marine systems, with time series of up to 50 years (Croxall et al. 1990; Bradley et al. 1991; Jenouvrier et al. 2003; Terauds et al. 2006b). Many of these population studies have linked changes in demographic parameters with anthropogenic threats, and for albatrosses and petrels in particular, the focus has been upon the impacts of fisheries related mortality (for example, Tuck et al. 2001; Arnold et al. 2006) which has been identified as a pervasive global threat to the seabird community.

It is now apparent that one of the most widespread threats to marine species is anthropogenic climate change. Climate, the long-term average of “weather”, influences a suite of ocean environmental conditions at a range of spatial and temporal scales (Hallett et al. 2004; Stenseth & Mysterud 2005; Durant et al. 2009). Marine species at a range of trophic levels respond to both direct changes in the physical environment (such as water temperature and winds) and to indirect effects (such as changes to predators or competitors and food supply). Increasingly, researchers are faced with assessing potential climate change impacts on these species and in future will have to
evaluate potential adaptation measures. Thus, understanding responses of marine species to climate variability is now of principal interest to many scientists and managers.

Beyond individual species and population management, understanding how species respond to climate variability is of interest for ecosystem-based management. The use of top order marine predators, which integrate ocean conditions over a range of spatial and temporal scales, as indicators of climate change and sentinel species is increasingly important (Frederiksen et al. 2007; Parsons et al. 2008; Einoder 2009). Seabirds possess a range of characteristics that make them ideal candidates for indicator species in marine ecosystems (reviewed in, Grémillet & Charmantier 2010).

Given the considerable investment made in collection of biological data over many years, it is important to establish if existing and established monitoring programmes can also be used to assess the impacts of climate change. Most long term studies were established before climate change awareness was heightened (Boyd & Murray 2001). Consequently, these studies may not monitor in the most appropriate way for detecting climate impacts and they may need adjustment to deliver ongoing benefit.

Whether the goal is to understand and predict population responses to climate change or to monitor populations as indicators of environmental change, an important first step is to determine whether the data collected are suitable for detecting relationships between biology and environmental conditions. It may be able to easily improve the strength and clarity of a climate signal by augmenting or optimising existing studies, or, new monitoring protocols may need to be implemented.

Many long term seabird monitoring programmes have a demographic focus, measuring survival, recruitment and breeding parameters. For species with K-selected life history characteristics such as albatrosses, these are the long term datasets necessary to evaluate the impact of anthropogenic threats. For logistical reasons, such as, if the colony is large or only partially accessible, a subset of
individuals or a defined area may be monitored (for example, Cuthbert et al. 2003; Walker & Elliott 2005; Rolland et al. 2009a). These monitoring designs may lead to biases if the sample group or study area is in some way functionally or demographically different from the larger population. For example, many albatross populations nest in discrete sub-populations and demographic monitoring is often focused on a single more logistically straightforward group of individuals (for example, Waugh et al. 1999b; Cuthbert et al. 2004). Differences between recruitment rates (and consequently the growth and trends in age) between smaller and larger sub-populations are conceivable, as are differences in breeding success if predation pressures vary with location (Forster & Phillips 2009). Accounting for potential differences in spatial or sub-population dynamics may be important for detecting climate impacts.

Here we focus on a specific example; a long term monitoring programme on a population of shy albatross (Thalassarche cauta), primarily established to monitor demographic trends in relation to fisheries threats, and we ask if this programme design is suited to determining the influence of environment variability and change. As understanding the potential impacts of climate change often requires many years of data (for example, Rolland et al. 2010; Wolf et al. 2010), the issue of maximising the value of existing programmes and data extends across a range of marine taxa monitoring programmes.

The monitoring of shy albatrosses on Albatross Island has two components common to other programmes: i) following known individuals through time to record survival and breeding frequency; and ii) measuring population annual breeding success from fixed plots. We hypothesise that there is an age bias inherent in the design that may impair our ability to detect the influence of environmental change. In the case of the individual-based monitoring, as the monitored birds age and become more experienced, unless young birds are continuously incorporated, the sample may become biased towards older cohorts. With the space-based monitoring, over many years and with the same birds returning to the fixed plots, similar biases can result if the monitored birds are not
representative of the wider population. This may occur if different sub-populations on the same island show different population trajectories or different demographic parameters. As such, there is the potential for inexperienced birds to be under-represented in the dataset, although it is in these individuals that environmental influences may be most strongly expressed.

Many studies have shown that birds with little or no breeding experience are more susceptible to environmental fluctuations that make it harder to successfully hatch and rear a chick (for example, Cam & Monnat 2000; Barbraud & Weimerskirch 2005; Nevoux et al. 2010a). Experienced individuals are likely better able to buffer mild effects that climate variation may exert on breeding performance (Aubry et al. 2009). For our shy albatross example, we predict that inexperienced breeding birds will show greater individual and inter-annual variation in breeding performance. If experienced birds show greater consistency in breeding performance overall, then any reduction in performance, to the extent that it is related to climate variability, may be detected only in relatively extreme conditions. If so, time series that explicitly include more marginal performers (young birds) may present the most unambiguous climate-biology relationships, thereby improving the ability to predict population consequences under climate change scenarios and proving a more sensitive ecosystem indicator of climate change.

We explore this hypothesis using two measures of breeding performance as potential indicators of a response to climate variability: the proportion of eggs which produce pre-fledging chicks (breeding success); and pre-fledging chick mass (an indicator of chick condition). The aim here is to consider how long-term data commonly collected from long-lived colonial seabirds might be supplemented or partitioned to elucidate a stronger climate signal and thus may prove more useful as an indicator of climate variation and change. We do not attempt to relate the differences we illustrate to environmental data, but aim only to determine how the biological signal differs depending on the data that are being collected. If we are successful in this, then other long-term monitoring programmes may also be able to derive time series in a way that advances the detection and
monitoring of climate change impacts, ultimately leading to selection of more effective conservation measures.

Methods

To examine the inter-annual and between-individual differences in demographic metrics derived from different components of a seabird population, we use data collected in a long-term study of shy albatrosses at Albatross Island.

Study site - Albatross Island

Of the three shy albatross colonies, all located in Tasmanian waters, Albatross Island off north-west Tasmania (40° 23’S, 144° 39’E, Figure 4.1) is the most studied due to its relative ease of access and proximity to the Tasmanian mainland. Once home to over ten-thousand pairs of shy albatrosses, feather collectors reduced the breeding population to as few as 400 pairs in the early 1800s (Green 1974; Alderman et al. 2011). The population has gradually recovered from historic exploitation and currently, with 5200 breeding pairs, is approximately half the estimated pre-exploitation size (Chapter 2).
While sub-colonies exist on Albatross Island today, historical guano deposits indicate that a single large colony existed prior to exploitation (Green 1974). The recovering population presently nests in four discrete sub-colonies: North (representing 25% of pairs); Main (60%); South (12%); and West (3%). The three largest sub-colonies are situated on the eastern side of the island, abutting the cliff edge (Figure 4.1). These nesting areas have increased in size since the 1980s, typically through westward expansion along distinct fronts, rather than by increasing in nest density within existing boundaries. The west sub-colony is atypical of the population with much steeper terrain, lower nest density and no increase in population size or area over time (DPIPWE, unpublished data). Pairs are so sparsely distributed in this sub-colony that growth may occur via infilling as well as boundary expansion.
**Species monitoring on Albatross Island**

Shy albatrosses breed annually and the Albatross Island population has been monitored each year since the 1981/1982 (hereafter 1981) breeding seasons (Gales 1998). Between 25-100% of chicks on the island have been banded just prior to fledging each year since 1981, with the exception of the 1989 and 1991 seasons in which no banding was undertaken (DPIPWE unpublished). Approximately 50% of breeding birds on the island are of known age. A range of demographic and ecological data has been collected (refer to Chapter 2 for details) but here we focus on just two breeding performance parameters – breeding success and pre-fledging chick condition. Breeding success is estimated from the proportion of eggs laid (counted at the end of the peak laying period, on or around 1 October, each year) that successfully produce chicks (counted just prior to fledging, on or around the 1 April). We used chick mass as an index of chick condition, noting that using mass without standardising for body size or gender may be a biased indicator of condition (e.g. Chastel et al. 1995). Chick mass at the time of banding was obtained by weighing the researcher whilst holding the bird on a platform scale (accurate to 50 grams), then subtracting the mass of the researcher immediately re-weighed without the bird. We focus on data collected since the 2000 breeding season from the north and main sub-colonies as it has been collected at both an individual and population sample level. While individual data might always appear preferable to population data, there is a trade-off in terms of time required to collect sufficient data on each short visit to the remote island, and wider coverage is possible when collecting population data (for example, counts without identification of individual birds via band reading).

**Individual-based data**

In 2000, a group individuals nesting in a defined area of the north sub-colony were designated “study-birds” (Figure 4.1). Approximately 170 nesting pairs have been monitored annually in this area for ten consecutive breeding seasons. The site boundaries are fixed and individuals are, therefore, lost from the study pool if they die or move to a nest location outside the study plot. New
individuals are added to the study-bird set through partner changes rather than via expansion of perimeter study area limits. From the study-birds, a range of individual-based data is collected, including breeding frequency, mate fidelity, breeding success, and nest quality.

Nest quality is scored at the end of the laying period on the basis of a qualitative assessment as “poor” (barest scrapings on rock – score of [0-1]), “medium” (moderate height and bowl shape [2-3]), or “high” (well developed, elevated nest bowl [4-5]).

**Population-based data**

Four sample “breeding-success plots” were established in the north and main sub-colonies in 2000 (one and three respectively; Figure 4.1) to monitor breeding success at a population level. All the eggs laid in the plots (including failed eggs) are counted by a researcher walking through the plot (ground counts). Three of the four plots include expanding colony edges and, thus, the number of breeding attempts recorded has increased over time. In 2006, band numbers were obtained from one of each incubating pair, thereby providing an estimate of the age range of birds nesting in these areas, but the fate of nesting attempts was not followed at an individual level. Nest-quality scores [0-5] are tallied at the time of the egg count, and an average score generated for each plot. Chick condition data have been obtained opportunistically in some plots in some years at the time of banding (April). In 2009, 15 chicks were weighed in each breeding-success plot.

Two additional plots, “edge plots”, were established on the expanding edges of the north and main sub-colonies (Figure 4.1) in 2009 to investigate spatial age structure and age related differences in breeding performance. Breeding success, nest quality and a sample of chick condition were obtained from these plots as described above. In addition, band numbers were obtained from one member of each breeding pair to estimate the age range of birds nesting on the colony edges.
Analysis

The three population sample types – the existing long-term individual-based study birds, the population-level breeding success plots, and the edge plot introduced in 2009 – were first characterised in terms of three metrics: i) mean age of breeding birds; ii) the edge ratio of sample areas; and iii) the mean nest quality.

Age data, calculated from the band numbers recorded on breeding birds in study-nest areas and edge plots in 2009 and from breeding-success plots in 2006, were used to test if the age distribution of breeding birds is spatially heterogeneous. The comparison of age data from 2006 with data collected in 2009 is a valid approach for our specific purpose; that is, characterising the age structure of the three sample types, because the relative age composition of this long-lived species will change little in three years. Differences in the mean age of breeding birds between the three groups were tested using ANOVA. A similar comparison was undertaken comparing nest quality in each of the three population sample types using χ² tests.

The total nesting area and the area situated within two metres (approximately) of the sub-colony edge were calculated for each sample type using GIS and a combination of hand-held GPS locations and geo-referenced aerial photographs. The resulting ratio of total area to edge area, or “edge ratio”, indicates the different capacity of the three population sample types for spatial expansion, which is likely an important determinant of underlying spatial age structure.

Breeding success was the first measure of breeding performance investigated, and we used individual-based study-bird data to investigate several assumptions related to our hypothesis that inexperienced breeding birds show more inter-annual variation in breeding performance than experienced birds. The relationship between experience and breeding success was determined by calculating the mean breeding success for each age across the ten breeding seasons, representing 1049 individual breeding attempts. We used age-groups rather than actual breeding histories in our
analysis as we are not confident that our sampling method reliably detects the first breeding attempt of an individual (c.f. Nevoux et al. 2007) and acknowledge that age-groupings are likely to include individuals with a range of breeding histories. We then separated all study-birds into “inexperienced” and “experienced” breeders based on the observed relationship between breeding success and age of individuals (see Results: Relationship between age and breeding success) and tested differences in breeding success between the two groups using one-tailed t-test.

Nest quality is a factor potentially complicating the relationship between breeding experience and breeding performance. We hypothesized a priori, based on observations over the years, that pairs on nests that are classified as high quality have increased breeding success. However, the best quality nests are also located in proximity to vegetation and soil on the expanding edges of the colony which may confound the detection of an environmental signal. Data from the study-birds, which are located in an area with few expanding edges, allowed exploration of relationships between breeding success, nest quality and breeding experience.

To examine the second measure of breeding performance, chick condition, we used the study-bird dataset to test for the significance of the Pearson’s correlation coefficient between breeding experience and chick weight. In all statistical tests, a p-value <0.05 was used to indicate statistical significance.
Results

The three groups compared in this study – breeding-success plots, edge-plots, and study-birds – differ in terms of the calculated metrics (Table 4.1) and these differences support the general hypothesis that the edge plots have greater edge-ratios and are populated by younger birds who occupy nests of generally higher quality.

Table 4.1: Shy albatross population metrics and sample size for the three groups based on data from the 2009 breeding season at Albatross Island. NR=not recorded. *data collected in 2006.

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<th>Sample group characteristics</th>
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<td>Breeding-success plots</td>
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<td>Study-birds</td>
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Relationship between area and bird age

There was a significant difference in the age distribution of birds in the three groups, with the study-birds generally older (mean 19.3 years) than birds in the breeding-success plots (mean 16.8 years). Birds in plots on the expanding edges were youngest (mean 11.8 years) ($F_{2,518}=31.277$, $p<0.05$, Tukey HSD all $p<0.05$, Figure 4.2). Thus, traditional sampling areas were biased towards older birds.
**Figure 4.2:** Age distribution of shy albatrosses breeding in the three population sample types in the 2009 breeding season on Albatross Island. Median and quartiles are shown for each sample. Dashed lines indicate 1.5 x the inter-quartile range.

**Influence of age on breeding success**

The study-bird dataset shows a strong relationship between overall breeding success and the age of individuals (Figure 4.3). The youngest ages at which shy albatrosses have been recorded breeding (age 6 and 7 years) exhibit very low breeding success. Breeding success then improves consistently until the birds reach ten years of age and then stabilises to a mean value in the range 40-60%.
Based on this result, we classified breeding individuals in the study-bird dataset as “inexperienced” if they were ten years of age or younger (n=119) and “experienced” if they were eleven years or older (n=989) in a given breeding season. A comparison of breeding success in the two categories over the ten year period (2000-2009) showed that inexperienced birds had significantly lower and more variable breeding success (mean 32%, range 0-67%) than experienced birds (mean 48%, range 32-63%; \( t_{13}=1.974, p<0.05 \); Figure 4.4).
Figure 4.4: Breeding success of inexperienced (age ≤ 10 years: solid line) and experienced (age > 10 years: dashed line) breeding shy albatrosses over the 2000-2009 breeding seasons on Albatross Island.

Influence of nest quality on breeding success

The study-bird dataset for the years 2000-2009, containing both non-edge and experienced birds, allowed consideration of the effect of nest quality on breeding success. Birds with poorer quality nest bowls had lower and more variable breeding success than those with high quality nests; nests of medium quality were intermediate (Figure 4.5; $F_{2,27} = 13.2, p < 0.05$). Pairwise comparison showed that poor quality nests had significantly lower breeding success than high and medium quality nests (Tukey HSD both $p < 0.05$), while there was no significant difference between medium and high quality nests ($p > 0.05$).
Figure 4.5: Shy albatross breeding success over the period 2000-2009 for the three categories of nest quality: poor (score of 0-1); medium (2-3); and high (4-5). The six potential nest scores were binned into three categories for this analysis to account for the fact that this attribute is a qualitative assessment and may the assignment of a value may be subjective. N=780, 1117 and 295 for high, medium and low nest score categories respectively. Vertical bars represent ± 1 SD.

Factors affecting nest quality

Two factors are likely to influence nest quality: breeding experience; and colony location. Because of limited samples sizes, we did not conduct joint analysis. Analysis of the study-bird dataset confirmed that the proportion of high quality nests for each age class (six to 20 years) significantly increased with age ($r=0.79$, $t_{13}=4.654$, $p<0.05$). However, the location of the nest with respect to expanding colony edges appears to have a greater influence on nest quality. We selected all nest-quality data from known-age birds in edge plots and study-birds in 2009 to control for other potential influencing factors. We compared the ratio of high quality nests [score of 4-5] to other lower nest scores [0-3] by
i) location (edge plots - study-nests; $\chi^2_{1} = 7.58, p < 0.05$) and ii) by breeding experience (experienced-inexperienced; $\chi^2_{1} = 0.02, p > 0.05$).

The influence of nest quality on breeding success and the influence of colony location on nest quality support the hypothesis that inexperienced birds, which tend to nest on the edge of colonies, are able to build higher quality nests on average than experienced birds, which tend to nest in the colony centre. These higher quality nests may confer a relative breeding success advantage compared to experienced birds in some years when the environmental conditions are favourable (Figure 4.4).

**Chick condition and parental experience**

There is limited evidence in the study-bird dataset to suggest that experienced birds produce chicks of greater mass. While chick-mass of known-age birds was not collected in 2009 (thus not in Table 4.1), 10 chicks were weighed from known-age nests in 2008. The sex of these 10 chicks was not determined, although it has been shown that male chicks tend to fledge at a higher mass than females (Hedd et al. 2002a). These data showed a significant positive correlation between parent-age and chick-mass ($r = 0.662, t_{8} = 2.495, p < 0.05$). This positive relationship between parent-age and chick-mass is also reflected in the data collected from the breeding success and edge plots in 2009. Although the age of the parents of individual chicks was not known, the average chick-mass in edge plots (inexperienced breeders) was lower than in breeding-success plots (experienced breeders) (Table 4.1, Figure 4.6; $t_{53} = 3.936, p < 0.05$).
Figure 4.6: Mass of shy albatross chicks sampled in April 2010 from Breeding-Success Plots (BSP) (with a higher proportion of experienced breeding birds) and Edge Plots (EDGE) (with a lower proportion of experienced breeding birds). N=68 and 30 for BSP and EDGE respectively. Median and quartiles are shown for each sample. Dashed lines indicate $1.5 \times$ the inter-quartile range and circles represent outliers.

Discussion

We were motivated to examine if traditional monitoring at seabird colonies was likely to be appropriate for detection of responses to climate variability. If population metrics vary spatially within a colony, lack of attention to spatial patterns within colonies may hinder attempts to detect and monitor influences of climate variability. For example, preferentially sampling experienced birds
may limit identification of relationships between breeding parameters and important environmental drivers as older birds are more robust breeders (Daunt et al. 2007; Limmer & Becker 2009; Rebke et al. 2010).

Using data from Albatross Island, we first showed that spatial structure in the age of breeding shy albatrosses – a result of population and colony expansion – can affect metric estimation. We then demonstrated that younger, inexperienced shy albatrosses show greater variability in two breeding-performance measures, breeding success and chick condition, than older individuals with more breeding experience.

**Age effects**

Improved breeding performance with age has been documented in numerous species including albatrosses (Weimerskirch 1992; Dearborn et al. 2008; Lecomte et al. 2010), petrels (Chastel et al. 1995), gulls (Vieyra et al. 2009), cormorants (Daunt et al. 2007), penguins (Lescroel et al. 2009; Nisbet & Dann 2009), raptors (Blas et al. 2009), and elephant seals (Sydeman et al. 1991). There are two major hypotheses to account for improvement in reproductive performance with age; the “restraint” and the “constraint” hypotheses (described in Limmer & Becker 2010). The restraint hypothesis suggests increased investment in breeding occurs due to declining residual reproductive values, while the constraint hypothesis suggests individuals improve their pre-breeding or parental care abilities with age, allowing them to buffer against environmental variability. There is empirical support for the constraint hypothesis in a range of taxa such as raptors (Blas et al. 2009), seals (Bowen et al. 2006) and terns (Limmer & Becker 2010). In each hypothesis, improvement also leads to reduced inter-annual variability in breeding performance, and thus the outcome of the breeding attempts of inexperienced birds may be more strongly influenced by environmental fluctuations than experienced birds.
Monitoring a more sensitive component of the population might be advantageous, as our analysis of breeding performance, represented by overall breeding success and chick condition, illustrates. We acknowledge that a range of confounding factors are important when analyzing demographic data, and may be affected by bird experience.

**Factors influencing breeding success**

The first performance measure, breeding success, as measured on Albatross Island, spans two different phases between the time of initial egg counts in September and final chick counts in April: i) hatching success; and ii) chick survival. Hatching success is potentially influenced by a range of factors that could be related to individual experience, such as body condition of the parents at the start of the breeding season (Crawford *et al.* 2008) or foraging success throughout the incubation period. Although it has been demonstrated here that nest quality is also important and related to bird age, nest quality on Albatross Island is more strongly influenced by nest location.

Nest quality is higher on colony edges where younger birds are breeding. In other albatross populations, nesting on the edge of colonies can be a disadvantage as unguarded chicks are exposed to greater predation pressure, particularly from giant petrels and skuas (Forster & Phillips 2009); but no equivalent predators occur on Albatross Island. Shy albatrosses nesting at colony edges are able to construct nests of superior quality to more centrally nesting birds because of the abundance of nest materials and limited competition for that material. Chick survival, the second phase of our breeding success measure, is also influenced by parent provisioning ability, which may increase with age and nest quality. If well-constructed nests improve the breeding success, being on the colony edge may provide an advantage that counteracts lack of experience and other potential physical disadvantages such as increased exposure to disturbance, predation risk or weather extremes (Svagelj & Quintana 2011).
Factors influencing chick condition

The second performance measure, chick mass (representing condition of the chick prior to fledging), may also provide a climate signal during the chick-rearing phase, when breeding birds must provision themselves and meet the needs of the growing chick. The ability to provision a chick – particularly in poor years – is likely dependent on adult body condition (Tveraa et al. 1998) and individual foraging ability (Hedd et al. 2002a; Limmer and Becker 2009). Limmer and Becker (2009) have shown that experience in terns (Sterna spp.) led to improved chick provisioning. Although age-related foraging ability has not been investigated in shy albatrosses, individual differences in provisioning rates exist (Hedd et al. 2002a) and these differences may be age-related. Reproductive performance has also been linked to age in other marine taxa, including grey seals (Halichoerus grypus) (Bowen et al. 2006) and Weddell seals (Leptonychotes weddelli) (Proffitt et al. 2007). There is abundant evidence that variation in ocean climate affects prey availability and that this, in turn, affects seabird reproductive performance through changes to food delivered to chicks (for example, Hedd et al. 2002b; Frederiksen et al. 2005). Although we have not linked ocean climate variation with breeding success in this species, the expanding body of literature suggests that such a relationship is probable, and we are exploring potential climate drivers in current research. For our population, sampling to expose rather than smooth variability in population metrics might lead to additional insights on population drivers. For example, moving plots over time, in addition to fixed plots or whole sub-area counts where the breeding history is unknown, might lend value to long-term monitoring.

By integrating results from breeding success and chick condition, we predict that the breeding performance of inexperienced shy albatrosses will be most sensitive to climate fluctuations (Table 4.2). In a “bad year”, experience will matter, and breeding success and chick condition will be greater in older birds. In an “average year”, breeding success will be similar or less (depending on mitigating effects of nest condition) and chick condition lower due to foraging experience of the
parents. In a “good year”, with abundant food and a favourable environment, breeding success will be similar for young and old birds (with edge-nesting birds even performing better if nest quality provides an advantage), and chick condition might also be similar as foraging experience will not be a limiting factor due to prey abundance. Although other studies have shown that prey availability is a principal mechanism through which climate influences breeding success and the condition of young (for example, Frederiksen et al. 2005), we do not have corroborating data for prey availability.

Table 4.2. Predicted breeding performance outcomes of inexperienced shy albatrosses relative to experienced individuals on Albatross Island. For example, an upwards arrow (↑) indicates that inexperienced birds will have higher performance for the metric in a given year. In the cases where two symbols are shown (e.g. =,↑), equal or greater/reduced performance is expected. In poor years, performance can be substantially lower for inexperienced birds (↓↓).

<table>
<thead>
<tr>
<th>Environment for the year</th>
<th>Breeding success</th>
<th>Chick condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>=,↑</td>
<td>=</td>
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<tr>
<td>Average</td>
<td>=,↓</td>
<td>↓</td>
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<tr>
<td>Poor</td>
<td>↓↓</td>
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Implications for monitoring protocols

The aim was to develop breeding performance indices for shy albatrosses that can be related to climate variation. Based on our results and those of other studies (for example, Pinaud & Weimerskirch 2002; Nevoux et al. 2007), we hypothesise that experience moderates the influence of the environment and that younger breeding birds will be the most responsive to climate variability. We identified spatial patterns in the age of breeding birds on Albatross Island and suggest that any inter-annual climate signal contained in breeding performance measures could be amplified if sampling protocols are modified to capitalise on that relationship.

Other studies might consider if their monitoring approach is smoothing across experience categories such that a damped response to climate variability is measured. As in our seabird example, other
Researchers use defined study areas to measure population factors such as overall breeding success (for example, Antipodean albatross, Walker & Elliott 2005), black petrels (Procellaria parkinsoni) (Bell et al. 2007), or monitor entire smaller well-defined colonies, such as Atlantic yellow-nosed albatrosses (Cuthbert et al. 2003), similar to our Albatross Island sub-colonies. We encourage researchers to consider partitioning or re-analysing existing population and demographic data, particularly given the recent need to understand the impacts of climate change. Monitoring breeding success and chick condition in older birds may prove least sensitive to a climate signal. Our goal is not to create more noise in biological metrics, but to partition data in such a way that a more responsive signal can be detected. A more responsive measure allows for more conservative management, with actions implemented earlier than would otherwise be the case. This may be particularly important for long-lived species with high adult survival and low reproductive output, such as the albatross, as population-level responses to changing climate may take a long time to become apparent.

This study demonstrates how existing monitoring that may be useful for climate studies might be enhanced in three ways: i) by developing new metrics (such as condition measures of chicks); ii) by subsampling the data that have been generated from existing metrics (such as partitioning age); iii) by additional monitoring of regions where more sensitive portions of the population may occur (for example, on colony edges). If existing monitoring programmes can be supplemented or fine-tuned to allow determination of the effects of climate variability, and, in the long term climate change, additional benefits may become evident, while at the same time enhancing the long-term value of studies. Accordingly, the principles and issues raised here might also be usefully considered in the design of new monitoring programmes.
5. Shy albatross breeding success: trends and climate influences

Abstract

Climate change is a potential threat to populations and ecosystems worldwide. Understanding relationships between biology and environmental variability is fundamental for predicting the potential impacts of climate change on species and for developing effective management and mitigation strategies. The shy albatross is an important and conspicuous marine species in the waters of south-east Australia. In order to increase our understanding of how climate change may affect this species, we investigated trends in breeding success of shy albatrosses from the Albatross Island colony and the relationship with a range of local and regional environmental variables throughout the breeding season. A significant decline was detected in the breeding success of this population between 1998 and 2010. A range of land and oceanographic variables were related to shy albatross breeding success throughout the year. The strongest relationships, however, in the models were found with environment conditions during the chick-rearing phase. Breeding success was negatively associated with rainfall and maximum temperature during chick-rearing at the breeding site, and with sea surface height anomalies associated with increased upwelling in the primary foraging areas during both incubation and the chick-rearing phases. Although there remains much uncertainty around climate change predictions, the forecast for increased maximum temperatures may have a detrimental effect on shy albatross breeding success. Conversely, predictions for decreased summer rainfall and increased upwelling trends under climate change may have positive benefits for the species. These results highlight the susceptibility of shy albatrosses to anthropogenic climate change and contribute to our understanding of the underlying climate-biology relationships. This knowledge is fundamental for assessing population impacts under climate
change scenarios and how these processes may interact with other key threats, particularly fisheries bycatch.

**Introduction**

Understanding how ecosystems and their species respond to anthropogenic climate change is a global research and conservation priority (Walther et al. 2002; Parmesan 2006; Felton et al. 2009). Climate change may affect species in a variety of ways, including changes to phenology, distribution, abundance and physiology (Walther et al. 2002). The climate-biology relationships underlying these direct impacts and the observed responses in phenology, distribution and abundance need to be studied in order to predict how populations may respond to accelerated rates of change and increased variability in climate conditions, whether these will threaten populations, and importantly, how these impacts may exacerbate existing threats (for example, Opdam & Wascher 2004; Mac Nally et al. 2009).

Climate-biology studies have proliferated over the last decade, with a distinct bias towards terrestrial ecosystems (Moller et al. 2004; Fazey et al. 2005; Felton et al. 2009), as marine environments pose particular challenges for monitoring. Marine mammals and seabirds have received much of the focus. These species spend some stage of their life-history either on land or in accessible shallow coastal waters and are therefore temporally and spatially predictable for monitoring. These highly visible and iconic top-order predators generate widespread conservation concern and attract considerable resources (Kovacs & Lydersen 2008; Moore & Huntington 2008). Where climate-biology relationships can be demonstrated, long-lived top-order marine species function as indicators of climate change, integrating effects over wide spatial scales and trophic levels and signalling and forecasting changing conditions in the hard to monitor marine environment (Weimerskirch et al. 2003; Shaffer et al. 2006; Wanless et al. 2007; Wolf et al. 2010).
In the southern hemisphere, much of the focus of research is in Antarctic and Southern Ocean ecosystems (Forcada et al. 2005; McMahon & Burton 2005; Trathan et al. 2007; Le Bohec et al. 2008; Saraux et al. 2011). Comparatively few studies have been undertaken in Australian waters that investigate specifically how marine mammal and seabird populations are responding to current climate variation and how they might respond to changes predicted for the future. A recent review however by Chambers et al. (2011) of the effects of climate on Australian seabirds found that species are affected by climatic variability at a range of temporal and spatial scales. That study concluded that although there are differences in how species and populations are predicted to respond to directed environmental change, with some populations possibly benefitting from predicted changes, overall, the potential for future detrimental impacts of climate change is high.

A conspicuous and important marine predator in the southern Australian waters is the shy albatross, *Thalassarche cauta*. Studies of other albatross species have linked environmental variability, particularly within the marine foraging environment, with key demographic parameters including breeding success (Nel et al. 2003; Rolland et al. 2008; Rolland et al. 2009a; Nevoux et al. 2010a; Rolland et al. 2010) and survival (Nevoux et al. 2010b), but no similar analyses have been undertaken on shy albatrosses. In this study we address these knowledge gaps by focussing on breeding success, an important component underlying population dynamics. Breeding success is an ideal candidate to investigate climate-biology relationships in long-lived species such as albatross because life-history theory suggests the influence of inter-annual variation in the environment will likely be greater on breeding parameters than other key parameters such as survival (Saether et al. 2004). The aim of this study is to assess temporal trends in the breeding success of shy albatrosses breeding on Albatross Island and to investigate the influence of environmental factors on this important demographic parameter.

The Albatross Island colony is located in the west of Bass Strait, a region with complex oceanography. The waters of the Strait are relatively shallow, with a mean depth between 50-70
metres and dropping to around 5 km on either side of the shelf. The area is characterised by strong tidal flows and high winds and a convergence of several major current systems (summarised in Sandery & Kämpf 2007). Oceanographic processes in and around the western Bass Strait are likely to be most important for shy albatrosses on Albatross Island. The most notable are the South Australian and Zeehan Currents (extensions of the Leeuwin current, Ridgway & Condie 2004) and wind driven coastal upwelling systems that establish on the southern shelves (Kampf et al. 2004). The influence of these processes on marine productivity varies seasonally and inter-annually.

Breeding success on Albatross Island is largely unaffected by extrinsic factors such as predation and disturbance (see Alderman et al. 2011) that are important at other populations (Forster & Phillips 2009; Wanless et al. 2009) thereby making relationships with climate potentially easier to detect. Understanding the influence of climatic factors on the temporal variation of the demographic parameters underlying shy albatross population dynamics is a critical first step towards assessing the population responses and consequences for conservation and management for this species under projected climate change scenarios.

**Methods**

**Study site and breeding success estimates**

Approximately 5200 pairs of shy albatrosses breed on Albatross Island (40° 23’ S, 144° 39’ E, Figure 1.1) off the north west of Tasmania, and this population is the site of a long-term annual demographic monitoring program that commenced in 1981 (see details in Alderman et al. 2011). Shy albatrosses breed annually, with eggs laid in September, hatching in early late November to early December and chicks fledging through April and May. Here, a breeding season is referred to by the year in which the egg was laid. Breeding success is estimated each breeding season from the proportion of eggs laid (with all breeding attempts, including failed eggs, counted in study areas at the end of the peak laying period, on or around 1 October, each year) that successfully produce
chicks (counted prior to fledging, on or around 1 April). On Albatross Island, breeding success has been estimated annually since 1998 (n=13 years) from the proportion of eggs laid (counted at the end of the peak laying period, on or around 1 October, each year) that successfully produce chicks (counted just prior to fledging, on or around the 1 April, at the end of the breeding season). Between 1086 and 1835 nesting attempts are sampled each year from a combination of whole sub-colony counts and sample areas (see Chapter 2 for further details). Counts are typically conducted once only to minimise disturbance to breeding birds and chicks. We calculated 95% binomial confidence intervals using the Wilson method in R package “binom” (Sundar 2009).

Environmental data

Spatial and temporal sampling

A number of spatial and temporal factors were considered before collating the environmental data for analysis. The shy albatross breeding season was separated into three distinct life history phases corresponding to i) the winter pre-breeding period (May to August) ii) incubation (September to December) and iii) chick-rearing (January to April), represented hereafter with “W”, “I” and “C”, respectively. Conditions experienced in any one of these phases may influence overall breeding success and some phases may be more important than others (for example, Rolland et al. 2008). Throughout the breeding cycle, adults of other albatross species exhibit considerable differences in foraging behaviour (Phalan et al. 2007) and resource allocation decisions (Weimerskirch 1999). For non-breeding albatrosses, foraging duration and at-sea distribution are not limited by any need to return regularly to the nest and all resources can be fully allocated to self-maintenance. Breeding albatrosses have an obligate dual pair parenting strategy where individuals in a pair take consecutive turns foraging and incubating the egg. Therefore, while all food obtained by a foraging individual during incubation may be self-allocated, the duration of foraging trips is constrained by the need to relieve the partner on the nest, who, if forced to fast too long, may abandon the nest to avoid starvation. When a young chick is left unattended, the parents can forage independently of one
another but must return regularly to feed the growing chick and resources must be balanced between self maintenance and provisioning the chick (Warham 1990).

As this species divides its time between breeding and foraging habitats, both oceanic and land-based environmental variables were used to explore climate-biology patterns. To account for potential spatial and temporal variability in oceanic conditions, we defined three areas corresponding to core foraging distributions of shy albatross from Albatross Island during each of these three breeding phases. This species differs from many other albatross species in its unusually restricted foraging range with adult birds in particular remaining resident in Bass Strait and south-east Australian waters year-round and returning regularly to colonies throughout the non breeding period (Hedd et al. 2001; Hedd & Gales 2005). The three core foraging areas were identified using the kernel density estimation procedure of Alderman et al.(2011) based on satellite tracking data collected in 1994, 2004 and 2005 from adult Albatross Island individuals (winter n=5, incubation n=16, chick-rearing n=7, unpublished data; Hedd et al. 2001 see Figure 5.1).
Figure 5.1: Core foraging areas of shy albatrosses from Albatross Island during the winter (pre-breeding), incubation and chick-rearing period used for the spatio-temporal sampling of oceanographic variables included in the analysis. 100 metre bathymetric lines are indicated.

For each of the candidate explanatory variables considered (see below) we calculated the average across the three breeding phases (with the exception of rainfall which was totalled for each of the four month periods).

Regional oceanographic variables

We extracted a variety of oceanographic variables for each of three core foraging areas identified and calculated averages across the corresponding four month periods. We used a 10-day SST composite product calculated at CSIRO from the Pathfinder single pass data. As a measure of ocean productivity we used the seven day chlorophyll concentration (Chl a) from the SeaWiFS sensor,
which has recently ceased operation. Thus, no data were available for the chick-rearing phase of the 2010 breeding season (January to April 2011). For these months we used AquaModis data (http://coastwatch.pfeg.noaa.gov/coastwatch/). There are differences between these two products and issues with generating composite time series have been raised (Gregg & Casey 2010). To test if our spatial and temporal averaging would allow a joint time series from the two chlorophyll products we extracted monthly time-series throughout 2010 from both products in three locations, corresponding to the centroid in each of the three core foraging areas identified (W: 38°52’ S 145°18’ E; I: 40°10’ S 143°38’ E; C: 39°21’ S 143°22’ E). The mean monthly values from each product (AquaModis 0.371 mg s⁻¹ and SeaWiFs 0.354 mg s⁻¹) were not significantly different ($t_{11}=1.293$, $p>0.1$) and thus we generated data coverage for the complete biological period. Zonal westerly winds (ZWW) are a primary driver of water movement through Bass Strait (Sandery & Kämpf 2007) and are also associated with regional productivity. We obtained daily wind speed (westerly ‘u’ component m/s⁻¹) from NOAA/NCEP http://www.esrl.noaa.gov/psd/data/reanalysis/ and averaged across the time period to obtain average ZWW strength for each time period.

Oceanographic fronts represent an interface between two dissimilar water masses and are often associated with high biological productivity (Etnoyer et al. 2006). We extracted the density of sea surface temperature fronts (SFD) in each of the three foraging areas using the single-image edge detection algorithm of Cayula and Cornillon (1992) as documented in Hartog et al. (2011), and used Maps of Sea Level Anomaly (MSLA), produced by AVISO, to measure sea surface height anomaly data (SSH) indicative of eddies and upwelling and down-welling activity.

Land based weather

Albatross breeding success might also be influenced by atmospheric variables. Monthly mean maximum temperature and total rainfall recorded by the Cape Grim weather station (station number 91245, situated approximately 35 km SE of Albatross Island; 40°41’ S, 144°41’ E) was obtained from the Australian Bureau of Meteorology http://www.bom.gov.au/climate/.
albatrosses nest building and maintenance activity intensifies dramatically during rain periods when the friable dirt substrate is converted to adhesive, malleable mud (R Alderman, personal observation). Breeding success increases with nest quality (see Chapter 4) and so might be influenced by total rainfall. We included maximum temperature during the breeding season (incubation and chick-rearing) as this may influence offspring survival directly by causing the egg or chick to overheat (Stahel & Gales 1987).

**Large scale climate variables**

Finally, we considered the influence of large scale climate drivers. The El Niño Southern Oscillation is a dominant driver of interannual climate variability globally and for Australia (Holbrook et al. 2009). Studies have found relationships between biological parameters and the Southern Oscillation Index with various lags (for example Guinet et al. 1998). We obtained monthly SOI values from the Australian Bureau of Meteorology [http://www.bom.gov.au/climate/](http://www.bom.gov.au/climate/) and calculated the average SOI value for each 12 month period corresponding to the shy albatross breeding cycle (May to April). To investigate potential time lag effects, we also calculated the 12 monthly SOI averages with successive one month lags through to 24 months prior to May each breeding season. We examined univariate correlations with breeding success to identify the strongest relationship, and used that lag in multi-variate analyses.

**Data analysis**

All analyses were conducted using R (R Development Core Team 2011). We used generalised linear models to assess temporal trends in breeding success and to investigate the relationship of this parameter with the suite of environmental variables and influence of environmental variables on this parameter. The breeding success data showed over-dispersion ($\rho=80$) which is common in ecological data and can indicate clustering or a lack of independence among samples (Zuur et al. 2007). We therefore used quasi-binomial models used to allow for the higher than expected
variance for true binomially distributed data. No autocorrelation was apparent in the breeding success time series. All variables were scaled and centred.

As climate variables are likely to be interdependent (for example, Grosbois et al. 2008) we initially undertook Principal Components Analysis (R function “prcomp”) on the candidate explanatory variables in each of the breeding phases. Results however were inconclusive in all three analyses (not presented). We therefore tested for multi-collinearity among the suite of variables in each of the breeding phases using variance inflation factors (using the "corvif" function in package AED; Zuur 2010)). A cut-off value of 10 was used to determine if variables should be eliminated from analysis (Zuur et al. 2009). We conducted separate GLMs for each of the three phases of the breeding season to identify which of the explanatory variables were important for each time period. The spatio-temporal range of each of the candidate predictor variables are indicated with the W, I or C suffix, such that ZWW extracted from the winter pre-breeding core foraging area and averaged for the corresponding months, May to August.

We used the ‘information theoretic’ approach of Burnham and Anderson (2002) for our model selection rather than a stepwise elimination process to identify a minimally adequate model because the large number of candidate predictors, the high likelihood that many would be correlated, and because selection of a minimally adequate model is affected by the order of parameter deletion, all combine to limit the reliability of the latter approach (Whittingham et al. 2005; Whittingham et al. 2006). As our data were over-dispersed, we used quasi-AIC (QAIC) as an appropriately conservative approach in R package “MuMin” (Barton 2011) and selected the parameters from the highest ranked (lowest QAIC) model. The variables from each of the separate breeding phase analyses were combined with the selected SOI index into a single ‘global’ model to investigate the relative contribution of the variables and identify which had the strongest relationship with annual breeding success of shy albatrosses.
Results

Breeding success temporal trend

Breeding success of shy albatrosses on Albatross Island has ranged from 35.3-57.1% (mean 45.4 ±6.5% SD, n=12) between 1998 and 2010 and shows a slight but significant decrease over the study period of approximately 1% per year ($F_{1,11}=6.815, p=0.024$; Figure 5.2).

![Breeding success temporal trend](image)

**Figure 5.2**: Annual breeding success estimates (diamonds) with 95% confidence intervals (dashed line) for shy albatrosses on Albatross Island 1998-2010 and temporal trends (model fit=solid line).

Environmental variables

No variables were discarded due to collinearity. The starting model for both the incubation and chick-rearing phase contained seven variables (SST, SSH, SFD, ZWW, CHLA, Rain and MaxT) and the
winter phase contained six variables (maximum temperature was not included). The multi-model comparisons in each case explored all possible subsets of variables (128 models in the incubation and chick-rearing, and 64 in the winter analyses). The top ten models, ranked in order of increasing QAIC, are presented for each analysis.

**Model selection**

The model with the lowest QAIC for the winter pre-breeding phase contained only ZWW.W – there was a positive relationship between annual breeding success and westerly wind strength ($p=0.039$). Two models in the incubation phase analysis had equal support ($\Delta$QAIC <1; Burnham & Anderson 2002); SFD.I and SSH.I were important explanatory variables in both models and one model also included Rain.I (Table 5.1). We selected the model with the least number of parameters following the principal of parsimony (Crawley 2005). Both SFD.I and SSH.I had a negative relationship with annual breeding success of shy albatrosses ($p=0.051$ and $p=0.006$ respectively). For the chick-rearing phase, the model with the lowest QAIC was one that included negative relationships between breeding success and MaxT.C ($p=0.013$), SSH.C ($p=0.052$) and Rain.C ($p=0.027$). The selected chick-rearing model had the lowest deviance of the three breeding phases, suggesting conditions during this period are the most important.

Six variables were retained from the three separate breeding phase analyses (ZWW.W, SFD.I, SSH.I, MaxT.C, Rain.C, SSH.C) for the global model. SSH during incubation and chick-rearing were highly correlated ($r=0.85$, $t_{11}=5.383$ $p=0.0002$) and were therefore averaged to create a single variable (SSH.IC) spanning the entire shy albatross breeding period from egg laying to fledging (September to April). The initial exploration of the relationship between shy albatross breeding success and the 12 monthly averaged SOI index found no significant correlations at any of the time lags considered (i.e. 0-24 months). The strongest non-significant relationship was at a lag of five months ($r=-0.431$, $t_{12}=-1.5646$, $p=0.141$) and this was selected for inclusion in the final model.
Table 5.1: Relationships between shy albatross breeding success and environmental factors experienced during the winter pre-breeding phase (top), incubation (middle) and chick-rearing (bottom). The top ten ranked models (according to QAIC) in each multi-model comparison are presented. The coefficients (strength and direction) of the relationship with breeding success of each variable retained in each of the models are shown.

<table>
<thead>
<tr>
<th>Model</th>
<th>MaxT*</th>
<th>Rain</th>
<th>Chla</th>
<th>SST</th>
<th>ZWW</th>
<th>SFD</th>
<th>SSH</th>
<th>Deviance</th>
<th>QAIC</th>
<th>ΔQAIC</th>
<th>Weight</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td>Winter pre-breeding (May-August)</td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
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<td>1.22</td>
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</tr>
<tr>
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<td>-0.17</td>
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<td>19.36</td>
<td>2.87</td>
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<td></td>
</tr>
</tbody>
</table>

*Maximum temperature was not included in the winter pre-breeding analysis as this variable was selected for its potential to affect the egg and the chick. MaxT=Maximum temperature; Rain=Total Rainfall, Chla =Chlorophyll a concentration; SST=Sea surface temperature; ZWW =Zonal westerly wind strength; SFD S=ea surface temperature frontal density; SSH=Sea-surface height anomaly.
The global model, therefore, consisted of MaxT.C, SSH.IC, Rain.C, SFD.I, ZWW.W and SOI. Of 61 models compared, the model with the lowest QAIC included MaxT.C, SSH.IC and Rain.C. (Table 5.2). There was also strong support for including ZWW.W that occurred in all three models within ΔQAIC <1 of the top ranked model. There was support for a relationship with both SFD.I and SOI (third and fourth ranked models respectively), however, the co-efficients of these variables were low compared to the other three variables indicating that the magnitude of the effects of these predictors on breeding success was minimal. The chosen model, with the lowest QAIC and the least number of parameters, modelled breeding success as a function of MaxT.C, SSH.IC and Rain.C. The p values on the parameter estimates in the final model were: SSH.IC (p=0.058), MaxT.C (p=0.010) and Rain.C (p=0.044) and the resulting model fit is shown in Figure 5.2. The breeding success estimates predicted by the chosen model were within 5% on average of the observed data, with the greatest discrepancy observed for the 2000 and 2006 predictions.

Table 5.2: Relationships between shy albatross breeding success and the environmental factors throughout the breeding season in the global model. The top ten ranked models (according to QAIC) in the multi-model comparison are presented.

<table>
<thead>
<tr>
<th>Model</th>
<th>MaxT.C</th>
<th>Rain.C</th>
<th>ZWW.W</th>
<th>SFD.I</th>
<th>SSH.IC</th>
<th>SOI</th>
<th>Deviance</th>
<th>QAIC</th>
<th>ΔQAIC</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
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<td>21.96</td>
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</tbody>
</table>

BR=Breeding (I+C); SOI= Southern Oscillation Index, averaged 12 monthly values with 5 month lag.
Figure 5.3: Fit of the breeding success values predicted by the global generalised linear model (black line) to the observed values (grey lines, dashed = 95% confidence intervals) for shy albatrosses on Albatross Island.

Discussion

Climate variability influences the performance of many marine species, particularly breeding parameters (Saether et al. 2004). Understanding these patterns and possible explanatory relationships is important in designing conservation and management intervention. Breeding success of shy albatrosses on Albatross Island averaged 45.4 ±6.5% per year but has exhibited an overall decline between 1998 and 2010. During this same time period, the number of annual breeding pairs on Albatross Island has stabilised following a sustained increase as the population recovered from past exploitation (see Figure 2.2). It is probable that density dependant effects have some role in
regulating the increase in the breeding population and are likely also to have some influence upon trends in annual breeding success for this colony. This, however, has not been examined in any detail.

The two other shy albatross populations, located on islands to the south of Tasmania are difficult to monitor and quantitative breeding success data are entirely lacking for the Mewstone population and limited for Pedra Branca (Alderman et al. 2011). The most reliable recent breeding success estimate for the tiny (~170 breeding pairs) Pedra Branca population is only 22% and breeding success is declining, likely due to inter-specific interactions with increasing population of Australasian gannets, *Morus serrator* (Alderman et al. 2011). Available breeding success data from species that are closely related to shy albatrosses (Nunn et al. 1996) and that inhabit similar latitudinal breeding and foraging ranges suggest that the breeding success of the shy albatross on Albatross Island is relatively low. For Buller’s albatrosses, *T. bulleri*, breeding on New Zealand Snares Island, breeding success is 72.7% (±5.6%, 1992-2004 ACAP 2010a). For the closely related white-capped albatrosses, *T. steadi*, on New Zealand’s Auckland Island, the estimate is 53-62% (2006 and 2007 breeding seasons (ACAP 2011b)). Further afield in the southern Pacific region, similarly-sized and annual breeding Black-browed albatrosses, *T. melanophrys*, on Australia’s Macquarie Island have similar breeding success values to the shy albatross (mean 47.7% ± 10.4 SD 1995-2007; unpublished DPIPWE data).

**Population consequences of this decline**

The relatively low and declining breeding success detected over the study period has consequences for Albatross Island population status and trends. All albatrosses are long lived species characterised by high natural adult survival, lower and more variable juvenile survival rates, delayed onset of breeding and low reproductive outputs (Warham 1990). These characteristics mean that albatross populations are most vulnerable to increases in mortality, particularly in adults (Arnold et al. 2006). A sustained decline in breeding success will influence population trajectories over longer time scales.
Recent analyses have demonstrated that adult survival rates of shy albatrosses on Albatross Island are high and show no temporal trend (Alderman et al. 2011). However, rates of juvenile survival appear to be declining in recent years (Alderman et al. 2011). If current trends are maintained, and without compensation in other demographic parameters, over time the combination of declining juvenile survival and breeding success will drive a decline in the Albatross Island breeding population through reduced rates of recruitment.

Relationships with environmental variables

We related variability in annual breeding success to variation in environmental variables and showed a negative relationship with maximum temperature and total rainfall at the breeding site during chick-rearing and with SSH throughout both incubation and chick-rearing. The low ΔQAIC values separating successively ranked models showed that other combinations of variables were plausible and illustrate the complex inter-relationships of environmental data. We addressed these complex relationships by accounting for multi-collinearity of variables and the model selection process which retained variables with the strongest and most consistent support, thus simplifying climate-biology relationships to facilitate practical interpretation and subsequent prediction.

Our study shows that local climate and ocean conditions during the breeding season are important for shy albatross breeding success, with conditions experienced during chick-rearing, particularly so. The importance of the chick-rearing phase has also been found in other seabird studies (for example auklets (Wolf et al. 2009)) and is understandable since this is the most energetically demanding period for an individual bird (Shaffer 2004).

While the relationships between breeding success with both land-based and ocean variables do not necessarily indicate cause and effect, some plausible mechanistic linkages can be identified. There are no comparable studies investigating relationships between local land-based environmental variables and breeding success in other albatross species. The negative relationship between
breeding success and maximum temperature during chick-rearing was the strongest relationship in this study (Table 5.2) and may arise through direct mortality of young chicks unable to thermo-regulate and overheating (for example in gulls, Salzman 1982). Although no site-specific data have been collected, the apparent temperatures in the breeding colonies on Albatross Island are often high during the summer months, particularly in the absence of cloud cover or wind. Adult albatrosses are regularly observed standing over their chicks to thermo-regulate and panting to assist in evaporative cooling (R. Alderman, personal observation) thereby suggesting that overheating may be a factor. Increased rainfall during the chick-rearing period was also associated with reduced breeding success. This relationship may arise if downy unattended chicks are soaked and chilled or, alternatively, if rainfall is heavy enough to cause flooding or destruction of nests.

Clear links can be made between breeding success of albatrosses and oceanographic features underlying resource acquisition and allocation factors including foraging trip duration (Kappes et al. 2010), adult mass (Weimerskirch et al. 2001) and provisioning rates (Pinaud et al. 2005). Accordingly, several studies have investigated the influence of oceanographic variables on the breeding success of other albatross populations, predominantly focussing on sea-surface temperature. These studies have reported a variety of interactions operating over a range of temporal and spatial scales (Rolland et al. 2008; Rolland et al. 2009a; Rolland et al. 2010). Strong foraging associations with SSH have been demonstrated in grey-headed albatrosses (Nel et al. 2001) and the relationship detected in this study between shy albatross breeding success and SSH is likely due to the fact that cold, nutrient enhanced waters and the associated mixing are more favourable for foraging.

Relationships between breeding success and El Niño cycles have been demonstrated in other albatross species that nest and forage in different geographic regions (Sooty and Indian yellow-nosed albatrosses, Rolland et al. 2009a; Rolland et al. 2010), but no similar relationship was found for the shy albatross. El Niño influences the Leeuwin and South Australia currents (Holbrook et al. 2009) and the five month lag in our analysis is consistent with the length of the current and time it
takes to reach Tasmania. The signal, however, is very weak by the time it reaches the west coast (Wijffels & Meyers 2004). In addition, compared to species in those other studies (Rolland et al. 2009a; Rolland et al. 2010), shy albatrosses have a comparatively small foraging distribution and local signals are likely to dominate over large-scale climate drivers.

**Predicted changes in the variables**

A motivation for the monitoring of albatross populations is to predict the population consequences of natural climate variability and anthropogenic climate change (Rolland et al. 2009b; Barbraud et al. 2011). Understanding the influence of climatic factors on the demographic parameters underlying population dynamics is a prerequisite for developing predictive models (Moller & Merila 2004). However, strong predictive relationships between demographic parameters and environmental variables are generally hard to find (Borstad et al. 2011). The strength of a climate-biology relationship may depend on the variability of the climate (Felton et al. 2009; Nevoux et al. 2010a), the length of the time-series required to detect the relationship, or other intrinsic variables such as population change or breeding experience could be obscuring the climate signal (see Chapter 4).

The good fit of the final global model estimates to the observed breeding-success data indicate this analysis has summarised a key climate-biology relationship. The breeding success time-series for Albatross Island is too short to divide and test the predictive power of these results, however we can make some qualitative predictions. Climate projections for Tasmania under both high and low emission scenarios predict that, although total rainfall will remain within historical values, there will be marked regional changes which include a general decrease of rainfall in the west of the state, including Albatross Island, during the summer months (Grose et al. 2010). Temperature changes in Tasmania are moderated by the Southern Ocean, but have nonetheless shown a consistent rising trend since the 1950s of 0.10°C per decade since the middle of the 20th Century. Under both high and low emissions scenarios, mean Tasmanian maximum temperature is predicted to continue to increase by between 1.2 and 2.8°C by the end of the 21st Century (Grose et al. 2010).
In the ocean environment, if the SSH is indicative of upwelling, then we can use the studies of the Bonney upwelling to understand and predict potential future impacts. The Bonney upwelling is strongly seasonal and primary production is maximised in February and March (Nieblas et al. 2009) and thus corresponds to the energetically demanding chick-rearing period in shy albatrosses. Under climate change projections, upwelling favourable winds are likely to increase (Hobday & Lough 2011). While we may expect increased productivity, there remain many uncertainties, including whether there is an upper threshold beyond which the positive relationship between wind strength and upwelling breaks down, and how other biological and physical processes may interact in these systems (Nieblas et al. 2009). Warm waters pulse from the Leeuwin Current into west Tasmanian waters in the winter months of June and July (Ridgway & Condie 2004) and these waters suppress upwelling. Climate change projections suggest that the strength of the southward flow of the Leeuwin current will continue to weaken (Feng et al. 2009) thereby suggesting coastal upwelling would be further favoured.

**Consideration of other factors**

Importantly, we do not know whether the observed relationships between breeding success, rainfall, temperature and SSH, will hold under projected climate change conditions. These may depend on species plasticity and the ability to respond to changes (Reed et al. 2009; Grémillet & Charmantier 2010). The diverse diet of shy albatrosses (Hedd & Gales 2001) and the year-round residency within a comparatively restricted geographic range (Hedd & Gales 2005) suggests this species has the capacity to respond to changes. In addition, no studies have been undertaken into how climate variation affects other shy albatross demographic parameters. In other seabird studies, climate fluctuation has been linked to changes in breeding phenology (Dunn 2004; Durant et al. 2006) and survival (Nevoux et al. 2007) and combined demographic impacts may amplify or counteract population consequences. Other untested features may also be important predictors of shy albatross breeding success, including density dependant effects associated with recent
population increases (Alderman et al. 2011) and competition or augmentation of prey from fisheries (James & Stahl 2000; Crawford 2004). Intra-colony differences also exist on Albatross Island, with different physical characteristics between the sub-colonies, including exposure, nesting substrate and topography which may influence breeding success. Another factor not yet considered for shy albatrosses is the presence of the avian pox virus (Woods 2004). This disease has only been recorded in chicks and only on Albatross Island where it affects breeding success by increasing chick mortality. The severity of the virus varies considerably from one year to the next, and although it has been documented throughout the colony at low levels, major outbreaks are confined to the South sub-colony, where in particularly bad seasons, the disease contributes to catastrophic breeding failure, in which up to 90% of breeding attempts may fail (unpublished data). Because these outbreaks are confined to the South sub-colony, which represents ~12% of the total Albatross Island population, the disease does not impact significantly on population-level breeding success. However, the expression of the disease is thought to be related to nutritional or stress factors in the chick (Woods 2004) and may respond to climate change in the future.

Implications for conservation and management

Our study linked breeding success on Albatross Island with climatic variation at both the breeding site and within the foraging environment and, importantly, showed that breeding success has declined over the study period, which, in combination with the decline in juvenile survival recently recorded (Alderman et al. 2011), is a trend that raises further concern for the conservation status of this population.

A fundamental goal of these climate-biology studies is to forecast the impacts of climate change on populations to improve management and conservation of species. By demonstrating relationships between temporal variation in the breeding success of shy albatrosses and variation within the environment, this study makes an important first contribution towards understanding how climatic variation shapes the population dynamics of this species. Under current predictions, there is
potential for future climate change to have either beneficial (increased upwelling and decreased rainfall) or detrimental (increased temperature) consequences for breeding success. How climate change may influence other underlying demographic parameters and how these interact to shape overall population trajectories may be investigated in the future through more comprehensive population modelling (for example, Barbraud et al. 2011).

In light of the decline in two key demographic trends (juvenile survival and breeding success) and the established vulnerability of this species to other anthropogenic processes, particularly fisheries bycatch (Appendix 1, Abbott et al. 2006a; Alderman et al. 2011), the demonstration here of a mechanism though which climate change may shape population dynamics in a potentially detrimental way suggests a precautionary approach to managing climate impacts should be adopted.

Although there is little that can be done to mitigate climate change directly, an important next step is to consider climate impacts in combination with fisheries bycatch (for example, Nevoux et al. 2010b; Rivalan et al. 2010; Rolland et al. 2010). Conservation efforts should focus on increasing the resilience of shy albatross populations with a focus on commercial fisheries, particularly by mitigating seabird mortality associated with trawl fishing and by accounting for dietary requirements when managing catch quotas (Read & Brownstein 2003; Frederiksen et al. 2004b). Further investigation into the mechanisms through which high temperatures during chick-rearing negatively affect breeding success could result in feasible actions at the breeding site to ameliorate this process.
6. The future for the shy albatross: population status, monitoring and management

**Summary**

This thesis presents the most comprehensive picture to date of the status of the shy albatross, the trends in key demographic parameters and the major processes influencing the three endemic Tasmanian populations. Prior to this work, the species was generally considered secure, continuing to recover from past exploitation and largely immune from any major systemic threats. The findings of this thesis suggest the need for a re-assessment of this status as it now presents clear evidence of decline in some key population parameters and demonstrates a number of potential threats.

**Population status and trends**

The differences in the physical settings of the three shy albatross colonies are striking; so too is the extent and certainty of the population and demographic data. There is comprehensive detailed population and demographic data for Albatross Island, but neither demographic nor population trend information for the Mewstone population, and somewhere in between the two sits the Pedra Branca population (Table 6.1). Both population size and breeding success are declining on both Albatross Island and Pedra Branca, albeit at different rates and for different reasons. Juvenile recruitment to Albatross Island is declining and there is circumstantial evidence that the same is occurring on Pedra Branca.
Table 6.1: Summary of the status and trends in key demographic parameters on each of the three shy albatross colonies, as of 2011

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Albatross Island</th>
<th>Pedra Branca</th>
<th>Mewstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population size (breeding pairs)</td>
<td>5200</td>
<td>170</td>
<td>9500</td>
</tr>
<tr>
<td>Trend in breeding population</td>
<td>Stable/recent decline</td>
<td>Steep decline</td>
<td>Unknown</td>
</tr>
<tr>
<td>Breeding success</td>
<td>Recent decline</td>
<td>Uncertain, probably declining</td>
<td>Unknown</td>
</tr>
<tr>
<td>Adult survival</td>
<td>High and stable</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Juvenile survival</td>
<td>Recent decline</td>
<td>Unknown/declining?</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Anthropogenic and environmental influences

This study improves our understanding of the factors that may be driving these trends. While mortality on pelagic longlines was once the major concern for shy albatrosses in the 1980s and 1990s (Gales et al. 1998), the combination of declining fishing effort and improved mitigation measures within the Australian EEZ has greatly reduced rates of seabird, particularly albatross, mortality in recent years (Lawrence et al. 2009; Trebilco et al. 2010). Shy albatrosses were subsequently considered largely immune from any major threat, fisheries or otherwise (Baker et al. 2002; Baker et al. 2007). Chapters two and three however, demonstrate that fisheries bycatch remains an issue, draw particular attention to interactions with the trawl fishery, and emphasise the population and age-related differences in the spatial and temporal overlap between shy albatrosses and fisheries, and the implications of this differential risk. Juveniles consistently have greater overlap than adults and birds from the Mewstone are, perhaps, at the highest risk.

The study also demonstrated that shy albatrosses are not immune to the potential threat of climate change. This vulnerability was revealed by exploring aspects of shy albatross demography and their relationships to environmental variables. The breeding success of shy albatrosses on Albatross Island was shown to be influenced by a suite of regional oceanographic and climate variables in chapter five. The survival of post fledging albatrosses was also shown to be related to oceanic conditions in
chapter three, and that importantly, this was a greater influence for the two southern populations than it was for Albatross Island.

Through the analysis of relationships between demography and environmental variables, this thesis suggests shy albatrosses are vulnerable to climate change. In chapter five, breeding success of shy albatrosses on Albatross Island was shown to be influenced by a suite of regional oceanographic and climate variables. In chapter three, the survival of post-fledging albatrosses is also shown to be related to oceanic conditions, and that, importantly, the influence is greater for the two southern populations than for Albatross Island.

*Filling the gaps: a global assessment*

Global assessments are critical for wide-ranging species, yet for many albatross species, their distribution across national boundaries makes this a particular challenge. The relatively restricted breeding and foraging ranges of the three shy albatross populations, however, makes a global assessment of this species less problematic.

The population trends of the Mewstone population have the greatest influence on overall species trajectory. Demographic data however, are entirely lacking for this remote and relatively inaccessible population. This study addresses knowledge gaps for this enigmatic population through an indirect and process-oriented approach. Knowledge of the at-sea distribution of the Mewstone and Albatross Island birds are roughly equivalent, thereby making it possible to quantify and compare the relative exposure and influence of at-sea processes upon birds from each population. It is therefore possible to make plausible inferences about the demographic consequences of these differences for Mewstone individuals using Albatross Island as a reference population. Juvenile and adult birds from the Mewstone population have greater exposure to fisheries with known albatross mortality, both within Australia and international waters, and, accordingly, survival of both age classes is likely lower than recorded on Albatross Island for this reason alone. Chapter three
demonstrates that the physical location of the Mewstone (> 500 km from highly productive shelf and upwelling areas) puts naïve fledging birds at a disadvantage when compared to Albatross Island chicks which fledge adjacent to productive waters. Based on these results, it is likely that post-fledging survival of Mewstone birds is generally lower, and possibly more variable, than those on Albatross Island. Breeding success on Mewstone is also unknown. On Albatross Island breeding success is declining, and in contrast to Pedra Branca which is also declining, there is no obvious local population-specific driver. Rather, a broader regional process is more likely, and so, in the absence of population specific data, it is reasonable to assume that this declining trend also holds true for Mewstone. In addition, qualitative observations suggest breeding success on Mewstone is lower than on Albatross Island for purely physical and topographic reasons. While four of the key demographic parameters for the Mewstone population remain unknown (Table 6.1), we may assume that values and trends are, at best, similar to those on Albatross Island, but given what is now known about the increased vulnerability of Mewstone birds to some key processes, we can plausibly argue they may in fact be worse.

**Implications and applications for conservation and monitoring**

**Trawl bycatch**

A key conclusion of this study is that mortality associated with trawl fishing represents the greatest threat to shy albatrosses. Globally, there has been significant increase in awareness of this threat and subsequent action in the last ten years, yet, somewhat surprisingly given Australia’s significant financial and intellectual contribution to albatross conservation, the issue of trawl bycatch within Australian waters has been largely overlooked until very recently. Despite being prevalent within the international arena (Bartle 1991; Yorio & Caille 1999; Weimerskirch et al. 2000b; Sullivan et al. 2006b; Watkins et al. 2008; Waugh et al. 2008), with the exception of the Subantarctic and Antarctic fishery (Wienecke & Robertson 2002), there were no similar contributions for the Australian EEZ on this topic and it was generally considered a rare event (Baker et al. 2002).
The potential impact of trawl bycatch was first highlighted by Phillips et al. (2010) and considered by Alderman et al. (2010). This was followed by a preliminary investigation of seabird interactions with the Commonwealth-managed trawl fishery that confirmed the occurrence of fatal interactions and raised concern about the potential impact on shy albatrosses in particular (see Appendix).

With evidence mounting, the need to address seabird bycatch in this Australia’s trawl fishery has gained general acceptance among fishers, managers and conservationists. In October 2011, the Australian Fisheries Management Authority (AFMA) required all trawl vessels within the Commonwealth-managed South East Scalefish and Shark Fishery (SESSF) to implement Seabird Management Plans (SMPs) which include offal management and physical mitigation measures (M. Gerner, Manager Bycatch Program, AFMA, personal communication). Evaluating the efficacy of any mitigation measures is hindered by a lack of baseline data on bycatch rates. As the shy albatross is the seabird species most affected by trawl mortality in southern Australian waters (see Appendix 1), the continued detailed demographic studies of the Albatross Island population is relevant for both species management and conservation and as an indicator of mitigation success.

While bycatch is the most obvious threat, commercial fishing operations may affect top order marine predators in a variety of ways, including influencing foraging behaviour and distribution (Votier et al. 2010; Granadeiro et al. 2011), and foraging efficiency and diet composition (James & Stahl 2000; Martinez-Abrain et al. 2002; Grémillet et al. 2008b), all of which may ultimately impact populations via resource allocation and breeding parameters. While it is known that fisheries discards are a component of the shy albatross diet (Hedd & Gales 2001) we do not yet have a clear understanding of the relative importance and extent to which the birds rely on this food source. Without this knowledge, it is not possible to consider the potential implications of temporal and spatial changes in fishing effort and associated changes in discharge rates and composition on population parameters (Votier et al. 2004). More importantly perhaps, shy albatrosses and commercial fisheries compete for many of the same species (Hedd & Gales 2001; Wilson et al. 2009)
and accordingly, quantifying the dietary requirements of shy albatrosses and accounting for these in fisheries management (Crawford 2004) offers the potential to increase resilience against other processes such as climate change.

*Climate Impacts*

Understanding the impact of climate change on populations, species and communities is a global research priority and a precursor to directed action (Hughes 2000; Parmesan 2006; Felton *et al.* 2009). This thesis has shown that two important shy albatross demographic parameters (breeding success and juvenile survival) are influenced by climatic and oceanographic variables. The goal for management and conservation initially, is to determine whether climate change will have a positive, neutral or negative impact upon shy albatross population trends, and to then identify and implement actions that increase population resilience. This study makes a significant contribution to our baseline understanding and has also established some processes with which to build upon this knowledge. Several changes, including longitudinal sampling of pre-fledging chick mass and the recommendations made in chapter four, have been incorporated into the Tasmanian long-term shy albatross monitoring programme specifically to enhance our ability to detect climate-biology relationships.

However there are a number of priority gaps. Given the importance of survival in determining population trajectories, an essential next step is to investigate the role of climate variation in both juvenile and adult survival rates of shy albatrosses (Nevoux *et al.* 2010b; Rolland *et al.* 2010). Breeding phenology is also a key parameter to investigate (Stenseth & Mysterud 2002; Barbraud & Weimerskirch 2006; Reed *et al.* 2009). Finally, any impact needs to be considered in relation to the species’ plasticity and its consequent ability to buffer fluctuations and adapt to change, for example through changes to diet, foraging behaviour and breeding parameters (Forcada *et al.* 2008; Devney *et al.* 2010; Grémillet & Charmantier 2010).
The shy albatross data have also been included in a collaborative project under the National Climate Change Adaptation Research Plan (NARP) entitled “Human adaptation options to increase resilience of conservation-dependent seabirds and marine mammals impacted by climate change”. Among other things, this project seeks to extract climate signals from selected time series data and develop a suite of multi-species spatial and temporal indicator metrics for climate change impacts and ultimately to provide practical adaptation guidelines for science and management (Hobday et al., NARP/FRDC project 2010/055). These findings also have implications for other seabird species that may be affected by climate change in Australia and elsewhere.

**Pedra Branca – a conservation dilemma?**

The tiny Pedra Branca population is in many ways exceptional. Although climate and fisheries mortality are likely to affect this population in much the same way as they do the other populations, the predominant influence is the increasing Australasian gannet (Morus serrator) population and associated frequency and intensity of inter-specific interactions, with a consequent reduction in breeding success and, possibly, reduced recruitment of young albatrosses into the breeding population.

The implications of possible extinction of this shy albatross population depend upon philosophical and scientific standpoints. On one hand, the loss of this population might be considered relatively inconsequential from an overall species perspective, as it represents just 1% of the total breeding population and there is no clear population genetic differentiation (Abbott & Double 2003b). On the other hand, it might be argued that the loss of this population represents a loss of habitat and a unique piece of natural history and associated diversity. There are as many possible management responses as there are opinions about consequence, ranging from a policy of “no intervention” through to the more extreme “culling of gannets”. Some of these proposals were canvassed in a workshop held in July 2009 that included several Tasmanian-based researchers and managers with
an involvement in albatross conservation (Alderman 2009). Factors considered at the workshop included whether the underlying increase of gannets is anthropogenic in origin (for example, Bunce 2004); what is the certainty associated with the predicted extinction; whether intervention would be effective in the longer term; and whether there are consequences for other species or communities. Yet, much of the necessary information is lacking. Given the logistical difficulties of collecting this information, a decision must be made as to whether a pre-emptive approach and intervention is warranted, or to wait for further data. With so many unknowns, there is a need for an evidence-based debate to develop a structured framework for management decisions that is based on consensus of opinion and takes specific account of the lack of available knowledge and the associated uncertainty in the decision making processes (for example, using Bayesian belief networks, Howes et al. 2010; Loyd & DeVore 2010).

Such a framework may be useful in other situations where conflicts arise from inter-specific interactions. Increases have been observed in many other gannet populations around the globe (Greene 1999; Bunce et al. 2002; Grémillet et al. 2006) and the predicament facing the Pedra Branca shy albatross could possibly be repeated on seabird colonies in other regions. In another example of a management challenge, Cape fur seals (Arctocephalus pusillus), which are increasing following past exploitation, kill a potentially unsustainably large numbers of threatened Cape gannets in South Africa (Makhado et al. 2006; Crawford et al. 2007).

The implications of this study extend beyond the Tasmanian shy albatross and the processes that affect its three populations, and contribute to a broader understanding of seabirds, their monitoring, management and conservation. Of course, no species lives in isolation and processes need to be understood and managed within a broader ecosystem framework. This research contributes to our understanding of the interactions between shy albatrosses and other species, including humans, whether through competition, predation or coexistence, in marine and breeding habitats.
Importantly, the approach taken in this thesis to assess and manage a species that is particularly difficult to monitor and for which there remain significant knowledge gaps in terms of demography and anthropogenic and environmental threats, is applicable more broadly to fisheries management, climate change and the challenges of population monitoring. These are conservation and management issues relevant for a diverse range of species and communities.
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Appendix

Interactions between seabirds and the Commonwealth Trawl Fishery:

A pilot investigation

Report by

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Tasmanian Department of Primary Industries, Parks, Water and Environment.

for the
Commonwealth Department of Sustainability, Environment, Water, Populations & Communities
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