

Part II: Species and species groups

Chapter 14

Vulnerability of seabirds on the Great Barrier Reef to climate change

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Birds are indicators of the environment. If they are in trouble, we know we'll soon be in trouble.

Roger Tory Peterson

14.1 Introduction

Seabirds are highly visible, charismatic predators in marine ecosystems that are defined as feeding exclusively at sea, in either nearshore, offshore or pelagic waters. At a conservative estimate there are approximately 0.7 billion individuals of 309 species of seabirds globally¹⁵. Such high population abundance means that in all ecosystems where seabirds occur the levels of marine resources they consume are significant¹⁵. Such high consumption rates also mean that seabirds play a number of important functional roles in marine ecosystems, including the transfer of nutrients from offshore and pelagic areas to islands and reefs, seed dispersal and the distribution of organic matter into lower parts of the developing soil profile (eg burrow-nesting species such as shearwaters)⁵⁷.

A total dependence on marine food resources makes seabirds key upper trophic level predators in marine ecosystems... This means that seabird demographics and reproductive parameters are strongly impacted by, and closely reflect, changing oceanographic and trophic conditions. Prey abundance and seabird reproductive biology have been significantly correlated many times (eg Anderson et al.³, Burger and Piatt¹⁹). For this reason seabirds are widely considered important indicator species in marine ecosystems⁴³. Therefore, understanding how changing oceanographic conditions impact seabird population dynamics and reproductive ecology leads directly to critical insights into the potential future impacts of climate change, not only on seabirds, but on other functionally important components of tropical marine ecosystems.

There are two primary purposes to this chapter. The first is to present and synthesise available information on the sensitivity of seabirds to climate variability at global, regional and local scales, emphasising relationships previously observed in tropical marine ecosystems. This synthesis will then be used to identify the magnitude and scale of resultant impacts attributable to specific climatic/environmental phenomena. When combined with climate change predictions (Lough chapter 2), these findings can be used to identify those climate change processes most likely to affect seabirds of the Great Barrier Reef (GBR) and the potential magnitude and direction of these effects.

Secondly, this chapter will examine evidence for the trophic or functional mechanisms underlying each of these relationships, while simultaneously summarising available information on the adaptive capacity of seabirds to respond to variability in these phenomena. Combined, the various components of this chapter will allow the overall vulnerability of seabirds on the GBR to be assessed under current climate change scenarios.

This chapter also aims to increase general awareness and understanding of both the vulnerability of seabirds to climate change and the potential broader effects these same threatening processes have on trophic dynamics in tropical marine ecosystems. This increased understanding can then be used to guide informed management decisions that protect Australia's marine biodiversity while allowing for long-term sustainable use of the GBR ecosystem.



14.2 Seabirds on the Great Barrier Reef

For tropical seabirds in Australia, research to date has been centred in the Houtman-Abrolhos Island group of Western Australia, or on the GBR and in adjacent Coral Sea locations. The Houtman-Abrolhos colonies support over one million pairs of tropical seabirds and are the largest seabird breeding rookery in the eastern Indian Ocean¹¹¹. Australia's Coral Sea Island territories also contain regionally significant populations of many of the 13 seabird species known to breed there. North East Herald Cay is the principle seabird rookery within this region²⁴ (Baker et al. unpublished data).

The importance of the GBR as seabird breeding and feeding habitat on a national scale has previously been summarised in Hulsman et al.⁵⁷. Seabirds breeding on the GBR constitute about 2.4 percent of the total population that breed in Australian continental waters. The enormous numbers of short-tailed shearwaters (*Puffinus tenuirostris*) that breed in southern Australia are included in this figure. This masks the true significance of the GBR as seabird breeding habitat. If short-tailed shearwaters are not considered, the GBR contains over 10 percent of Australia's breeding seabirds, ranking fifth in Australia in terms of the number of breeding pairs. The importance of the GBR increases when type and range of breeding species are considered. More than 25 percent of Australia's tropical seabirds nest on the GBR, including greater than 50 percent of Australia's roseate terns (*Sterna dougalli*), lesser-crested terns (*Sterna bengalensis*), black-naped terns (*Sterna sumatrana*), and black noddies (*Anous minutus*); and about 25 percent of the wedge-tailed shearwater (*Puffinus pacificus*), brown booby (*Sula leucogaster*), masked booby (*Sula dactylatra*) and red-tailed tropicbirds (*Phaeton rubricauda*)⁵⁷.

Most major seabird colonies are located in either the far northern, northern or southern regions of the GBR⁵⁷. Raine Island in the far northern region is one of the largest and most significant tropical seabird breeding sites in Australia^{66,117,67,86,113}. Of the 24 seabirds recorded as breeding in Queensland, 14 breed at Raine Island⁸. Recently Batianoff and Cornelius⁸ have undertaken a comprehensive review of the trends in seabird numbers at this site since the beginning of last century.

Michaelmas Cay in the northern region of the GBR is a tropical seabird colony rated as the second most important nesting site in the GBR⁴⁶. The island constitutes a major nesting site for sooty terns (*Sterna fuscata*), common noddies (*Anous stolidus*), crested (*Sterna bergii*) and lesser-crested terns (*S. bengalensis*)^{65,68}. At Michealmas Cay demographic parameters for these four principal species have been collected from 1984 to 2001 as part of the coastal bird atlas (Queensland Parks and Wildlife Service). These data are of critical importance as they represent one of the few large long-term seabird monitoring data sets in Australia²², and one of the few focused on a tropical region globally (Table 14.1a,b).

Table 14.1a Local scale studies that correlate environmental variability with effects on various reproductive parameters, and proposed mechanisms

Paper	Location	Temperate/ Tropical	Species	Environmental Parameter	Seabird Parameter	Proposed mechanism?	Long/ Short term
Heatwole et al. ⁵³	Local	Sub-tropical	brown booby, silver gull	Reductions in available food, probably associated with ENSO-associated SST increases; deterioration of nesting habitat possibly related to frequency of severe storms	Population size	Reductions in available food, probably associated with ENSO-associated SST increases	Inter-annual
Smithers et al. ¹⁰⁶	Local	Sub-tropical	wedge-tailed shearwater	SST	Chick growth and foraging success	Changes in SSTs entrained by large-scale processes such as ENSO cause seasonal-scale declines in productivity at lower trophic levels	Inter-annual
Peck et al. ⁹²	Local	Sub-tropical	wedge-tailed shearwater	SST	Chick growth and foraging success	Associated underwater predators or forage fish either leave area or move to cooler deeper water	Within-season
Dyer et al. ³⁶	Local	Sub-tropical	wedge-tailed shearwater, black noddy	None	Population size		Inter-annual
Erwin and Congdon ³⁸	Local	Sub-tropical	black noddy	SST	Chick growth and foraging success	Associated underwater predators or forage fish either leave area or move to cooler deeper water	Within-season
Blaber et al. ¹²	Local	Tropical	great frigatebird, least frigatebird, brown booby, roseate tern, black-naped tern, sooty tern, bridled tern, common noddy, black noddy, crested tern, lesser crested tern, caspian tern	Effects of trawling	Population size	Extra food in the form of trawl discards may influence breeding success and hence population size in some species	Inter-annual



Paper	Location	Temperate/ Tropical	Species	Environmental Parameter	Seabird Parameter	Proposed mechanism?	Long/ Short term
Baker et al. unpublished data	Local	Tropical	red-footed booby, great frigatebird, least frigate- bird, red-tailed tropicbird, black noddy, masked booby, wedge- tailed shearwater	ENSO-associated increases in SST	Population size		Inter-annual
Batianoff and Cornelius ⁸	Local	Tropical	wedge-tailed shearwater, masked booby, red-tailed tropicbird, brown booby, least frigatebird, red- footed booby, bridled tern, sooty tern, common noddy	Lack of correlation with significant increases in human disturbance or habitat loss and/or deterioration of nesting habitat suggests decreases in food availability probably related to ENSO-associ- ated increases in SST	Population size	Population decline in 13 of 16 spp over 24 year period (69.7% reduction of total population of rookery); no evidence of significant human disturbance, no habitat loss/deterioration of nesting habitat	Decadal
Erwin and Condon ³⁷	Local	Tropical	sooty tern	SST and daily fisheries catch	Foraging success	Associated underwater predators and/or forage fish either leave area or move to cooler deeper water	Within- season
Erwin and Congdon ³⁹	Local	Tropical	sooty tern, common noddy	SST and daily fisheries catch	Size of the breeding population	Precursors to traditional parameters associated with ENSO events- depth of the thermocline	Within- season

Table 14.1b Principal regional-scale studies that correlate environmental variability with affects on various reproductive parameters, and proposed mechanisms

Paper	Location	Temperate/ Tropical	Species	Environmental Parameter	Seabird Parameter	Proposed mechanism?
Lyster et al. ⁷⁶	Regional: New Zealand	Temperate	sooty shearwater	SOI and SST anomalies in the following 12 months	Harvest rates and burrow occupancies	Significant precursors in SST around Pacific up to 1 year prior to ENSO
Bunce et al. ¹⁷	Regional: Victoria	Temperate	Australasian gannet	Mean monthly SOI and mean monthly SST; changes in activities of commercial fisheries	Population trends (3 fold increase since 1980s)	Short supply of food as result of severe curtailment of upwelling
Chambers ³¹	Regional: Victoria	Temperate	little penguin	Local scale SST, global scale SST and SOI	Breeding success, date of egg laying, hatching success, number of chicks raised per pair and weight of chicks when left nest	During ENSO events increases in westerly winds over Tasmania result in upwelling of nutrient-rich cold subantarctic waters which has been associated with increases in a number of commercially important fish stocks
Dunlop et al. ³³	Regional: Western Australia	Sub-tropical	wedge-tailed shearwater	Three year aggregate annual SOI	Three year running mean in active burrow numbers	ENSO robust controller of marine variables such as SST, salinity and sea level and hence associated with recruitment rates of various prey
Nicholson ⁸⁴	Regional: Western Australia	Sub-tropical	wedge-tailed shearwater, bridled tern, crested tern, lesser crested tern	Monthly SOI, SST and cyclonic activity	Breeding success, meal size and feeding frequency, chick growth	Differences in ocean temperatures across years associated with ENSO influencing fish populations and activity
Surman et al. ¹¹¹	Regional: Western Australia	Sub-tropical	wedge-tailed shearwater, sooty tern, roseate tern, common noddy, lesser noddy, crested tern	ENSO patterns and fisheries activity	Diets and breeding patterns- hatching success, fledging success and breeding success	Change in distribution of prey associated with ENSO-driven ocean temperature changes



Paper	Location	Temperate/ Tropical	Species	Environmental Parameter	Seabird Parameter	Proposed mechanism?
Schreiber and Schreiber ¹⁰⁴	Global	Tropical	red-footed booby, masked booby, brown booby, red-footed booby, great frigatebird, least frigatebird, red-tailed tropicbird, sooty tern, grey-backed tern, common noddy, white tern, crested tern	ENSO event	Breeding participation/success	Depression of prey availability from unusual ocean currents and thermocline as a response to atmospheric forcing of ENSO
Schreiber ¹⁰²	Global	Tropical	red-tailed tropicbird	ENSO event	Provisioning and chick growth	Nutrient content of water decreases and fish die or leave area due to ENSO
Cruz and Cruz ²⁹	Global	Tropical	dark-rumped petrel	Marine primary productivity	Chick growth rate and timing of fledging	Short supply of food as result of severe curtailment of upwelling
Boersma ¹³	Global	Tropical	Galapagos penguin	Three month average SOI	Reproduction, body condition, population trends and distribution	Overall warming in Pacific during last 20 years associated with more frequent El Niño events and less frequent La Niña events; reduced advection and upwelling during ENSO
Ramos et al. ⁹⁵	Global	Tropical	roseate tern	MEI over laying season; average SST for month of breeding initiation	Timing of breeding; size of breeding population	Influence of factors such as predatory fish on food availability overridden by importance of weather events and oceanographic conditions which determine marine productivity
Ramos et al. ⁹⁶	Global	Tropical	white-tailed tropicbird	Average monthly MEI	Reproductive success	Changes in food availability caused by changes in oceanographic-atmospheric parameters where periods with higher MEI are linked with lower ocean productivity
Ramos et al. ⁹⁷	Global	Tropical	common noddy	Occurrence El Niño or La Niña	Timing of breeding, productivity, growth rates and adult body condition	ENSO linked to high SST and lower ocean productivity

* MEI = multivariate El Niño Index; SOI = Southern Oscillation Index

The islands of the Swain reefs in the far southeast of the GBR constitute one of six core seabird breeding areas^{67,53}. Bi-annual census of seabird populations in the Swains reefs have been collected over more than a ten year period from 1984 to 1995⁵³.

Finally, the Capricorn-Bunker group of islands in the southern GBR also contains nationally and internationally significant seabird breeding populations. This island group supports the Pacific Ocean's largest breeding colony of wedge-tailed shearwaters³⁶. The Capricornia Cays also contain 73 to 75 percent of the seabird biomass of the GBR¹¹⁰, and over 97 percent of the black noddy populations of the GBR³⁶. There have been approximately 15 censuses of black noddies breeding at Heron Island between 1910 and 2000, including a series of annual comprehensive surveys of the population in the whole Capricorn-Bunker group from 1996 to 2000^{57,36}.

Many seabird species that breed within the GBR and in adjacent areas are considered migratory species and/or threatened species and are listed under the *Australian Environmental Protection and Biodiversity Conservation Act 1999*^a in a variety of categories. Many are also variously protected under international agreements such as the China-Australia Migratory Bird Agreement (CAMBA), Japan-Australia Migratory Bird Agreement (JAMBA) and the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention 1979). Additionally, the GBR region hosts migrating populations of some northern hemisphere breeding species such as common tern (*Sterna hirundo*) and much of the Asian population of roseate tern⁸⁸.

14.3 Vulnerability of seabirds to climate variation

Most previous studies (Table 14.1b) document the impact of climate on seabirds as seasonal or longer-term correlations between reproductive demographics and large-scale oceanographic processes, such as the El Niño-Southern Oscillation (ENSO). Specifically, this work suggests that ENSO type phenomena impact important demographic parameters, such as the timing of breeding, year-to-year recruitment, number of breeding pairs and hatching success on an annual or longer-term basis^{116,49,94,95,62}. Both beneficial and detrimental seasonal or longer-term impacts have been observed in a number of temperate ecosystems^{69,54,34,47}, but to date only detrimental effects have been documented in tropical ecosystems.

As well as these larger-scale longer-term impacts, there is also recent evidence that sea temperature variation at smaller within-season and day-to-day time scales significantly impacts seabird foraging success, growth patterns and reproductive output, regardless of prevailing ENSO type conditions. While not totally independent these longer- and shorter-term processes may operate on different reproductive parameters and involved substantially different trophic interactions. Therefore, documented impacts at each of these scales will be examined separately, along with available evidence of the possible trophic mechanisms responsible for each.

Other climate driven processes that may influence seabird distribution and abundance include sea level rise, changing rainfall patterns and changes to the frequency and intensity of tropical storms and cyclones. However, for these processes significantly fewer data are available from which to establish current impacts. Therefore, this group of phenomena can only be considered in less detail.

a For more information see: <http://www.environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl?wanted=fauna>

Finally, predicted changes to ocean chemistry and light/ultraviolet (UV) radiation (Lough chapter 2) will impact seabirds via trophic interactions that destabilise overall reef trophic ecology and reduce food resource availability. The potential impacts of these phenomena at lower trophic levels and the possibility that these impacts may cause trophic collapse are discussed in earlier chapters in this volume. The predicted changes in ocean chemistry and UV are not considered significant for seabirds and until further information becomes available, the likely effect of changing ocean chemistry and light/UV radiation on seabirds remains extremely difficult to predict. For this reason these phenomena will not be considered further in this chapter.

14.3.1 Seasonal-scale and longer-term climate variability

14.3.1.1 Seasonal-scale and longer-term impacts

A number of natural circulation patterns, most importantly the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and the El Niño-Southern Oscillation (ENSO), drive global climate variation⁶¹. The influence of these processes on seabirds varies with geographic location and each tends to operate at different temporal scales. The ENSO produces the strongest natural climatic fluctuations at inter-annual time-scales. The NAO displays irregular oscillations on inter-annual to multi-decadal time-scales, while the PDO is associated with decadal to multi-decadal climate variability. Within each ocean basin, extreme variations in seabird reproductive performance have been related to both seasonal-scale^{33,95,103,106} and longer-term^{104,2,102} fluctuations in these major oceanographic phenomena.

North Atlantic Oscillation (NAO) – In the Atlantic Ocean, large-scale fluctuations in the NAO have been observed to impact a wide range of seabird demographic parameters³⁵. For example, annual variability in the breeding performance of northern fulmar (*Fulmarus glacialis*) has been linked to variation in both the winter NAO and Northern Hemisphere summer temperatures with a time lag of up to five years¹¹⁴. Reduced adult survival and altered breeding phenology in North Atlantic alcid and kittiwake species has also been closely correlated with lagged effects from the NAO and associated sea temperature increases^{42,101}.

The NAO and changes in Arctic sea ice are thought to be closely coupled⁶¹ and the limited number of studies from the Arctic Ocean show changes in seabird breeding phenology, reproductive output and adult body mass related to sea ice changes¹. Breeding phenology of thick-billed murre (*Uria lomvia*) at Arctic colonies in both the northern and southern limits of the species range is positively correlated with summer ice cover. Documented trends suggest that increased global temperatures during winter and spring benefit populations at the northern limit of this range but adversely affect populations on the species southern limit⁴⁵. The recent positive temporal trend of the NAO has also been correlated to changes to both natal and breeding dispersal in Arctic terns (*Sterna paradisaea*)⁸². Southern Ocean examples of similar relationships include decadal scale population changes in adélie and emperor penguins (*Pygoscelis adeliae* and *Aptenodytes forsteri*) that have been closely related to winter sea ice extent²⁸.

Pacific Decadal Oscillation (PDO) – In the eastern Pacific the ongoing 30-year warm phase of the PDO⁴¹ has been associated with significant breeding population declines of Cassin's auklets (*Ptychoramphus aleuticus*), and with the northward retraction of multiple Pacific Ocean subarctic species including albatrosses, shearwaters and murre¹. In the same region numbers of migrating sooty shearwaters

(*Puffinus griseus*), the most abundant species in the California current system, have declined 90 percent since the 1980s¹¹⁶. This decline is thought to be linked to decreasing zooplankton volume associated with reduced upwelling and increasing sea-surface temperatures over the same period¹.

El Niño-Southern Oscillation (ENSO) – Tropical waters comprise half the total open water on earth⁷⁴ and ENSO-associated variability and fluctuations in sea surface temperature are greatest in the tropics⁴¹. Increasingly, data correlating reproductive parameters with global climate phenomena for tropical seabirds (Table 14.1b) demonstrate the potential for ENSO-associated variability to have severe detrimental impacts in tropical ecosystems at a range of different temporal scales. Substantial data exist for the central and southeast Pacific where detailed results correlate ENSO frequency and/or intensity with lengthened fledging periods, slowed chick development, a reduced incidence of breeding, and significant decreases in nesting success^{2,13}.

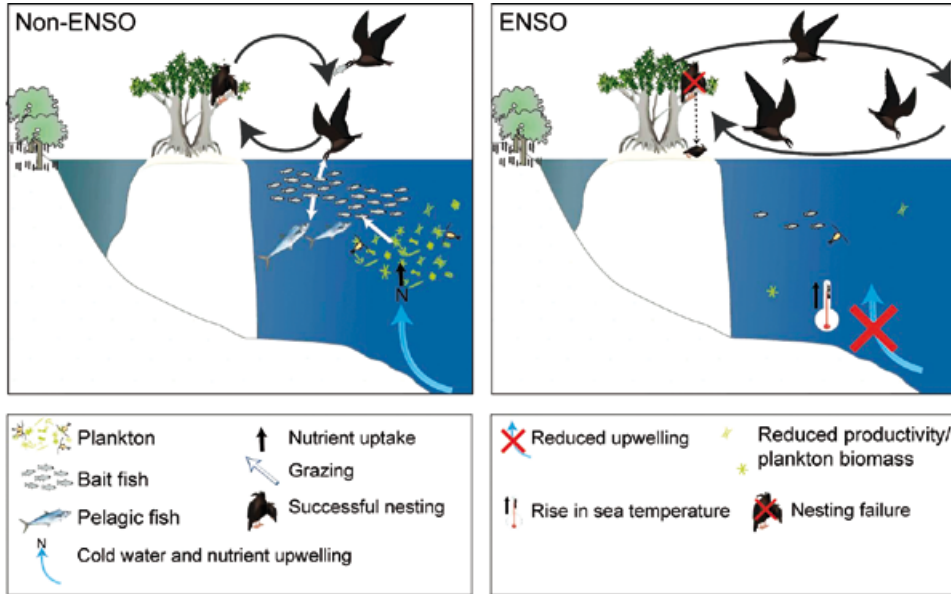
A single severe ENSO event in 1982 to 1983 produced both reproductive failure and high adult mortality in multiple seabird species breeding at Christmas Island in the central Pacific^{104,2,102}. These populations took more than a decade to regain their pre-ENSO levels¹⁰³, with brown boobies (*Sula leucogaster*) being one of the slowest species to recover¹⁰⁴. Christmas bird count data for another location in the central Pacific following this same ENSO event showed population declines of between 65 and 96 percent for red-footed boobies (*Sula sula*) and great frigatebirds (*Fregata minor*), respectively¹¹⁵. Similar population crashes were also recorded for cormorant and murre populations in the eastern Pacific Ocean in association with El Niño intensity¹¹⁵.

In the Indian Ocean seabird reproductive biology has been strongly tied to ENSO-driven processes. For example, in the Seychelles seasonal-scale variation in ENSO intensity and sea temperature have been correlated with changes in both food availability and timing of breeding for two noddy species (black noddy and common noddy) and roseate terns⁹⁷. Common noddies bred later, less successfully and with significantly reduced body condition⁹⁷. For roseate terns, larger-scale ENSO-associated fluctuations also affect the timing of breeding, while local variation in sea temperature impacts the size of breeding populations⁹⁵.

Within tropical, subtropical and temperate Australasia, significant impacts on seabird biology have been linked primarily to fluctuations in the ENSO. In Western Australian colonies, sensitivity to oceanographic conditions during ENSO years has resulted in delayed breeding and poor breeding success in wedge-tailed shearwaters and poor foraging returns for at least three of four tropical tern species (Table 14.1). At these colonies the number of active wedge-tailed shearwater burrows excavated per season directly reflected fluctuations in ENSO and oceanographic conditions from previous years: there being a significant correlation between the three-year running mean in active burrow numbers and the annual Southern Oscillation Index over the same period³³. In temperate eastern Australasia during the 2002 ENSO event, sooty terns at Lord Howe Island experienced almost complete breeding failure, with virtually all chicks that hatched dying of starvation (L. O'Neill pers comm). This reproductive crash followed a non-ENSO year with approximately 99 percent fledging success.

Large-scale ENSO processes have also been associated with negative impacts on tropical seabird breeding success in the Coral Sea and along the northeast Australian coastline, especially for colonies on or adjacent to the GBR (Figure 14.1). Such impacts have been particularly obvious during events like the 1997 and 1998 ENSO. Extremely high sea surface temperature increases during this event were also accompanied by severe reef-wide coral bleaching^{55,10}.

Figure 14.1 Breeding success of seabirds has been impacted by environmental changes associated with ENSO events; for example, reduced primary productivity of plankton can lead to reductions in food availability for hatchlings

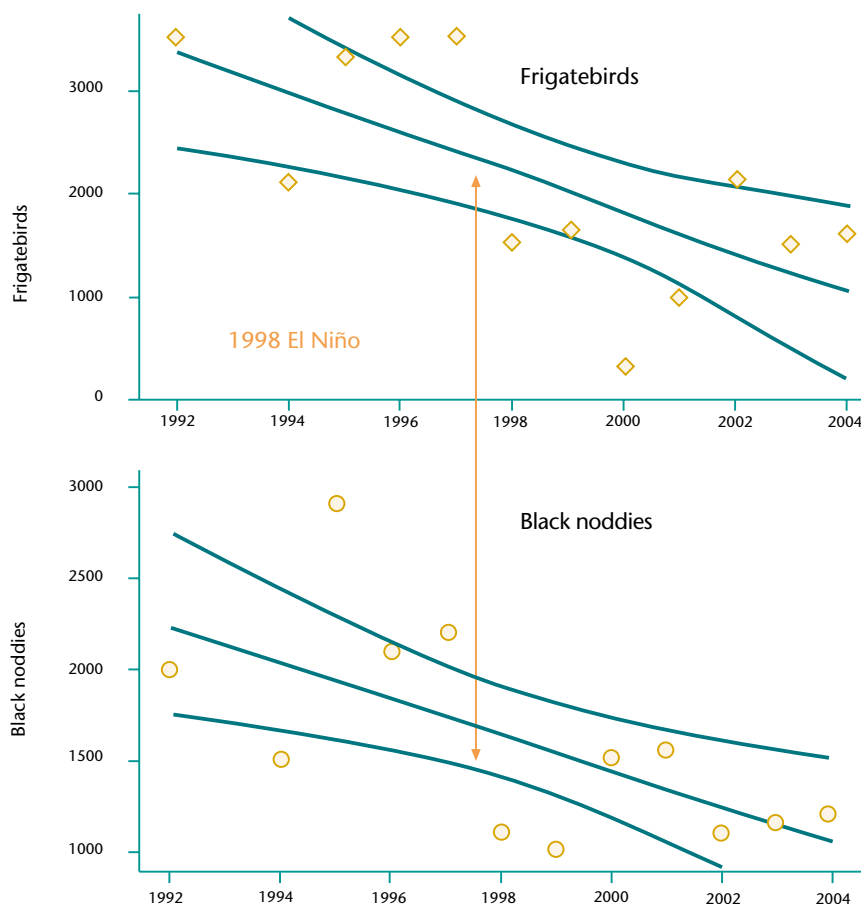


For Coral Sea populations, data over the 12-year period from 1992 to 2004 show significant declines equivalent to greater than 6 to 7 percent per annum for populations of great and least frigatebirds (*Fregata minor*, *F. ariel*) and possibly black noddies at this site⁵⁰ (Figure 14.2; Baker et al. unpublished data). Significant change in numbers of these species appears to relate to population crashes at the time of the 1997 to 1998 El Niño event. Numbers of each species remained relatively stable both before and after this event. Importantly, despite a return to presumably more favourable conditions, both the frigatebird and noddy populations have still not returned to their pre-1998 levels.

Breeding populations of both red-footed boobies and red-tailed tropicbirds in the Coral Sea have also fluctuated substantially over the 1992 to 2004 period, but based on increased numbers of sightings during annual counts in 2003 to 2004, these species appear not to have declined below pre-1998 levels. Adult breeding populations of masked boobies and wedge-tailed shearwaters have changed little during this 12-year period and no decreases were observed in association with the 1997 to 1998 ENSO event, although fewer data are available to test trends for these species.

Current population data at Raine Island in the far northern GBR indicate a potential progressive decline in breeding populations of at least 10 of the 14 breeding species. This negative trend is consistent across all species with relatively large breeding populations. Declining species listed in descending order of reduction are: common noddy (95.5%), sooty tern (84.4%), bridled tern (*Sterna anaethetus*) (69.1%), red-footed booby (67.9%), least frigatebird (67.6%), brown booby (40.4%), red-tailed tropicbird (38.5%), masked booby (26.9%) and wedge-tailed shearwater (18.6%)⁸.

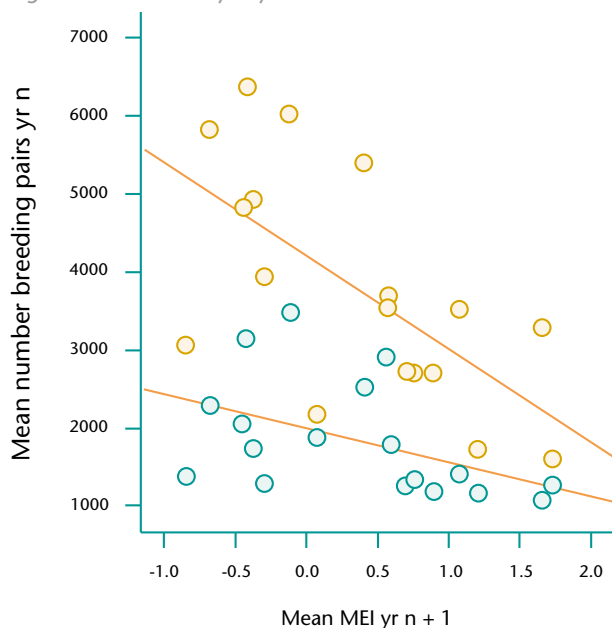
Figure 14.2 Declines in frigatebird and black noddy populations at Northeast Herald Cay in the Coral Sea Marine Protected Area between 1992 and 2004 (Baker et al. unpublished data)



The cause of the apparent declines at Raine Island is unknown. However, there is no evidence of significant human disturbance, and no deterioration of nesting habitat or habitat loss over the period of decline⁸. This lack of other mechanisms, and the fact that species which commonly form foraging associations at-sea have similar declining trends, highlights depletion of marine food stocks linked to changing climate and oceanographic regimes and/or human influences such as trawling as the most likely possible driving factors⁸.

Eighteen years of data from Michaelmas Cay in the northern GBR also show significant relationships between population trends and ENSO climatic indices at multiple levels³⁹ (Erwin et al. unpublished data). Of primary importance is that breeding populations of the two pelagic foraging species, the sooty tern and common noddy, showed significant negative correlations with ENSO intensity in the year following each breeding survey (Figure 14.3). Similar relationships were not found for the inshore foraging crested tern that is thought to supplement natural food sources with discards from trawlers¹².

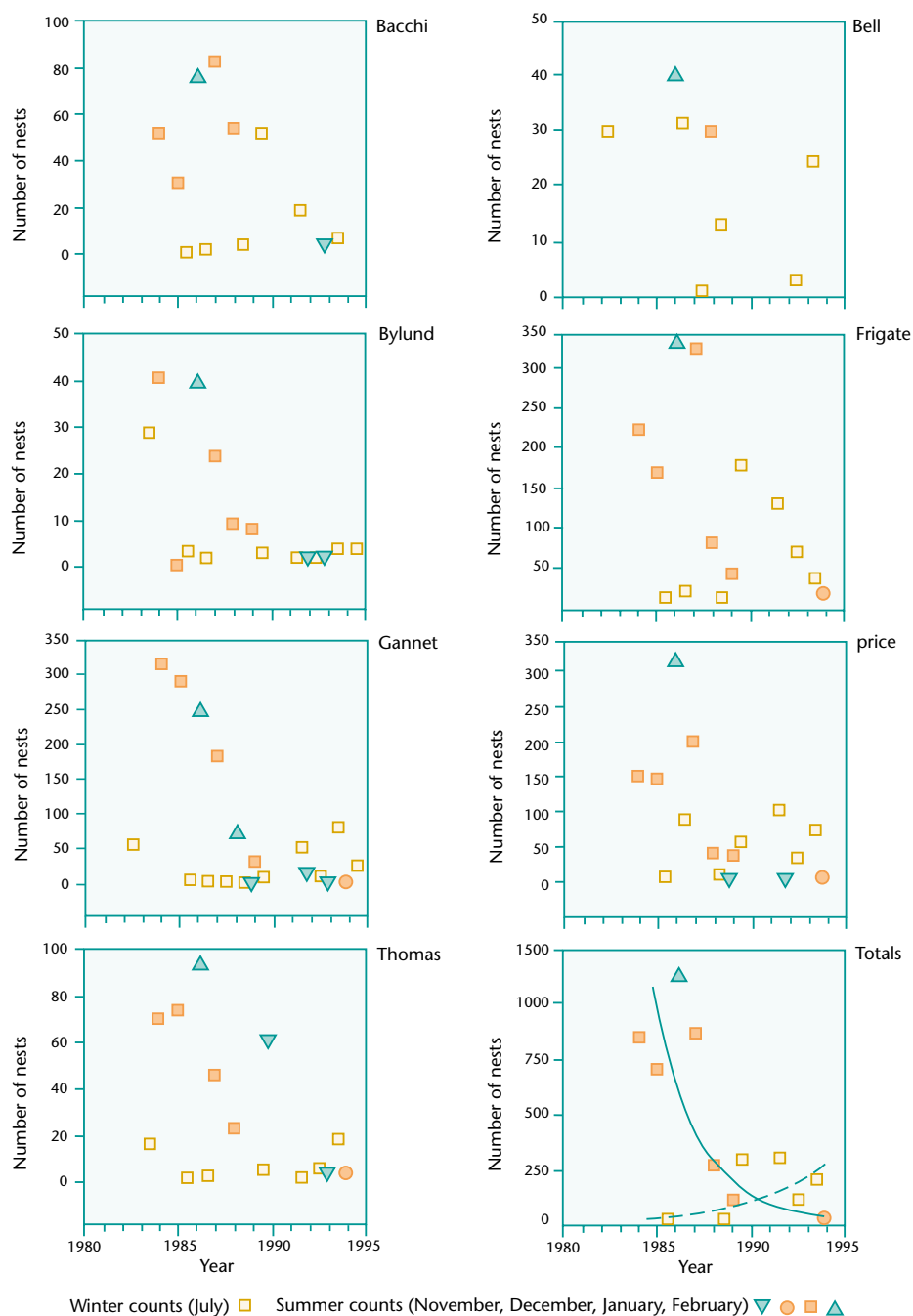
Figure 14.3 Significant negative relationships between mean annual multivariate El Niño Index (MEI) in year $n + 1$ and mean annual numbers of breeding pairs of sooty terns (○) and common noddies (○) breeding at Michaelmas Cay in year n ³⁹



These findings imply that the number of pelagic foraging adult terns that return to Michaelmas Cay to breed in any given year can be significantly impacted by ENSO precursors long before ENSO indices register an impending event. Significant negative relationships between precursor changes in the depth of the 20°C thermocline and the number of breeding pairs of sooty terns and common noddies at Michaelmas Cay³⁹ suggest a plausible mechanism for the observed ‘predictive’ ability of these pelagic tropical terns. Similar relationships between breeding numbers and the direction and intensity of ENSO and sea temperature anomalies over the following 12 months have also been observed in sooty shearwaters breeding in New Zealand⁷⁶ and multiple seabird species breeding along the southern African coast⁷⁰. Further analyses of sooty tern and common noddy data for Michaelmas Cay also suggest that levels of recruitment are impacted over longer periods, negative impacts being clearly manifested as poor recruitment to the breeding population approximately three years after ENSO conditions (Erwin et al. unpublished data).

Long-term data on seabird abundance and demography from the Swains Reefs in the southern region of the GBR show negative population trends for brown boobies in both the number of active nests and total adults on all but one of seven islands studied. Figure 14.4 illustrates the cumulative declines that occurred on individual cays as well as the overall trends. This figure clearly shows that the declining trend was consistent throughout the region and was not simply a consequence of inter-seasonal migration between islands⁵³. The causes of these significant declines are unclear, but the authors believe that they are unlikely to be human disturbance induced. Aerial surveillance data obtained over the same period suggest no increase in the level of human visitation to the area⁵³.

Figure 14.4 Number of brown booby nests recorded between 1980 and 1995 on seven cays in the Swains Reefs (source Heatwole *et al.*⁵³)

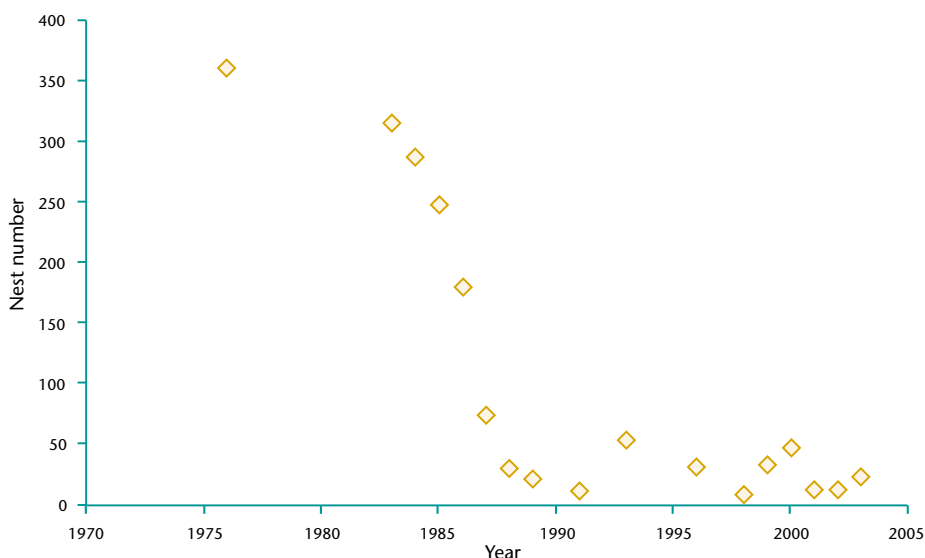


Similarly, there are no data to suggest that changes in charter or fishing boat operations have caused higher levels of seabird disturbance. Instead, the most likely explanation for the declines is purported to be decreases in food availability associated with three significant ENSO events that occurred between 1984 and 1995⁵³. The presence of high numbers of emaciated brown booby chicks following these events further suggests that food availability linked to ENSO variation played a major role in the observed declines⁵³. Masked booby did not exhibit similar declines, possibly because of differences in its feeding ecology⁵³, although the exact reasons for species-specific differences in response are unknown. More recent data for Gannet Cay within the Swains group indicates the impacts of the larger 1997 to 1998 and 2002 events are barely discernible because breeding numbers have not recovered from declines that occurred during the 1980s (Figure 14.5).

Wedge-tailed shearwaters and black noddies numerically dominate breeding seabird species of the Capricorn Island group in the southern GBR^{67,58,36}. The black noddy population on Heron Island has increased exponentially since early last century^{7,85}, however, recent censuses on Heron Island demonstrated a substantial decrease in active nests from approximately 70,000 to 30,000 between 1996 and 2000³⁶. Mass mortality of both adults and chicks was observed in January 1998 coinciding with the 1998 ENSO event and extensive coral bleaching in the region⁹.

Similarly, in 2002, a second year of abnormally high sea surface temperature, reduced provisioning, decreased growth rates and almost complete reproductive failure of wedge-tailed shearwaters occurred at Heron Island¹⁰⁶. Compared with data from the previous year, adult shearwaters were unable to compensate for changes in either the availability or accessibility of forage-fish by increasing food loads or foraging rates.

Figure 14.5 Decline in numbers of active brown booby nests (summer) at Gannet Cay in the Swain Reefs GBR during the period 1976 to 2004 (Heatwole et al.⁵³, O'Neill et al. unpublished data)



14.3.1.2 Seasonal-scale and longer-term trophic mechanisms

In general, the observed large-scale upper trophic level impacts of climate variability described above have been attributed to interrelated seasonal-scale decreases in productivity or prey species abundance at lower trophic levels^{108,34,60}. These studies propose that, during intense ENSO events, unfavourable sea temperatures disrupt or block nutrient rich upwelling zones, thereby disrupting phytoplankton distribution and abundance^{77,64,122}. This in turn produces seasonal-scale declines in productivity at lower trophic levels^{100,108} that impact recruitment of seabird prey species^{104,30,108,109,34}.

Work in temperate ecosystems has expanded this model by showing that sea surface temperature variation can induce changes in the timing of peak productivity during spawning or juvenile life-history stages of prey species. Such changes can impact seabird breeding success via phenological 'mismatches' between prey recruitment and seabird breeding requirements^{11,54,34,42}. By definition, these models predict that foraging success during ENSO events should be lower at the beginning, and possibly for the duration of the breeding season, and that these impacts will be general across all seabird species using the impacted resources.

A third seasonal-scale hypothesis is that particular food types may be associated with individual water masses that move out of reach of breeding birds during ENSO events^{59,69}. This hypothesis has even greater merit if the vertical, as well as horizontal distribution of potentially favourable water masses is considered. For example, the reason that pelagic foraging sooty tern and common noddy are sensitive to ENSO precursors up to twelve months in advance of an ENSO event is closely associated with changes in the depth/gradient of the Pacific Ocean thermocline³⁹. Many seabird taxa are known to forage in association with specific thermocline depths. In particular, eastern tropical Pacific piscivorous seabirds have been shown to forage preferentially in areas where the thermocline is deepest and most stratified¹⁰⁷. This suggests that any change in thermocline depth will significantly influence prey accessibility to these taxa. In the Pacific, substantial changes in thermocline depth and stratification are important precursors that can occur up to one year preceding ENSO anomalies^{81,99}.

While evidence exists in support of each of these seasonal-scale productivity or distributional models, most studies to date have not attempted to identify any direct mechanism linking ENSO and sea surface temperature variation with adult or fledgling survival. Therefore, the exact trophic mechanisms involved remain relatively unclear^{32,77,51,109}.

14.3.1.3 Seasonal-scale and longer-term vulnerability and thresholds

In general, the accumulated evidence of impacts presented in the preceding sections clearly highlights the sensitivity of seabirds to variation in large-scale oceanographic phenomena. Unfortunately, there is little consistency in research methodology among these studies. Detailed comparisons between data sets are hampered by the wide variety of demographic, phenological and environmental parameters measured at different temporal and spatial scales. This makes it difficult to formulate and parameterise general models of impacts for specific climate change scenarios across different ecosystems or species. However, some generalities are apparent.

Significant impacts have been observed in all ocean basins as well as in all regions of the GBR and adjacent areas of Australasia. Impacts occur at inter-annual, decadal and even longer time scales and across taxonomic and functional groups. Virtually all taxa examined show some degree of impact at one or more locations, with these taxa being from different families, genera, and/or species.

Impacts have been observed to occur across all foraging guilds (ie inshore, offshore and pelagic species) with offshore and pelagic species appearing to be significantly more sensitive than inshore foragers. Negative impacts have also been observed on nearly all components of seabird reproductive biology, such as timing of breeding, year-to-year recruitment, number of breeding pairs, annual hatching and fledging success, chick growth and adult survival, etc. Combined, these findings imply that recent climate fluctuations linked to these large-scale oceanographic phenomena are already having significant detrimental impacts on seabird populations both globally and within the Australasian region. Available evidence also suggests that predicted changes in the frequency and intensity of phenomena associated with climate change trends are likely to further compound these impacts.

14.3.1.4 Seasonal-scale and longer-term adaptive capacity

As evidence of the influence of climate variation on seabird reproductive dynamics increases, it is becoming obvious that individual species and even individual birds with distinct phenotypic characteristics respond differently to climatic anomalies. Different responses are manifested depending upon diet^{69,94,60}, dispersal characteristics⁴², sex^{48,63}, age^{114,94,18} and the demographic parameters being measured⁶³. Major differences in foraging ecology between species are presumed to be one of the main reasons for variable responses to ENSO conditions³⁹.

Different seabird species also show different sensitivity and rates of recovery to both ENSO events^{104,96} and associated sea surface temperature anomalies dependant upon breeding location^{69,60}. In the clearest example, varying rates of recovery over a two-year period were documented in seabirds nesting on Christmas Island in the central Pacific during the severe 1982 to 1983 ENSO event¹⁰⁴.

Why species-specific sensitivity differs between specific ENSO events and locations is unknown, but data suggest much of this variation may relate to interactions between a species' population size, foraging ecology, and the pattern and intensity of previous location-specific impacts. Such location and species-specific variations in response make generalising about adaptive capacity difficult and suggest that assessments of resilience or adaptive capacity will need to be undertaken on a colony by colony, or regional basis with data obtained specifically for that purpose.

14.3.2 Short-term and within-season climate variability

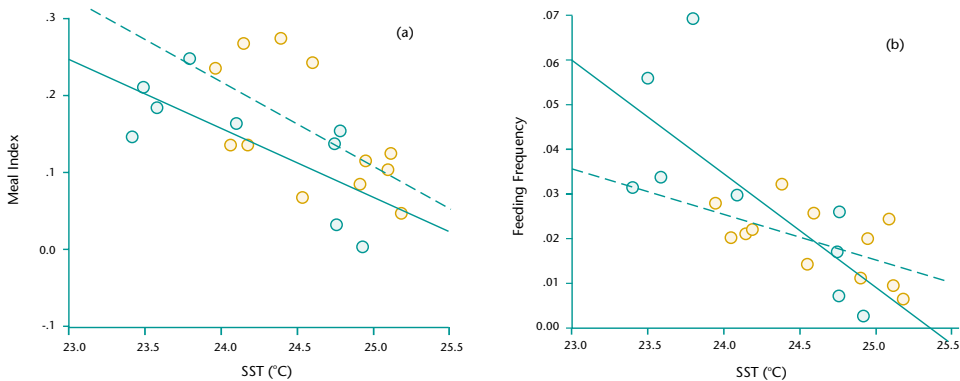
14.3.2.1 Short-term and within-season impacts

As discussed, most evidence of potential climate change impacts on seabirds comes from large seasonal-scale correlations between reproductive biology and ENSO type activity. The three seasonal-scale mechanistic hypotheses described above all involve within-season time lags between shifting sea surface temperature and the availability of prey species to seabirds^{108,34}. Moreover, they predict that food availability should be lower and/or delayed over entire breeding seasons.

However, recent research in both the northern and southern regions of the GBR has highlighted previously undescribed spatial and temporal links between within-season variation in sea surface temperature and seabird reproductive success. Considerable evidence now exists that the foraging success of multiple seabird species fluctuates daily in direct association with small-scale variation in sea surface temperature. These relationships are consistent both within and among breeding seasons and have been observed in multiple study years regardless of prevailing El Niño conditions^{92,37}.

For example, at Michaelmas Cay during the latter two-thirds of two consecutive breeding seasons in 2004 and 2005, significant negative relationships were observed between day-to-day variation in sea surface temperature and both feeding frequency and the amount of food fed to sooty terns chicks (Figure 14.6). Both provisioning variables responded to changes in sea surface temperature in a similar manner among seasons. However, during 2004, both were consistently lower for equivalent sea surface temperature values, suggesting that food was generally less abundant³⁷. Consistency in the

Figure 14.6 *Sterna fuscata*: effect of daily sea surface temperature (SST) at Michaelmas Cay on (a) age-adjusted Meal Index (○), 15 September to 3 October) of 2004 and (○), 20 May to 22 June) of 2005 and on (b) age-adjusted feeding frequency during the same periods in 2004 (○) and 2005 (○)³⁷



rate at which food availability changed between years implies that short-term variation in sea surface temperature impacted sooty tern provisioning similarly across breeding seasons for temperature ranges of 23 to 26°C as measured at Michaelmas Cay. Neither season was significantly influenced by ENSO driven anomalies in sea surface temperature or ocean circulation.

During the beginning of each breeding cycle in both 2004 and 2005, rapid changes in foraging success and food availability also occurred at Michaelmas Cay that were independent of, and an order of magnitude greater than, those attributable to day-to-day variation in sea surface temperature. This highlights that sea surface temperature variation in the vicinity of Michaelmas Cay may only impact foraging success during periods of low food availability and that other within-season mechanisms also have a significant influence on sooty tern reproductive potential. Limited evidence from the same data set suggests the distribution of subsurface predators as one possibility³⁷. That other processes may also operate is significant, as the potential for these as yet unidentified trophic links to be impacted by climate change is unknown.

Day-to-day fluctuations in prey availability and reproductive success have also been correlated with small-scale day-to-day variation in sea surface temperature for wedge-tailed shearwaters and black noddies at Heron Island^{92,38}. For wedge-tailed shearwaters daily increases in sea surface temperature negatively impacted average meal sizes, feed frequencies and chick growth rates, both within and among seasons⁹² (Figure 14.7a-c). During 2003, a 1°C increase in sea surface temperature reduced

feeding frequency from approximately one night in two, to one night in five and daily chick mass gains were reduced by approximately six to seven percent of body weight per day.

Similarly, detailed studies of black noddy reproductive success during an extreme warm water event (1 to 1.5°C above long-term averages) in December 2005 to February 2006 showed significant negative relationships between day-to-day variation in sea surface temperature and adult provisioning rates, daily meal mass and relative chick growth³⁸ (Figure 14.8a-c). For each 1°C increase in sea surface temperature over the study period, feeding frequency declined on average by one-half a meal per day for each chick (from an average of approximately 3 meals per chick per day) and daily chick mass gains were reduced significantly. These findings were consistent with results for the northern GBR on the relationship between sooty tern foraging success and day-to-day variation in sea surface temperature³⁷.

In each of the three studies described above, significant decreases in prey availability tracked changes in sea surface temperature over short time scales and did not remain depressed over entire breeding seasons. These findings provide the first evidence that declines in seabird breeding success previously coupled exclusively to seasonal, yearly or decadal scale El Niño variation may not exclusively involve large-scale, inter-annual processes. Instead, these impacts may also result from the cumulative effects of day-to-day trophic interactions that operate within all breeding seasons.

Figure 14.7 *Puffinus pacificus*: the relationship between: (a) sea surface temperature at Half-tide rocks (SSTHALF) and meal mass per gram of chick (MMASS); (b) SSTHALF and feeding frequency (FFREQ) during the 28 day study period in 2003; (c) change in chick mass per gram of chick (CMASS) and SSTHALF during the 2003 study period⁹²

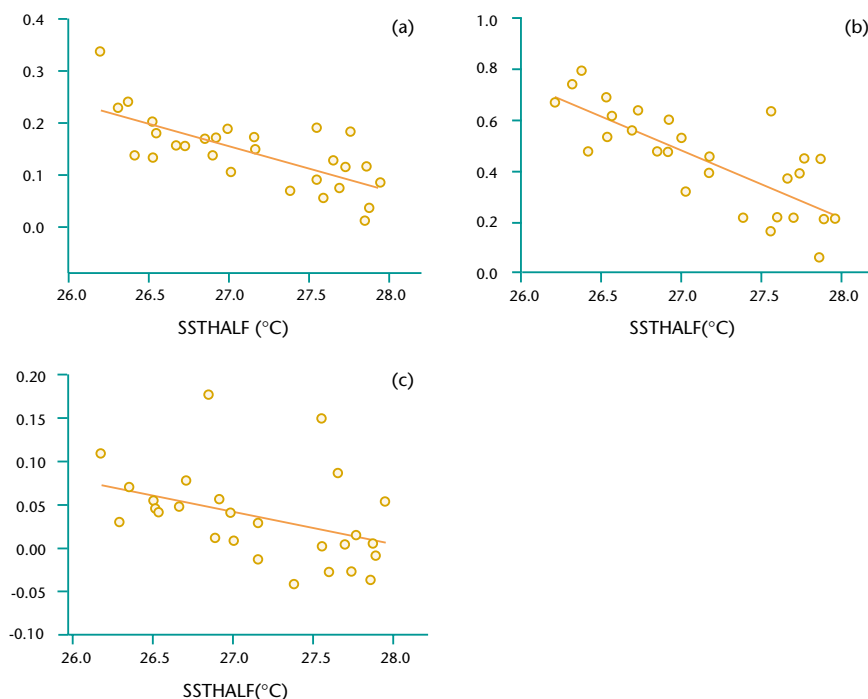
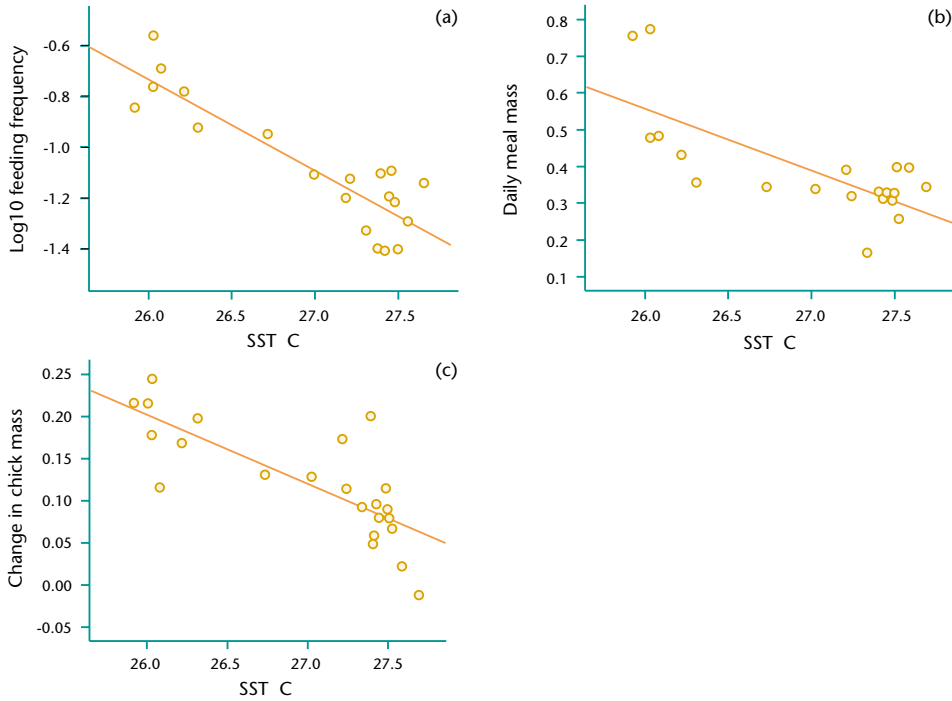


Figure 14.8 *Anous minutus*: significant negative relationships between (a) sea surface temperature (SST) at Heron Island and log10 transformed feeding frequency during December 2005; (b) SST and meal mass per gram of chick and; (c) 24-hour chick mass change per gram of chick and daily SST³⁸



This is a mechanism that operates on much shorter temporal-scales than previously thought^{29,116,49,95}. An assessment of data available for Southern Ocean species⁸⁹ also suggests that short-term variations in prey abundance are strongly associated with day-to-day fluctuations in sea surface temperatures, regardless of prevailing ENSO conditions, although these data have not been specifically analysed to test for such relationships.

14.3.2.2 Short-term and within-season trophic mechanisms

Peck et al.⁹² identify two trophic mechanisms previously described in the literature that may influence food availability to seabirds on a day-to-day basis. Firstly, fluctuations in sea surface temperature may affect the short-term vertical and/or horizontal distribution of prey. Such rapid shifts in prey distribution could be driven by numerous physiological^{123,20,118}, ecological^{64,78,79} and behavioural¹⁰⁷ factors. For example, the generally low productivity of most tropical waters means that foraging seabird may be required to track shifting zones of prey availability located in small areas of enhanced primary productivity¹²¹. The number and spatial and temporal distribution of these favourable sites will be related to changing patterns of oceanography and may be significantly depleted by increases in sea surface temperature.



Previously this mechanism has been assumed to effect seabird breeding success only at seasonal scales^{80,49,69,83,107,112}. However, if prey species prefer specific temperature regimes it is reasonable to assume that rapid movement in vertical or horizontal space to preferred temperatures could decrease their accessibility to aerial predators on a day-to-day basis.

A second possible day-to-day mechanism is that sea surface temperature directly influences the abundance of sub-surface predators^{72,95}. These predators drive prey to the surface making them available to seabirds^{16,105,5}. The most important predators associated with this behaviour in the tropical Pacific Ocean are tuna (*Thunnus spp.*)^{4,52}. Extensive work has documented a close relationship between foraging seabirds and tuna^{52,6}, and it is generally accepted that specific oceanographic parameters linked to sea surface temperature, particularly thermocline depth¹⁰⁷, are important to the foraging ecology of both these groups^{73,75,14}. However, the complex relationships among tuna and oceanographic variation remain poorly understood^{4,52,73,75}. Consequently, the validity of this mechanism requires further investigation.

14.3.2.3 Short-term and within-season vulnerability and thresholds

To date there have only been a small number of studies examining the effects of day-to-day variation in sea surface temperature, but already this body of work suggests these effects are important. Significant negative impacts have been observed across multiple species and throughout the entire GBR. At present there are no equivalent studies from other regions.

Data available for the GBR also indicate that there are sea surface temperature limits above which provisioning rates are so poor that sooty tern, black noddy, wedge-tailed shearwater and possibly other species' chicks show zero or negative growth. Currently the exact species-specific sea surface temperatures at which zero growth occurs are not known. This is because data on existing day-to-day temperature effects use average sea surface temperature indices generated from multiple stationary data loggers positioned throughout the regions of interest. Determining this relationship more precisely for each species and location requires sea surface temperature data obtained from foraging dive profiles of individual birds so that provisioning rates can be directly linked to oceanography at each foraging site. However, from existing data it is possible identify the magnitude of change in sea surface temperature that is important. Regression models show that the chicks of all species so far examined receive no food or begin to show zero growth at between 2 and 4°C increases in background sea surface temperature.

Of course, the period of time over which sea surface temperature remains high is also important for determining the overall level of impact. The length of time that chicks can cope with food stress will be species-specific and will depend on chick energy requirements, which vary with chick age⁹⁸. Chicks of Procellariiform seabirds in general and wedge-tailed shearwaters in particular, have physiological adaptations that allow them to cope with relatively long periods of food deprivation⁹⁰. Chicks of smaller pelagic tern species maintain significantly lower body reserves and consequently adults need to provision more frequently. This suggests that terns will be more sensitive to shorter periods of higher sea surface temperatures than shearwaters. It also implies that wedge-tailed shearwaters maybe useful indicators of the maximum period that chicks of tropical pelagic species are able to cope with sea surface temperature increases of between 2 and 4°C. Young shearwater chicks (3 to 4 weeks post-hatching) commonly survive six to seven days without food and even periods of 12 days with

only a single meal, but mortality consistently occurs after 8 to 10 days of no provisioning (Congdon unpublished data). Older chicks (4 to 8 weeks post-hatching) show similar levels of sensitivity. Chicks are able to survive for up to 20 days when provided only with a single meal, but mortality regularly occurs after 8 to 10 days of no provisioning (Congdon unpublished data).

Combined, these findings suggest that in any single breeding season a 4°C rise in sea surface temperature maintained for periods of two weeks or longer will cause catastrophic reproductive failure of pelagic foraging species. The significance of similar sea surface temperature increases to more inshore and offshore foraging guilds is currently unknown. However, observed declines in less pelagic species such as brown boobies and frigatebirds at some locations suggest such impacts may be substantial and require further detailed examination.

Despite the current lack of data for non-pelagic species, it is likely that relatively small increases in average sea surface temperature or in the number and duration of large hot water incursions into the GBR will cause repeated and catastrophic reproductive failure of many seabird species.

14.3.2.4 Short-term and within-season adaptive capacity

In the short-term, the adaptive capacity of seabirds within the GBR rests on the ability of either adult foraging behaviour or chick growth patterns to respond to sea surface temperature-associated decreases in food availability.

When local food resources surrounding a breeding colony are unable to simultaneously support both chick development and adult self-maintenance, Procellariiform seabirds often adopt a unique dual foraging strategy^{119,120}. Adults alternate multiple short foraging trips in resource-poor, near-colony waters with longer trips to highly productive areas 'at-distance' from breeding colonies. During near-colony trips, adults assimilate little food and sacrifice body condition to satisfy chick energy requirements.

Wedge-tailed shearwaters breeding at Heron Island use this dual foraging strategy²⁷. Foraging adults repeatedly performed short-trip cycles of multiple one to four day trips, followed by a single long-trip of eight to ten days during which they build body reserves that are passed onto chicks by not self-provisioning adequately during the early stages of the next short-trip cycle²⁷.

The use of this foraging strategy in the southern GBR implies that only resource-poor waters are readily available adjacent to breeding colonies and that there is extremely limited potential for adult shearwaters to increase either food loads or provisioning rates if they are to compensate for sea surface temperature-associated decreases in food availability. The inability of black noddies to increase provisioning rates during a period of increased sea surface temperature during 2005 suggests they may be similarly constrained. No data are available to make comparable predictions for other species or locations.

Less is known about the adaptive capacity of chick developmental patterns. Manipulative experiments on black noddy chicks suggest that pelagic foraging terns have a hierarchical pattern of nutrient allocation during growth, where body reserves needed for maintenance are preferentially maintained at the expense of feather development²⁵. This implies that chicks of these species can compensate, to some degree, for reduced food availability or greater variation in delivery rates by lengthening



fledging periods, as long as starvation does not become pathological or predation pressure increase. Inshore foraging species do not appear to have similar levels of flexibility in the way incoming nutrients can be allocated to different components of growth⁶⁶.

In addition, data for shearwaters suggest that different adult foraging environments cause coordinated divergence in chick developmental characteristics⁹¹. Shearwater growth patterns differ significantly between temperate and tropical locations. Relative to more temperate locations, chicks at Heron Island in a resource-poor foraging environment preferentially store and maintain body mass at the expense of skeletal development⁹¹. It is currently not known if this is a plastic response to seasonal variation in food availability, or a colony-specific physiological adaptation to long-term average provisioning rates. Based on existing evidence the latter seems more likely⁹¹. If correct this implies shearwater growth responses to increasing sea surface temperature can only occur via natural selection over generations and will not be effective in mediating any negative impacts in the short-term. Unfortunately, more data are required to clearly establish the level of developmental flexibility and potential response in this species.

14.3.3 Physical disturbance – tropical storms and cyclones

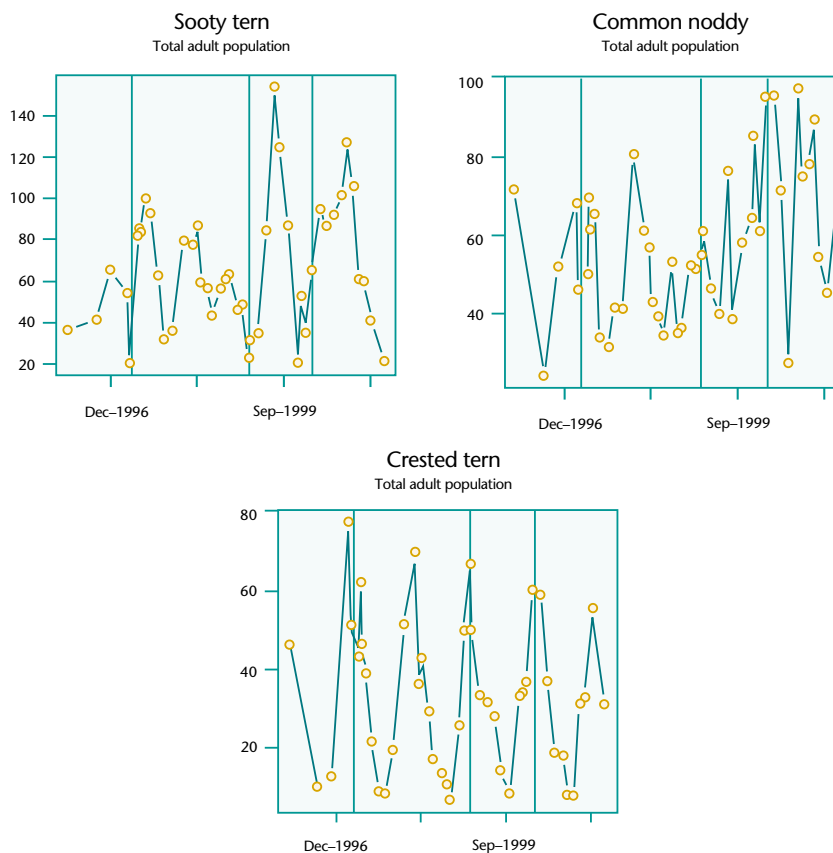
14.3.3.1 Tropical storms and cyclones – impacts

Climate change and associated ENSO variation have been predicted to increase the intensity and possibly the frequency of tropical storms and cyclones in the Australasian region (Lough chapter 2). Therefore, the exposure of seabirds to these phenomena can also be expected to increase accordingly.

Potential impacts on seabirds include the immediate effects of cyclones tracking over breeding sites, such as the destruction of eggs and increased mortality of chicks and adults, as well as the indirect impacts of wave inundation and erosion under the influence of gale force winds, storm tides and intensified currents⁶⁵. Cyclones form over warm water. Therefore, there may also be a correlation between conditions under which cyclones form and lowered feeding success due to higher sea surface temperatures, as described in the previous section of this chapter. Delayed effects of cyclones may also be manifest through decreased recruitment associated with years of high chick loss, or years when cyclones reduce foraging success and so produce fledglings that are smaller than average and have lower survivorship^{71,109}. At present populations of two relatively isolated and critically endangered species that breed on Christmas Island in the Indian Ocean, the Abbott's booby (*Papadula abbotti*) and the Christmas Island frigatebird (*Fregata andrewsi*), have been identified as vulnerable to increases in major storm or cyclone activity due to their restricted distributions and small population sizes^{44, 23}.

Only limited site-specific evidence of the potential impact of tropical storms on seabird reproductive biology is available (Table 14.1a,b). For the GBR region the majority of data come from the most intensely monitored population at Michaelmas Cay. Sooty terns at this site show individual instances of altered periodicity of breeding, declines in breeding numbers and reduced breeding success in association with cyclone activity⁶⁸. This suggests that individual cyclones can significantly impact and limit the ability of Michaelmas Cay seabirds to reproduce in the short-term. However, longer-term trends do not demonstrate significant impacts of major tropical storms in the region. Both the incidence and intensity of cyclones are poor predictors of subsequent changes in the number of breeding pairs^{31,40} (Figure 14.9).

Figure 14.9 The total populations of sooty terns, common noddies and crested terns at Michaelmas Cay from 1996 to 2001. Cyclone occurrences are shown as green vertical lines; none showed an effect on populations for any of the three species (adapted from De'ath³¹)



Food availability at Michaelmas Cay is such that tropical pelagic terns are able to breed during most months of the year^{68,40}. Therefore, cyclonic impacts at this site may be ameliorated should cyclone-affected breeders return to re-nest in subsequent months, or in the next cycle, with minimum overall impact to reproductive output. Such resilience to cyclone losses may not be possible at locations where food availability is more seasonal. At such sites the production from an entire year may be lost after a severe cyclone.

14.3.3.2 Tropical storms and cyclones – vulnerability and thresholds

A lack of other comprehensive data sets means that the longer-term effects of changes in cyclone frequency or intensity on seabird population stability remain largely unknown and unpredictable. However, the impacts of tropical storms and cyclones are specific to their level of overlap with sensitive breeding phases and the size of the breeding colony affected. Any increase in the frequency or intensity of these phenomena could be expected to increase both the spatial and temporal

potential for them to coincide with important reproductive periods and so cause significant negative impacts. Ultimately, increasing cyclone frequency and intensity is an additional stressor that, when combined with other ENSO and sea surface temperature related impacts previously described, is likely to further reduce foraging efficiency and suppress reproductive potential.

14.3.3.3 Tropical storms and cyclones – adaptive capacity

The potential for seabirds to adapt to, or compensate for, changes in the frequency and intensity of tropical storms is dependent on their ability to either adjust breeding phenology so as to better avoid peak periods of storm activity, or relocate to less impacted breeding sites. The capacity for seabirds breeding on the GBR to do either of these two things is largely unknown (also see section 14.4.3). Most suitable habitat appears to already support breeding populations. However, it is not known if these populations are at, or near, carrying capacity with regard to either food resource or breeding habitat availability.

14.3.4 Sea level rise and rainfall patterns

14.3.4.1 Sea level rise and rainfall patterns – impacts

Both rising sea level and altered rainfall patterns will influence seabird reproductive output through the effect they have on the availability of breeding habitat. Sea level rise will alter erosion and deposition patterns that effect island size, while changing rainfall regimes will cause significant changes in the distribution and abundance of specific vegetation types (Turner and Batianoff chapter 20). Based on this, sea level rise and changing rainfall patterns are likely to impact the majority of seabird breeding colonies within the GBR and Coral Sea region in some way. However, these are longer-term processes that are unlikely to have consistently negative impacts.

Changes in sea level and rainfall are also expected to alter flow regimes and discharge patterns for major coastal river systems adjacent to the GBR. Any potential impact of these changes on seabird reproductive biology will be via effects on primary productivity and trophic stability at lower trophic levels. The potential impacts of altered discharge regimes on trophic ecology within the GBR are discussed in chapter 19. Changes in sea level or variation in rainfall patterns have not previously been quantitatively linked to changes in the distribution and abundance of nesting seabirds.

14.3.4.2 Sea level rise and rainfall patterns – vulnerability and thresholds

Most seabirds have different species-specific breeding habitat requirements. Functional groups include: burrow nesters that need either a tree, hummock grass, or open beach rock over-story to stabilise soil structure and allow tunnelling (eg wedge-tailed shearwaters), tree nesters that require mature woodland and forest vegetation (eg black noddies), and open ground nesters that prefer ground vegetation ranging from bare sand or soil (eg brown boobies), through light grass cover (eg sooty tern, common noddy), to a dense grassy over story (eg bridled terns). Therefore, the long-term impacts of rising sea levels and changes to rainfall patterns will depend on exactly how these phenomena change the distribution and abundance of species-specific breeding habitat on the GBR (Turner and Batianoff chapter 20).

In general, breeding islands are unlikely to decrease in size in the short to medium term (Turner and Batiannoff chapter 20) and so little detrimental impact is expected to result from a decrease in absolute breeding area within the GBR. Decreasing annual rainfall and potential increases in sand and rubble deposition rates at windward edges of islands are likely to favour colonising ground cover and woody shrub vegetation types. If so, tree and burrow nesting species that rely predominantly on mature *Pisonia* (*Pisonia grandis*) forest may be disproportionately negatively impacted by reductions in breeding habitat and so more vulnerable to these particular phenomena.

Ultimately the magnitude and significance of these impacts will be determined by whether breeding numbers at specific colonies are currently limited by habitat availability. For ground-nesting species at Michaelmas Cay there is no evidence to suggest that population numbers are currently habitat limited. For example, no significant relationships have been observed between the mean area of available nesting habitat each year and the mean number of breeding pairs of any species of seabird breeding at this cay⁴⁰.

Rising sea level or changes in vegetation patterns may also have specific negative impacts at some important breeding sites depending on the current distribution of available habitat. For example, at Raine Island in the far northern GBR rising sea level has the potential to flood the only cavernous beach rock areas available to burrow nesting seabirds such as red-tailed tropicbirds and to redistribute marine turtle nesting habitat such that levels of inter-specific disturbance of seabirds by turtles could increase by orders of magnitude.

14.3.4.3 Sea level rise and rainfall patterns – adaptive capacity

As with the ability to adapt to changes in tropical storm frequency, the potential for seabirds to adapt to, or compensate for, changes in the abundance and distribution of species-specific breeding habitat depends on their ability to relocate to suitable breeding sites elsewhere. As previously discussed, the potential for birds to move to alternative breeding locations is unknown within the GBR system.

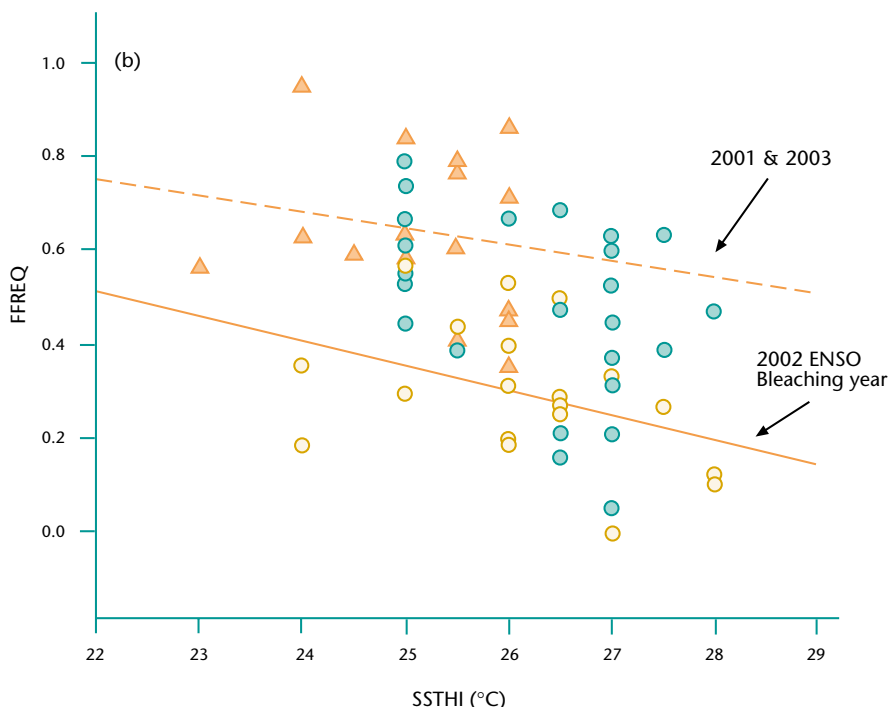
14.4 Linkages and interactions

14.4.1 Interactions between climate change stressors

Although data for the GBR suggest that the within-season impacts of sea surface temperature variation operate regardless of prevailing larger-scale ENSO conditions, these two processes are not mutually exclusive. Nor are their impacts independent of the influence of tropical storm and cyclone activity or other threatening processes.

For example, during an El Niño event in the southern GBR in 2002 seasonal-scale decreases in overall prey availability were observed as predicted by the large-scale models based on upwelling suppression, even after the daily effect of sea surface temperature variations were accounted for (Figure 14.10). During this ENSO event chick feeding frequencies were approximately one third those predicted to result from within-season sea surface temperature impacts alone⁹². This indicates that both inter-seasonal and within-season scale process were operating synergistically to depress foraging success and growth rates during this event. Consequently, the combined impact of both these phenomena

Figure 14.10 *Puffinus pacificus*: the effect of sea surface temperature at Heron Island (SST_{HI}) on: feeding frequency (F_{FREQ}) in 2001 (\blacktriangle), 2002 (\circ) and 2003 (\bullet). There was a significant effect of SST_{HI} on F_{FREQ} across years ($F_{FREQ} = 2.856 - 0.092 SST_{HI}$). The effect of year on F_{FREQ} was also significant. There was no effect of year on SST_{HI} . The dashed line represents the 2001–2003 regressions while the 2002 regression is represented by the solid line⁹²



on the long-term stability of seabird populations is likely to be considerably greater than the effects of each independently. Both processes need to be incorporated into any mechanistic models examining climate change related impacts on seabird breeding success at specific tropical locales.

Both inter-seasonal ENSO and within-season sea surface temperature impacts affect seabirds via the control they have on prey distribution and abundance. Therefore, there is potential for any other taxa that use similar prey to also be impacted. In particular, this could include many of the large predatory pelagic fish species known to forage in association with seabirds (Kingsford and Welch chapter 18).

14.4.2 Linkages between colonies and foraging resources

Wedge-tailed shearwaters from Heron Island use a dual foraging strategy. Adults forage locally in resource-poor waters to provision chicks, but also perform regular self-provisioning trips to specific sectors of ocean 'at-distance' from breeding colonies where localised oceanographic features such as seamounts or oceanographic fronts promote consistent high productivity and prey abundance²⁷.

Satellite tracking of individual shearwaters indicates that these sites are small in number and located adjacent to Coral Sea mounts and along the eastern edge of the Australian continental shelf in areas where there is likely to be significant localised upwelling (Congdon unpublished data, Figure 14.11).

Such observed linkages between the Coral Sea and southern GBR are significant. These links mean that shearwaters from the Capricorn Bunker island group are reliant on two independent resource bases simultaneously. One of these 'at distance' foraging areas is up to 1000 km from GBR breeding colonies and also appear also to have been impacted by increasing ENSO/sea surface temperature variations over the last decade⁹² (Figure 14.2). The breeding success of shearwaters, as well as other seabird species on a regional scale may be totally dependent on the continued stability of a small number of these highly productive areas.

It is possible that these locations also form a major component of the over-winter or non-breeding foraging grounds of wedge-tailed shearwaters and many other seabird taxa. At present little is known about the potential effect of ENSO/sea surface temperature variation on upwelling or productivity at these important foraging refuges, or the effects that any loss in productivity at these locations will have on the wider GBR ecosystem. The conservation significance of such key foraging sites cannot be overstated.

14.4.3 Inter-colony movement and breeding

Ultimately, the influence that repeated localised reproductive failures have on seabird populations of the GBR will be determined by the potential for individuals to move elsewhere, or for impacted colonies to be buffered by input from unaffected sites.

Any ameliorating effects of inter-colony movement will decrease as levels of inter-colony gene flow decrease. To date, studies of gene flow and levels of interbreeding among seabirds of the GBR have been equivocal in their results. All detailed molecular analyses have found a lack of observed genetic structuring that suggests high levels of inter-breeding and movement between colonies over broad geographic scales^{91,50}.

However, these same studies have also demonstrated that a rapid population expansion and colonisation of the GBR by at least some seabirds has occurred in the recent geological past, most likely in association with the appearance of new breeding habitat following the final Pleistocene glacial retreat⁹⁰. Evidence of a recent expansion-colonisation wave implies that measures of contemporary gene flow are confounded by historic associations among populations established during colonisation and are therefore inaccurate^{26,90}.

In contrast to data indicating high levels of inter-colony gene flow, significant morphological differences have been observed among shearwaters from different colonies that are unrelated to inter-colony distances⁹³. These findings suggest some restriction on levels of interbreeding between colonies and the possibility of local adaptation. A lack of inter-colony gene flow is further supported by limited data on the movement of banded birds⁸⁷. For both masked and brown boobies strong breeding colony fidelity has been observed at a regional scale within the broader GBR Coral Sea area, while breeding site fidelity is significantly weaker within smaller localised areas such as the closely spaced colonies of the Swain Reefs⁸⁷. Most extra-limital recaptures of both species were young birds suggesting that only young birds disperse large distances, most likely during their extensive pre-breeding period⁸⁷. Whether they preferentially return to natal colonies to breed is unknown.

Any restriction on gene flow at a regional scale implies that displacement of regional population clusters, such as those in the Swains Reef or Capricorn Bunker Island group, due to climate change impacts will result in permanent loss of those colonies with little chance of re-colonisation from other regional populations improve.

14.5 Summary and recommendations

14.5.1 Major vulnerabilities to climate change

For seabirds, the key vulnerabilities to climate change are clearly identified as the predicted increases in sea surface temperature and changes to the major seasonal-scale weather patterns that influence circulation and upwelling, such as the ENSO. There are also implications from predicted sea level rise and changes in the frequency and intensity of tropical storms and cyclones, but these potential impacts are not as well understood.

Sea temperature variation is closely linked to ENSO and other types of large-scale oceanographic phenomena, with more frequent and more intense El Niño events producing significantly more variable sea temperatures⁶¹. Significant detrimental impacts of ENSO related increases in sea surface temperature are already likely to have occurred at all major breeding rookeries throughout the GBR. Principal species known to be effected include three pelagic foraging terns (black noddy, common noddy, sooty tern), and wedge-tailed shearwaters. Other species also likely to have been effected include two booby species (red booby, brown booby) and both frigatebird species (great frigatebird, least frigatebird).

This same group of seabirds have also been impacted elsewhere in the tropical Indo-Pacific, along with other species that breed on the GBR for which no local data are available. Species impacted elsewhere that are known to breed on the GBR include the crested tern, bridled tern, and roseate tern, while other impacted species that breed elsewhere in tropical Australian waters include the lesser noddy, white tailed (*Phaethon lepturus*)⁹⁶ and Red tailed tropicbird and Abbott's booby. This list of species constitutes virtually all of the major tropical seabirds breeding on the GBR⁵⁶ and encompasses most seabird foraging guilds within the ecosystem. Therefore, it is likely that impacts affecting these species are also affecting GBR species for which limited or no data are available.

Previously, impacts have been observed over long-term (decadal), inter-annual and within-season time scales. The intensity of response to a particular ENSO event is often location specific, with species affected at one location showing different levels of response at other sites. This is likely due to the location specific interactions between changing oceanography and seabird prey availability.

Both in Western Australia and on the GBR, the more pelagic offshore foraging tern and shearwater species were influenced most strongly by oceanographic change, while inshore foraging terns showed a lesser response^{111,39}. The more strongly affected species share a number of life-history characteristics. They have larger breeding populations, they are generally synchronous breeders and they feed regurgitated food to young at relatively long intervals, rather than provision young with whole fish more frequently. Consequently, their chicks have longer pre-fledging periods and slower overall growth rates, life-history characteristics that may make them particularly sensitive to ENSO associated fluctuations in food availability.

Based on these findings predicted increases in both sea surface temperature and the intensity or frequency of ENSO events are likely to have serious detrimental impacts on some component of the breeding biology of virtually all tropical seabird species breeding throughout the GBR and in adjacent areas. Importantly, it is likely that breeding populations of at least some species at most significant breeding colonies in the GBR or Coral Sea have already declined due to climate change related phenomena.

14.5.2 Potential management responses

With the current level of available information, options for local or regional scale management of climate impacts on seabirds remain very limited. This is because most impacts are directly linked to large-scale global climate phenomena rather than more local threatening processes. In addition, there is a lack of long-term monitoring and associated research studies on seabird population dynamics in tropical and subtropical regions in general, and particularly on the GBR. At present, correlative analysis aimed at detecting potential threatening processes in the GBR rely on general physiochemical data generated independent of any seabird research program and fragmentary population demographic data from just a few principal breeding locations and species.

Managing potential climate change impacts on seabird populations requires identifying general and population-specific causes of observed declines, their associated threatening processes and the functional relationships between these factors. At present only limited data exist about the key foraging locations or foraging modes used by any seabird population of the GBR, or about the direct relationships between oceanographic characteristics and seabird productivity. Without detailed information on foraging areas, resource use and the direct links between seabird reproductive parameters and associated oceanographic variation it is not possible to further identify, predict or adaptively manage climate change or other anthropogenic threats appropriately. Therefore, the principal management response required is to establish comprehensive research and monitoring programs that will fulfil these management needs.

Pelagic seabirds have limited capacity to increase foraging rates. The majority of these species have single egg clutches. This means that in any given season they are either able to rear a chick or not. Therefore, for these species, reproductive viability changes over a small change in productivity or prey accessibility. Thus, climate change stressors are unlikely to produce a slow linear decline in reproductive output. Once productivity is reduced below critical levels breeding colonies fail catastrophically and remain unviable as long as productivity remains low.

Monitoring for slow population declines will not identify potential impending colony failures of this type. Therefore, a management priority needs to identify the rates of change in critical resource levels, the driving processes behind these changes and the species- or colony-specific tipping points at which reproduction is no longer viable. Without these data a broad range of short-term management options are not available prior to colony collapse.

Importantly it must be recognised that impacts to food resources in specific locations, such as in and around known areas of localised upwelling, may have important cascading negative effects over large areas of the GBR. Similarly, based on the current limited information available on inter-colony movement, it must also be assumed that the potential for localised impacts to be buffered by immigration of new breeding recruits from other regions is limited.

Without appropriate data, potential management responses are restricted to attempting to minimise the impacts of other potential or perceived stressors in the system. Whether such measures would be effective is equivocal, since little quantitative data are available linking seabird reproductive output to these phenomena. However, areas for consideration could include the protection of known important forage-fish resources, especially where they overlap with commercial or recreational use, and particularly during ENSO warm years. This may also include increased protection of pelagic predatory fish species such as tuna and mackerel, taxa that seabirds rely on to drive prey species into the surface waters.

Management aimed at minimising general threats could also involve increased protection of breeding sites and/or local foraging resources. This could include limited or no visitation during peak breeding periods, along with recognition that breeding seasons may shift or become extended. These options may be particularly useful to minimise secondary risk at small or threatened colonies.

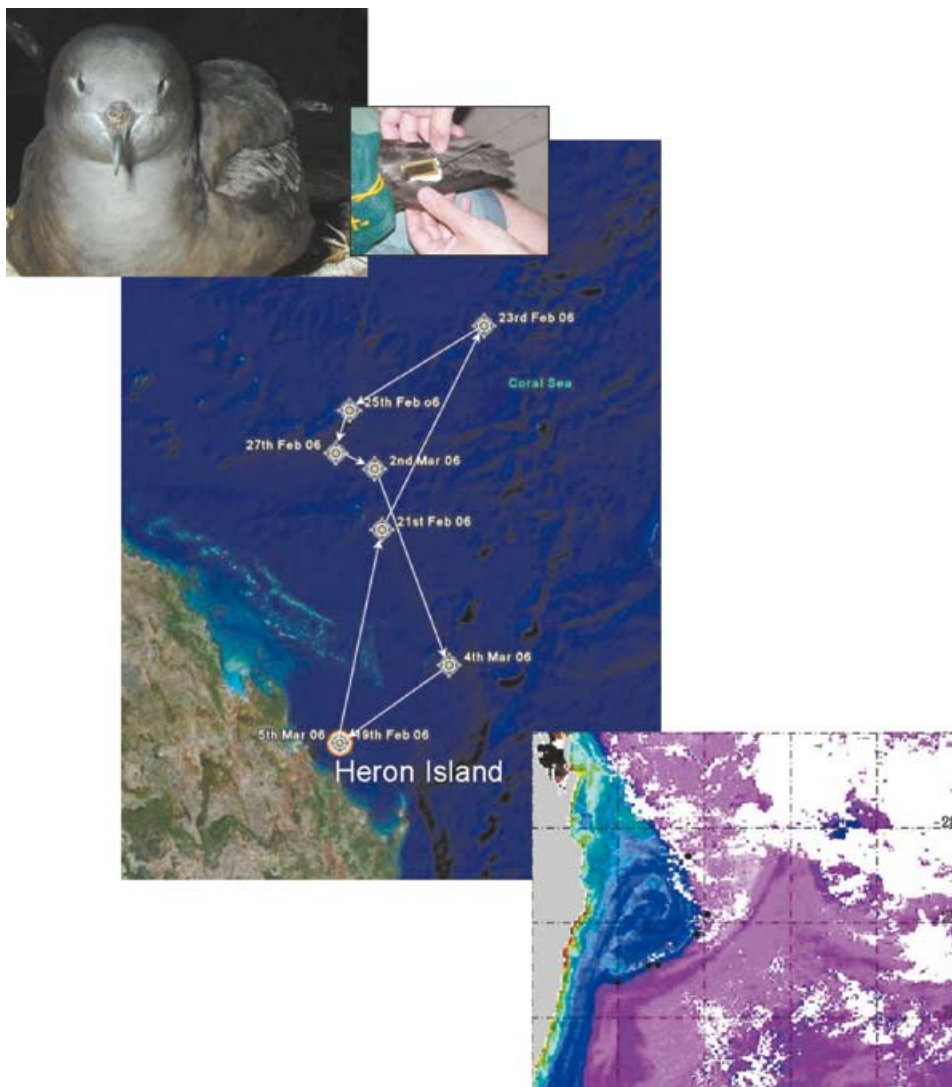
14.5.3 Further research

Seabirds are sensitive indicators to changes in forage fish availability and accessibility associated with ENSO and sea surface temperature variation. Therefore, seabird reproductive responses can be used to develop models of, and monitor for, these potential climate change impacts within the GBR.

Platform terminal transmitter type satellite tags (PTT), global position system data loggers and temperature, depth and activity recorders are now routinely and successfully deployed on seabirds of various sizes to link patterns of resource use and foraging behaviour with physical oceanography (Figure 14.11). When combined with information on prey acquisition, provisioning success and satellite imagery on large-scale variation in physiochemical oceanography, these data can be used to identify critical foraging locations, habitat associations and establish trophic relationships that underpin the perceived negative impacts of increases in sea surface temperature.

Ultimately, such data would enable the development of colony-specific predictive models of forage fish distribution and abundance from physiochemical data and permit long-term seabird population viability to be established under alternative climate change scenarios. These are the baseline data needed to determine the types of management options available and how to implement these options in a timely fashion.

Figure 14.11 Example of satellite transmitter tracking of wedge-tailed shearwaters. Photos display a wedge-tailed shearwater fitted with a PTT satellite transmitter. Centre map displays PTT foraging track for a single adult during February to March 2006. Map on lower right displays wedge-tailed shearwater foraging positions (●) along the edge of an oceanographic frontal system off the northern NSW coast (Photo credit: B Congdon, S Weeks)





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