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Climate as a driver of phenological change in southern seabirds

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Abstract

Seabirds are one of the most threatened groups of birds globally and, overall, their conservation status is deteriorating rapidly. Southern hemisphere countries are over-represented in the number of species of conservation concern yet long-term phenological data on seabirds in the southern hemisphere is limited. A better understanding of the implications of changes in the marine and terrestrial environments to seabird species is required in order to improve their management and conservation status. Here we conducted a meta-analysis of the phenological drivers and trends among southern hemisphere seabirds. Overall there was a general trend towards later phenological events over time (34 % of all data series, $N = 47$; 67 % of all significant trends), though this varied by taxa and location. The strongest trends towards later events were for seabirds breeding in Australia, the Laridae (gulls, noddies, terns) and migratory southern polar seabirds. In contrast, earlier phenologies were more often observed for the Spheniscidae (penguins) and for other seabirds breeding in the Antarctic and subantarctic. Phenological changes were most often associated with changes in oceanographic conditions, with sea-ice playing an important role for more southerly species. For some species in some locations, such as the Little Penguin *Eudyptula minor* in south-eastern Australia, warmer oceans projected under various climate change scenarios are expected to correspond to increased seabird productivity, manifested through earlier breeding, heavier chicks, an increased chance of double brooding, at least in the short-term.

Keywords: Penguin, *Eudyptula minor,* Sea surface temperature, Southern hemisphere, Seabirds

Introduction

Seabirds are one of the most threatened of all bird groups globally and, overall, their conservation status is deteriorating rapidly (Croxall et al. *2012*). When countries are ranked according to the number of species of conservation concern, 16 of the 21 highest ranked countries are in the southern hemisphere (top 10 ranked: New Zealand, Chile, USA, Australia, South Africa, Peru, Argentina, Mexico, Namibia, French Southern Territories;

Croxall et al. *2012*), emphasising the need to better understand the drivers of population change in these regions for current and future conservation and management efforts.

Within the seabird group, penguins (Spheniscidae), albatrosses (Diomedeidae) and petrels (Procellariidae) are the most threatened, the significance of this highlighted by the fact that penguins and petrels represent nearly half of all seabird species in the world (Croxall et al. *2012*).

Seabirds are recognised as potential indicators of marine environments (Woehler *2012* and references therein) and are relatively well-studied compared to other marine organisms (Croxall et al. *2012*). Large- and local-scale climate processes, including El Niño-Southern Oscillation (ENSO) and sea surface temperature (SST), have been shown to influence seabird reproduction, distribution, phenology and survival in many regions of the globe. For example, breeding of seabirds in the northern Japan Sea is delayed when air and sea temperatures are lower, as a result of the influence of temperature on access to breeding sites and prey availability (Watanuki and Ito *2012*), and a multivariate index of ENSO partly explained variations in tropical seabird breeding in the Seychelles (Ramos et al. *2002*, *2006*).

As breeding and moult require considerable amounts of energy, the timing of these activities should correspond to periods of peak prey availability and favourable environmental conditions. The timing of breeding in seabirds can influence annual breeding productivity, thereby impacting on population dynamics. The timing of breeding has been hypothesised to be the reproductive parameter most influenced by climate change (Przybylo et al. *2000*;

Ramos et al. *2002*). An earlier onset to breeding often corresponds to increased seabird productivity (number of chicks raised per pair, clutch size, and chick mass on fledging) (e.g. Cullen et al. *2009*; Ramos et al. *2002*).

Most seabirds are migratory or dispersive during the non-breeding season and are dependent upon the availability of prey resources while on migration or away from nesting sites. During the non-breeding season many seabirds moult and may lose 50 % of their pre-moult body mass while in moult (Baduini et al. *2001*; Cherubini et al. *1996*; Knox *2007*). The timing of moult has been shown to influence breeding timing and to be influenced by it (Paredes et al. *2002*; Wolfaardt et al. *2009a*).

Changes in seabird phenology, be it the timing of migration, breeding or moult, also have the potential to create a mismatch (or asynchrony) between species. This has the potential to disrupt predator-prey relationships and influence inter-species competition for resources, with subsequent changes in population abundances (Durant et al. *2007*).

In light of the conservation status of many of the world's seabirds, that a high proportion of the most threatened species are in the southern hemisphere, and that many seabirds are influenced by climatic changes in their marine and terrestrial environments (reviewed by Chambers et al. *2011*, *2013a*, *b*), this paper aims to:

1. Review published literature on the phenology of southern hemisphere seabirds, with particular emphasis on the highly threatened taxon Spheniscidae (penguins),

identifying where phenological changes have or have not been observed and possible climate drivers for any observed change(s).

2. Explore in more detail similarities and differences in the phenologies of Little Penguins *Eudyptula minor*among various breeding locations and possible climate drivers of these, using published and unpublished data from various locations throughout their range in Australia and New Zealand.
3. Discuss the implications of phenological change(s) for southern seabirds.
4. Identify possible adaptation options to reducing any adverse effects of predicted climatic changes.

Data and methods

A literature search was used to identify seabird datasets from the southern hemisphere of at least 10 years duration and extending post-1990. In addition, known researchers of Little Penguins were contacted directly and invited to participate in this study.

Trends in the seabird datasets were obtained primarily from the literature. The exception was the case of the Little Penguin where researchers provided the time-series of the relevant phenological data. Long-term (>10 years) data were available on the timing of breeding in Little Penguins from five locations throughout their distribution (four in Australia and one in New Zealand) (Table 1). In addition, three datasets of shorter duration were available for Oamaru (two sites; 1993–1998) and Taiaroa Head (1 site; 1992–1998) on the Otago Peninsula, New Zealand (Perriman et al. *2000*; Perriman and Steen *2000*), which allowed some comparison of similarities in timing among colonies. Trends were calculated for the

Little Penguin datasets using generalised linear models, and raw time-series were correlated to identify potential similarities in year-to-year variability at the different sites. A number of the Little Penguin datasets are presented in this study for the first time, providing additional novel and relevant biological information on this species.

Little Penguins nest in burrows in sandy soil, under vegetation, among rocks or in nest-boxes placed throughout the colonies. On each visit to the various colonies, the tag numbers of the adult(s) present in the burrow, and the numbers of eggs and/or chicks were recorded. The number and location of study sites visited, and the frequency of visits to the burrows in these study sites have varied over the years, with the frequency of visit generally ranging from twice-weekly to monthly (for further details see Cullen et al. *2009*; Allen et al. *2011*; Cannell et al. *2012*). The mean laying dates (MLD) of first clutches were observed from field observations or inferred retrospectively from hatching dates or the age of young chicks.

The longest and most detailed study of Little Penguins is from the Summerland Peninsula, Phillip Island, Victoria, Australia (38° 30′ S, 145° 10′ E), since 1968. Approximately 32,000 Little Penguins are estimated to nest at this site (Sutherland and Dann *2012*). At this site breeding and moult status were recorded. All the breeding data are for the period starting in March and ending in February of the following year, and are recorded as the year in which the season started to allow for the breeding season of the penguins overlapping with the calendar year. We confined our moult analysis to records of the first stage of moult, and restricted the analyses to years with at least 30 observations; 1969–2012. The first stage of moult is characterised by worn plumage, swollen flippers, increased body mass and some raised old feathering (see Stahel and Gales *1987*). The first stage ends once old feathers have started to moult. Breeding and moult dates were converted to the number of days since 1 January (day of year).

Relationships between the timing of breeding and moult in Little Penguins at Phillip Island and monthly sea surface temperature (SST) data were assessed using methodology similar to that of Cullen et al. (*2009*). Based on known foraging regions of the birds and water movements within Bass Strait, a 2° × 2° SST box was constructed by averaging SST data obtained on a 1° × 1° grid from the UK Meteorological Office Ice and Sea Surface Temperature data set (GISST, version 1.1; Parker et al. *1995*; data from 1968 to end of 1981) and the National Oceanographic and Atmospheric Administration (ftp://ftp.emc.ncep.noaa.gov/cmb/sst/oimonth_v2/; Reynolds and Smith *1994*; used to extend the data to January 2012) (see Cullen et al. *2009* for further details).

Results and discussion

Overall, there was a greater number of datasets with trends towards later phenological events over time than earlier ones, but there were also many datasets that had no detectable trend over time (Tables 2, 3). Additionally, there were some differences according to taxonomic family and location. For the Procellariidae (petrels and shearwaters), no trends towards earlier phenology were observed (Table 3; four cases of later events, six of no change). Spheniscidae (penguins) were more likely to exhibit earlier phenologies or have no change (7 and 15 cases, respectively) than later timing (3 cases). For the Laridae (terns, gulls and noddies), phenology was generally delayed (eight cases) compared to earlier or no change (one and three cases, respectively). For Antarctic and subantarctic seabird species, both earlier and later phenologies were observed in almost equal proportions (seven and six cases, respectively; Table 2), whereas in Australia, the only other region to have multiple documented shifts, delayed or no shift in phenologies were more likely than advances (nine later, one earlier, nine no change).

Seabird migration phenology

Long-term information on seabird migration timing was available only for the Antarctic/subantarctic region (18 datasets, Table 2). Wilson's Storm-petrel *Oceanites oceanicus*, Southern Fulmar *Fulmarus glacialoides*, Antarctic Petrel *Thalassoica antarctica* and Cape Petrel *Daption capense* have all delayed their arrival at their breeding colonies in more recent years, while South Polar Skua *Catharacta maccormicki*, Southern Giant-Petrel *Macronectes giganteus* and Snow Petrel *Pagodroma nivea* have exhibited no consistent change in arrival timing (Barbraud and Weimerskirch *2006*). Similarly, migration timing in the penguins located in the Antarctic and subantarctic has not changed significantly over time (Barbraud and Weimerskirch *2006*; Crawford et al. *2006*; Emmerson et al. *2011*; Saraux et al. *2011*) though breeding and migration timing are known to vary by latitude (Ainley *2002*; Emmerson et al. *2011*).

Whilst there has been no change over time in the phenology of some seabird species in the Antarctic, their phenology is influenced by environmental variability. For example, reductions in the extent of sea-ice and increases in its duration impact seabird prey abundance and availability, increasing the amount of time required for some seabirds to obtain breeding condition, thereby influencing arrival times at breeding colonies (Barbraud and

Weimerskirch *2006*). For penguins in East Antarctica, such environmental conditions appear to delay breeding but not their arrival timing (Barbraud and Weimerskirch *2006*). However, when near-shore ice is extensive and maximum air temperatures are low, Adélie Penguins *Pygoscelis adeliae* arrive later at their breeding colonies on Béchervaise Island, East Antarctica (Emmerson et al. *2011*). Although later arrival did not appear to influence breeding success, it did lead to reduced courtship and egg-laying, later clutch initiation, later parent departure for foraging trips and later chick-hatching.

Seabird breeding phenology

There was a significant difference among the seabird families and observed changes in breeding timing (Chi-square = 14.11, df = 4, $P = 0.007$). Laridae were more likely to have shifted to later breeding over time (eight later, one earlier, two no change), while Spheniscidae are generally breeding earlier over time (seven earlier, three later, ten no change). The Procellariidae showed little shift in phenological timing (none earlier, one later, four no change).

Observed changes in phenology also differed significantly according to location, though only Australia and the Antarctic/subantarctic region had sufficient information for a formal test to be applied (Chi-square = 9.04, df = 2, $P = 0.011$). Seabirds breeding in the Antarctic/subantarctic were slightly more likely to breed earlier over time (seven earlier, two later, six no change), while those in the Australian region were more likely to breed later (one earlier, nine later, eight no change).

Earlier breeding for Adélie and Emperor Penguins *Aptenodytes forsteri* in East Antarctica occurred in years of higher sea ice extent; however, only Adélie Penguins showed a significant trend towards later breeding over time (Barbraud and Weimerskirch *2006*). In Emmerson et al.'s (*2011*) study of Adélie Penguins in East Antarctica, there was no change in laying dates over time; however, the laying dates were correlated with the Southern Annular Mode (SAM), a broad-scale climate index of north-south movement of a westerly wind belt around the higher latitudes of the southern hemisphere (positive SAM was linked to later laying), and wind direction (southerly winds corresponding to later laying). For the birds in their study, later hatching dates but not later fledging dates were associated with later arrival to the colony. For three penguin species in the Western Antarctic Peninsula (Adélie, Chinstrap *P. antarctica* and Gentoo *P. papua*) earlier laying dates were linked with higher air temperatures before laying, with warmer temperatures leading to an earlier appearance of snow-free areas necessary for breeding in these species (Lynch et al. *2012*). However, response rates varied among the species; Gentoo Penguins advanced their laying at a higher rate than the other two species, potentially increasing competition for nesting space in mixed-species colonies.

For Royal Penguins *Eudyptes schlegeli* nesting on Macquarie Island, laying dates during the 1990s were on average 3 days earlier than during the 1960s (Hindell et al. *2012*). Breeding timing in this species was associated with the SAM; years of lower values of the SAM, and associated reduced food availability, resulting in a delayed start to breeding.

In East Antarctica, variations in laying dates in Snow Petrels and South Polar Skuas were not linked to sea ice extent, and only South Polar Skuas had a noticeable shift in breeding timing (earlier egg laying; Barbraud and Weimerskirch *2006*). In contrast, breeding timing in the Cape Petrel was related negatively to sea ice extent, with breeding occurring later over time. The observed reduction in sea ice extent in East Antarctica has been linked to reduced prey availability for many Antarctic seabirds (Barbraud and Weimerskirch *2006*).

For some species, such as the migratory Wedge-tailed Shearwater *Ardenna pacifica*, breeding is highly synchronous with very little inter-annual variability and, perhaps as a consequence, its breeding phenology had not shifted over time and did not appear to be influenced by climatic variables, such as ocean temperatures (Surman et al. *2012*). In contrast, there has been a shift towards later breeding for other seabird species breeding in Western Australia, including at the same location in Houtman Abrolhos (Dunlop and Surman *2012*; Surman et al. *2012*). Over the last two decades, breeding participation in three species, Lesser Noddy *Anous tenuirostris*, Brown Noddy *A. stolidus* and Sooty Tern *Onychoprion fuscata*, was lower in years of later breeding, though the resident Lesser Noddies appeared to be more resilient than the two migratory species (Surman et al. *2012*). There is some evidence that ENSO influences the timing of breeding in Western Australian Laridae, with potentially new (but as yet unknown) complicating factors appearing in more recent years, resulting in reduced reproductive performance in both ENSO and non-ENSO years (Surman and Nicholson *2009b*; Chambers et al. *2011*).

Relationships between breeding phenology and environmental variability are not always static. For example, Mills et al. (*2008*) found breeding in New Zealand Red-billed Gulls was earlier and productivity increased when the population was at its maximum; food availability being higher during La Niña conditions. Later, when the population began to decrease, laying dates became later, even when prey availability was high. Links between the timing of breeding and colony size have also been reported for African Penguins *Spheniscus demersus* (Wolfaardt et al. *2009a*), with nest density suggested as having a greater influence on nesting synchrony than wide-scale seasonal effects.

The Little Penguin is one of the better studied seabirds in the Australian/New Zealand region and, accordingly, various aspects of its phenology are well documented, and the species is considered separately to other species herein.

Little penguin phenology: breeding

Little Penguins generally start breeding when they are 2 or 3 years old (Dann and Cullen *1990*). The timing of breeding and moult in this species varies by location (Table 4); however, the same general annual pattern of moult following breeding by 1–2 months is observed. Adult Little Penguins do not migrate although there are pronounced local movements and dispersion of the penguins breeding on Phillip Island in winter (McCutcheon et al. *2011*). Little Penguins remain ashore for up to 3 weeks during moult (Reilly and Cullen*1983*), making them vulnerable to extreme heat and rainfall events (Cannell et al. *2011*; Dann and Chambers *2013*), predation and human disturbance.

There was considerable inter-annual variability in the breeding timing of Little Penguins at each of the colony sites (Table 4). Interestingly, the timing of breeding was generally not highly correlated among colonies (notable exceptions being the New Zealand sites surveyed by Perriman et al. *2000*). No significant temporal trends in the mean laying dates were observed across all Little Penguin breeding colonies.

The timing of Little Penguin breeding appears to be related to ocean temperatures before the start of the breeding season. For example, in Western Australia Cannell et al. (*2012*) found that laying occurred later when local sea level, an indicator of the strength of the Leeuwin Current and, therefore, ocean temperatures, was higher before breeding. In New Zealand and on Phillip Island in eastern Australia, higher ocean temperatures lead to earlier laying (Perriman et al. *2000*; Cullen et al. *2009*). Earlier laying corresponded to improved breeding success in this species, with heavier chicks and an increased chance of double breeding in a season (Perriman et al. *2000*; Cullen et al. *2009*; Cannell et al. *2012*). A number of mechanisms have been proposed to explain the relationship between ocean temperature and breeding productivity including SST affecting recruitment, productivity and the distribution of prey and warmer water earlier in the year which may result in more prey close to the colony at the time of breeding (Cullen et al. *2009*). Projected increases in ocean temperature under climate change are expected to improve breeding success for some colonies, at least in the short term (Cullen et al. *2009*; Dann and Chambers *2013*).

Little penguin phenology: moult

Although all seabirds moult, very few studies in the Southern Hemisphere have investigated changes in moult phenology over long periods of time. A notable exception is for the Little Penguin at Phillip Island (1969–2012). Moult timing appears to be less variable inter-annually than the timing of breeding (mean laying date day 278.4 ± 3.1 days; mean moult date 67.5 ± 1.5 days). Greater synchrony for moult compared to breeding was also observed in African Penguins breeding at Dassen Island, South Africa (Wolfaardt et al.*2009a*). Two alternative hypotheses have been proposed for why the timing of moult in penguins is more constrained than breeding timing; the timing of breeding activities determines when moult can occur or, alternatively, moult drives the annual cycle and is the priority activity (Paredes et al. *2002*; Wolfaardt et al.*2009a*).

For the Little Penguins of Phillip Island, the timing of moult did not appear to be related to timing of breeding, at least not based on mean laying date of first clutch ($r = -0.11$, $P = 0.587$) nor to any measure of breeding productivity (number of chicks raised per pair or chick mass at fledging, $P > 0.1$) and has not changed significantly over the available time-series (trend = −0.20 days per year, $P = 0.116$). Wolfaardt et al. (*2009a*) found that the timing of breeding did not determine moult timing and suggested that other environmental or biological variables may be involved. For example, the timing of moult may be constrained by availability of food resources (e.g. Paredes et al. *2002*; Wolfaardt et al. *2009a*), potentially more so than breeding as it is more energetically expensive. Unlike breeding, once the moult process is started it can not be brought to a premature end (Wolfaardt et al. *2009a*).

As was the case for mean laying date, the timing of moult at Phillip Island appeared to be predictable from ocean temperatures, with higher ocean temperatures in October (Spring) leading to an early start to moult in the subsequent summer (−7.38 days per °C, $P = 0.016$), possibly indicating relatively more abundant prey resources during the pre-moult fattening period.

Projected warming of land surface temperatures is expected to have a negative impact on breeding and moult in Little Penguins (Dann and Chambers *2013*) with temperatures above 35 °C leading to increased heat stress (Cannell et al. *2011*; Dann and Chambers *2013*). As warmer (ocean) conditions are expected to shift moult and breeding towards earlier (cooler) periods of the year, at least for the colonies in south-eastern Australia and New Zealand, there is some potential to offset the negative impacts of increased land surface temperatures. Additional ways to reduce heat stress and related mortality are discussed below.

Management-based adaptation options

Adaptation options for southern hemisphere seabirds under projected climate change scenarios have been considered most highly for Australian seabirds (e.g. Chambers et al. *2011*), in particular for the Little Penguins of Phillip Island (e.g. Dann and Chambers *2013*). Most suggested adaptation options designed to allow managers to buffer seabirds against changing climatic or oceanographic conditions are land-based, with few developed around the marine environment. Therefore, increasing the resilience of seabirds by managing non-climatic effects, including reducing fisheries competition and predator control, becomes increasingly important. Two examples of adaptation options that have the potential to directly buffer seabirds against environmental change are given below.

Heat stress in Little Penguins is a significant issue, particularly as air surface temperatures are projected to rise (Dann and Chambers *2013*). There are a number of simple adaptation options that can be used to reduce heat exposure by the penguins. Little Penguins readily use artificial structures for nesting (and moult) and it is possible to design artificial burrows to reduce heat exposure (e.g. Ropert-Couder et al. *2004*). Other options include the provision of shade through appropriate vegetation and other structures (such as boardwalks) and active management during forecast heat events (e.g. cooling heat-stressed birds) (Fig. 1). Various management agencies in Australia and New Zealand are presently trialling these adaptation options under local management regimes to assess their efficacy.

For some species, alternative breeding sites may be sought by individuals as sea level and SST rise. New breeding sites may include artificial habitats, such as artificial islands, breakwaters (e.g. Little Penguin, in St Kilda, Australia) and navigation structures (e.g. Australasian Gannet *Morus serrator*, Port Phillip Bay, Australia), providing an opportunity for managers to directly buffer seabirds against changing oceanographic conditions.

Conclusions

Seabirds are a highly threatened group globally; however, long-term phenological data on seabirds in the southern hemisphere are limited to a few regions and species. Although there was a general trend towards later phenological events over time, this varied by both taxa and location. The strongest trends were towards later events occurring in Australia for Laridae (gulls, noddies, terns) and migratory southern polar seabirds. In contrast, earlier phenologies were more often observed for breeding seabirds in the Antarctic and subantarctic and for Spheniscidae (penguins).

Proposed climate drivers for southern hemisphere seabird phenology vary, but are generally related to oceanographic conditions, with sea-ice playing an important role for the more southerly species. For some species in some locations, such as the Little Penguin in south-eastern Australia, warmer oceans projected under various climate change scenarios are expected to correspond to increased productivity, manifested through earlier breeding, heavier chicks and an increased chance of double breeding, at least in the short-term (Dann and Chambers *2013*). For other species, productivity has the potential to be reduced as higher temperatures bring greater competition for nesting sites (Lynch et al. *2012*).

The conservation status of many southern hemisphere seabird species highlights the importance of obtaining a better understanding of the implications of changes in the marine and terrestrial environments to seabird species, including on their phenology, in order to improve their management and conservation status.

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Table 1

Phenological trends broken down by species and location. Data type: *B* breeding dates (*B* laying, *B1* first laying, *B2* mean lay, *B3* last lay, *B4* hatching, *B5* creching, *B6* fledging), *Mi* migration (*A* arrival: *A1* first; *D* departure), *Mo* moult

Species	**Location**	**Years**	**Data Type**	**Trend direction**	**Reference**
Australia					
Little Penguin *Eudyptula minor*	Phillip Island, Vic	1968–2007	B2	Later	Cullen et al. (2009)
Little Penguin	Phillip Island, Vic	1968–2011	B2	No change	L.E.C. and P.D. (unpublished)
Little Penguin	Phillip Island, Vic	1969–2012	Mo	No change	L.E.C, and P.D. (unpublished)
Little Penguin	St Kilda, Vic	1986–2011	B1	No change	Zoe Hogg, Earthcare St Kilda (unpublished)
Little Penguin	Penguin Island, WA	1986–2011	B2	No change	Cannell et al. (2012)
Little Penguin	Penguin Island, WA	1986–2011	B1	Earlier	Cannell et al. (2012)
Little Penguin	Penguin Island, WA	1986–2011	B3	No change	Cannell et al. (2012)
Little Penguin	Bowen Island, NSW	1987–1997	B2	No change	Fortescue (1998)
Sooty Tern *Onychoprion fuscata*	Houtman Abrolhos, WA	1993–2007	B1	Later	Surman and Nicholson (2009b)
Sooty Tern	Houtman Abrolhos, WA	1991–2010	B1	Later	Surman et al. (2012)
Sooty Tern	Houtman Abrolhos, WA	1991–2010	B2	Later	Surman et al. (2012)
Bridled Tern *O. anaethetus*	Penguin Island, WA	1986–2011	B1	Later	Dunlop and Surman (2012)
Brown Noddy *Anous stolidus*	Lancelin Island, WA	1994–2011	B1	No change	Dunlop and Surman (2012)
Brown Noddy	Houtman Abrolhos, WA	1993–2007	B1	Later	Surman and Nicholson (2009b)
Brown Noddy	Houtman Abrolhos, WA	1991–2010	B1	Later	Surman et al. (2012)
Brown Noddy	Houtman Abrolhos, WA	1991–2010	B2	Later	Surman et al. (2012)
Lesser Noddy *A. tenuirostris*	Houtman Abrolhos, WA	1991–2007	B1	Later	Surman and Nicholson (2009b)

Lesser Noddy	Houtman Abrolhos, WA	1991–2010	B1	Later	Surman et al. (2012)
Lesser Noddy	Houtman Abrolhos, WA	1991–2010	B2	No change	Surman et al. (2012)
Wedge-tailed Shearwater*Ardenna pacifica*	Houtman Abrolhos, WA	1991–2007	B1	No change	Surman and Nicholson (2009b)
Wedge-tailed Shearwater	Houtman Abrolhos, WA	1991–2010	B1	No change	Surman et al. (2012)
Wedge-tailed Shearwater	Houtman Abrolhos, WA	1991–2010	B2	No change	Surman et al. (2012)
New Zealand					
Little Penguin	Flea Bay	1996–2009	B2	No change	(unpublished data) from study described in Allen et al. (2011)
Caspian Tern *Hydroprogne caspia*	Invercargill	1964–1993	B1	No change	Barlow and Dowding (2002)
Argentina					
Magellanic Penguin *Spheniscus magellanicus*	Punta Tombo	1983–2006	B2	Later	Boersma and Rebstock (2009)
Antarctica - subantarctic					
Adelie Penguin *Pygoscelis adeliae*	Dumont d'Urville Station	1950–2004	MiA1	No change	Barbraud and Weimerskirch (2006)
Adelie Penguin	Dumont d'Urville Station	1950–2004	B1	Later	Barbraud and Weimerskirch (2006)
Adelie Penguin	Béchervaise Island	1995–2008	MiA	No change	Emmerson et al. (2011)
Adelie Penguin	Béchervaise Island	1990–2003	B	No change	Emmerson et al. (2011)
Adelie Penguin	Béchervaise Island	1990–2005	MiD	No change	Emmerson et al. (2011)
Adelie Penguin	Béchervaise Island	1990–2005	MiD	No change	Emmerson et al. (2011)
Adelie Penguin	Béchervaise Island	1990–2005	B4	No change	Emmerson et al. (2011)
Adelie Penguin	Béchervaise Island	1990–2005	B5	No change	Emmerson et al. (2011)
Adelie Penguin	Béchervaise Island	1990–2005	B6	No change	Emmerson et al. (2011)
Adelie Penguin	Western Antarctic Peninsula	1991–2007	B	Earlier	Lynch et al. (2012)
Gentoo Penguin *P. papua*	Western Antarctic Peninsula	1991–2007	B	Earlier	Lynch et al. (2012)
Chinstrap Penguin *P. antarctica*	Western Antarctic Peninsula	1991–2007	B	Earlier	Lynch et al. (2012)
Pygoscelid penguins	Western Antarctic Peninsula	1991–2007	B	Earlier	Lynch et al. (2012)
Emperor Penguin *Aptenodytes forsteri*	Dumont d'Urville Station	1950–2004	MiA1	No change	Barbraud and Weimerskirch (2006)

Emperor Penguin	Dumont d’Urville Station	1950–2004	B1	No change	Barbraud and Weimerskirch (2006)
Royal Penguin *Eudyptes schlegeli*	Macquarie Island	1964–1999	B2	Earlier	Hindell et al. (2012)
Southern Giant Petrel*Macronectes giganteus*	Dumont d’Urville Station	1960–2004	MiA1	No change	Barbraud and Weimerskirch (2006)
Southern Fulmar *Fulmarus glacialoides*	Dumont d’Urville Station	1950–2004	MiA1	Later	Barbraud and Weimerskirch (2006)
Antarctic Petrel *Thalassoica antarctica*	Dumont d’Urville Station	1980–2004	MiA1	Later	Barbraud and Weimerskirch (2006)
Cape Petrel *Daption capense*	Dumont d’Urville Station	1950–2004	MiA1	Later	Barbraud and Weimerskirch (2006)
Cape Petrel	Dumont d’Urville Station	1950–2004	B1	Later	Barbraud and Weimerskirch (2006)
Snow Petrel *Pagodroma nivea*	Dumont d’Urville Station	1970–2004	MiA1	Later	Barbraud and Weimerskirch (2006)
Snow Petrel	Dumont d’Urville Station	1950–2004	B1	No change	Barbraud and Weimerskirch (2006)
Wilson’s Storm Petrel *Oceanites oceanicus*	Dumont d’Urville Station	1959–2004	MiA1	No change	Barbraud and Weimerskirch (2006)
South Polar Skua *Stercorarius maccormicki*	Dumont d’Urville Station	1950–2004	MiA1	Later	Barbraud and Weimerskirch (2006)
South Polar Skua	Dumont d’Urville Station	1960–2004	B1	Earlier	Barbraud and Weimerskirch (2006)
South Africa					
African Penguin *S. demersus*	Dassen Island	1995–2008	B	Earlier	Durant et al. (2010)

Table 2

Summary statistics. Number of studies by species and region and data type (no long-term data ending post 1990 was found for any other regions). Note only 48 of the 83 datasets had reported trends over time in the phenological variables[a]

					Phenological type			Trend over time		
Region	N	No. locations	No. species	No. years data: median (min, max)	Breeding	Migration	Moult	Earlier	Later	n.s.
Antarctic/ subantarctic	41	9	15	16 (10–55)	23	18	0	7	6	14
Argentina	1	1	1	24	1	0	0	0	1	0
Australia	21	5	7	20 (10–40)	20	0	1	1	9	9
New Zealand	14	7	6	16 (11–28)	14	0	0	0	0	1
South Africa	7	2	1	13 (13–23)	1	0	6	0	0	0
Total	84	24	30	19 (10–55)	59	18	7	8	16	24

[a] Data sources: Antarctic/subantarctic (Barbraud and Weimerskirch *2006*; Crawford et al. *2006*; Emmerson et al. *2011*; Hindell et al. *2012*; Lynch et al. *2009*; Lynch et al. *2012*; McMahon and Hindell *2009*; Saraux et al. *2011*; Baylis et al. *2012*), Argentina (Boersma and Rebstock *2009*), Australia (Cannell et al. *2012*; Cullen et al. *2009*; Fortescue *1998*; Surman and Nicholson *2009a*, *b*; Surman et al. *2012*; unpublished (St Kilda Earthcare; Dann and Chambers)), New Zealand (Allen et al. *2011*; Barlow and Dowding *2002*; Imber et al. *2003*; Mills et al. *2008*; Peacock et al. *2000*; Sagar et al. *2003*), South Africa (Underhill and Crawford *1999*; Wolfaardt et al. *2009a*, *b*)

Table 3

Summary statistics. Number of studies by family and data type (N is the number of datasets within this family and may include the same species more than once). Data sources as in Table 1

		Phenological type			**Trend over time**		
Family	N	Breeding	Migration	Moult	Earlier	Later	n.s.
Hydrobatidae	1	0	1	0	0	1	0
Laridae	17	16	1	0	1	8	3
Procellariidae	16	11	5	0	0	4	6
Spheniscidae	50	32	11	7	7	3	15
Total	84	59	18	7	8	16	24

Table 4

Summary of Little Penguin breeding timing information. Timing is measured in mean laying date (MLD; day of year), except in the case of St Kilda where date first eggs are seen is used

Colony	Latitude (º S)	Period of data	N	Mean timing	S.E.
Penguin Island, Western Australia	32.3	1986–2011	22	209	4.9
Bowen Island, New South Wales	35.12	1987–1997	10	246	4.2
St Kilda (Melbourne), Victoria	37.86	1986–2010	25	187*	7.9
Phillip Island, Victoria	38.52	1968–2011	43	279	3.1
Flea Bay (New Zealand)	43.87	1996–2007	12	275	2.7
Oamaru (NZ) (Site 1)	45.12	1993–1998	6	257	7.9
Oamaru (NZ) (Site 2)	45.12	1993–1998	6	267	6.3
Taiaroa Head (NZ)	45.83	1992–1998	7	265	8.6

Fig. 1

Artificial burrows of Little Penguins can be designed to reduce the chance of heat stress during extreme heat events. Additional gains can be made through providing shade either through man-made structures (*left*) or vegetation (*right*). Images L.E.C.