Chapter 7
Antarctica

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Abstract Antarctica was the last continent to be discovered and colonized by people, and this has resulted in generally sparse meteorological, oceanographic and biological data for the Antarctic and much of the Southern Ocean. Within the Antarctic region, here defined to include all regions south of the Antarctic Polar Front, much of the land-based biological research occurs at or near international scientific stations, leading to some regions, such as the Amundsen Sea, being poorly researched. In the last decade, evidence has emerged of significant differences, but also some similarities, in species' responses to changing environmental conditions, including climate change. However, most of the studies have been confined to larger organisms, such as seabirds and marine mammals, with few long-term studies on the phenology of plants, invertebrates and other species. This highlights the need for greater spatial and species coverage in the southern regions of the globe to assess and quantify regional and ecosystem-scale processes and patterns.

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7.1 Introduction

Antarctica is defined within this chapter as including all regions within the biological Antarctic boundary, which extends to the oceanic Antarctic Polar Front (formerly known as the Antarctic Convergence) and includes the islands of the Southern Ocean that lie on or close to the Front, and covers ~34.8 million km^2 (Young 1991; Griffiths 2010, Table 7.1). This biological boundary is not static, shifting with time and longitude, with an average position around 58°S, but extending as far north as 48°S.

The coldest continent on Earth, Antarctica is isolated from more northerly landmasses due to the perpetually circulating Antarctic Circumpolar Current and associated strong westerly wind field. Seasonality is extreme, with the thermal energy and light from the sun absent during winter at higher latitudes. Antarctic sea ice is also highly seasonal, more so than in the Arctic (Cattle 1991), and it is this variability that is an important climatic feature of the Southern Hemisphere. During winter, sea ice can reach the Polar Front, essentially doubling the continental surface area, but in summer only covers parts of the continental shelf (DASET 1992). The growth and decay of the pack ice, in conjunction with latitude and water mass movements, influence productivity of the system (Young 1991; Massom and Stammerjohn 2010) with the most productive regions of the Southern Ocean generally occurring within the sea ice zone, also known as the marginal ice zone (Griffiths 2010).

According to Young (1991, and others listed within) the Antarctic region can be divided into three biogeographical zones (Table 7.1). However, ecosystems on individual islands, and potentially their phenologies, may vary depending on the extent of sea ice or open water surrounding the islands during the summer period.

The northeast and western parts of the Antarctic Peninsula, and the surrounding seas, have seen significant warming trends in recent decades (Turner et al. 2005, 2007; Griffiths 2010; Trathan and Agnew 2010). Rapid changes in the marine environment include reduced sea ice formation and a shortening of the sea ice season in the Amundsen and Bellingshausen Seas, increased sea ice extent in the Ross Sea region, and altered coastal habitats associated with the collapse of ice shelves (Griffiths 2010; Trathan and Agnew 2010). Warming oceans have also been associated with a decrease in Antarctic Krill, an important food source for several species of fish, seabirds and marine mammals (Trathan and Agnew 2010). In terrestrial systems, changes have been observed in vascular plant populations, but are generally restricted to local population expansion (Convey et al. 2011).

Most coastal stations around Antarctica have recorded an increase in surface wind speeds over the last 50 years (Turner et al. 2005, 2007). At Casey, East Antarctica, increased winds have resulted in lower growth rates in mosses due to reduced water availability at some sites (Clarke et al. 2012).

Table 7.1 Antarctic bio-geographical zones

Zone	Maximum mean monthly temp	Comprises	Vegetation characteristics	Other biological characteristics
Cool (sea-ice free zone)	3–7 °C	Subantarctic islands close to or immediately south of the Polar Front, i.e. South Georgia, Marion and Prince Edward Is., Crozet Archipelago, Kerguelen Archipelago, Heard and McDonald Islands and Macquarie Island	Polar deserts and open fellfields at high altitudes developing to closed herbfield, mire and grasslands at lower altitudes. Dominated by bryophytes, graminoids, herbs and megaherbs	Terrestrial systems: high in marine-derived nutrients from seals and seabirds, high primary productivity at low altitudes. Low rates of decomposition Marine systems: nutrient concentrations variable reflecting complex oceanic regime. Influences from intrusions of Antarctic and subantarctic surface waters, and local off island enrichment from terrestrial (ex-marine) runoff. Antarctic Krill (*Euphausia superba*) is virtually absent Islands with permanent ice areas are exhibiting retreat of glaciers and decreases in the extents of permanent ice areas, opening areas for plant and animal colonization. In some cases, these colonisation events are facilitating animal population increases (e.g., fur seals and penguins)
Cold (seasonal sea-ice zone)	0–2 °C	Antarctic Peninsula to about 70°S, South Sandwich, South Shetland and South Orkney Island groups	Closed stands of bryophytes, lichens and algae extensive only in wet or mesic areas. Only two flowering species present.	Terrestrial systems: Low productivity, stark seasonality Marine systems: zone of highest productivity moves north and south with sea-ice migration; important zone for phytoplankton blooms; complex food web with krill at the centre
Extreme (permanent packice zone)	<0 °C	Continental Antarctica and islands close to continent, such as Peter I Is, Scott Is, Balleny Islands	Vegetation largely restricted to scattered colonies of mosses, lichens or algae and endolithic communities. Vascular plants absent, liverworts very rare	Terrestrial systems: low productivity, stark seasonality, low summer temperatures Marine systems: intense short period of high productivity for most species Strong seasonal pulse of biological activity for ~6 months (October–March inclusive) with high marine productivity manifested by bird and mammal breeding. Only vertebrate species that breeds on the continent in winter is the Emperor Penguin *Aptenodytes forsteri*

Based on Young (1991) and DASET (1992)

7.2 Agency Data and Research

Due to its extreme climate and isolation, Antarctica was the last continent to be discovered and colonized by people, though contemporary human residents are transitory. This has resulted in generally sparse meteorological, oceanographic and biological data for the Antarctic and much of the Southern Ocean (but see Laws 1984; Cattle 1991; El-Sayed 1994; and Knox 1994 for reviews).

Nations claiming territories in the Antarctic are: Argentina, Australia, Chile, France, New Zealand, Norway and the United Kingdom. Australia has the largest claim, its two sectors covering approximately 42 % of the continent. The Antarctic Treaty, enacted in 1961, is concerned with the governance of Antarctica and involves two tiers of membership: (i) nations which conduct significant science programs in the region, and (ii) those who subscribe to the provisions of the Treaty but are yet to establish scientific programs (DASET 1992).

Much of the land-based biological research in the Antarctic occurs at or near the scientific stations (37 of 64 are open year-round) (Griffiths 2010). Due to the locations of these stations, and their proximity to their home countries, this has meant that Australian, New Zealand and Asian (Japan, China, South Korea) research is concentrated in East Antarctica while European and South American research is conducted mainly in West Antarctica, the Scotia Sea and Weddell Sea areas. The United States and Russia conduct research in both regions (Griffiths 2010). As a result, the regions of Antarctica with no neighboring continent, such as the Amundsen Sea, have been and continue to be poorly researched. A summary of continuous long-term (commencing pre-1970) biological research programs is given below. Many other nations operate, or participate, in short-term biological monitoring programs in the Antarctic (http://www.scar.org), but these are not discussed here. Further details of logistic, operational and research efforts for all stations and Treaty partners are available at http://www.ats.aq/devAS/ie_annual.aspx?lang=e and http://www.ats.aq/devAS/ie_permanent.aspx?lang=e.

7.2.1 Scientific Committee on Antarctic Research

The Scientific Committee on Antarctic Research (SCAR) is composed of members from national scientific academies or research councils interested in Antarctic research, and the relevant scientific unions of the International Council for Science. Full membership is reserved for countries (31 as of 2011) with active Antarctic research programs (http://www.scar.org). SCAR's mission is to provide science leadership and to provide independent scientific advice to the Antarctic Treaty System. The SCAR scientific research program of most relevance to phenology is "*Evolution and Biodiversity in the Antarctic*", which includes the study of the 'response of life to change'.

7.2.2 Argentine Antarctic Institute

Argentina has six permanent research stations and three summer-only stations in the Antarctic, including Orcadas Base in the South Orkney Islands, which opened in 1904, making it the earliest Antarctic base (Griffiths 2010).

The Argentine Antarctic Institute (Instituto Antártico Argentino) was created in 1951. The Institute conducts a number of long-term biological studies including population dynamics and reproductive biology of seal and seabird species (http://www.scar.org/about/nationalreports/argentina/99to00/).

7.2.3 Australian Antarctic Program

The Australian Antarctic Program is a joint agency and university program, run from the Australian Antarctic Division (AAD: http://www.antarctica.gov.au) within the Federal Department of Sustainability, Environment, Water, Population and Communities. The basis of the science program is a 10 year Science Strategic Plan (http://www.antarctica.gov.au/science/australian-antarctic-science-strategic-plan-201112-202021).

The AAD is the lead Antarctic scientific agency in Australia and also administers the Australian Antarctic Territory (AAT) and Heard and McDonald Islands. Australia has three coastal Antarctic continent stations in East Antarctica (Mawson, Davis and Casey) and one subantarctic station on Macquarie Island. Visits to Heard Island are intermittent and at decadal scales.

Two of the four current priority research programs are relevant to phenology: *Southern Ocean Ecosystems: Environmental Change and Conservation* and *Terrestrial and Near Shore Ecosystems: Environmental Change and Conservation*. Long-term Adélie penguin (*Pygoscelis adeliae*) population and phenological studies occur near Mawson Station (Béchervaise Island) as a contribution to the Commission for the Conservation of Antarctic Marine Living Resources Ecosystem Monitoring Program (CCAMLR-CEMP). A number of other long-term population studies were undertaken in the AAT, some extending from the 1950s to the early 2000s, in addition to on-going long-term glaciological and meteorological research. Long-term albatross and fur seal population and phenological studies occur on Macquarie Island with intermittent penguin studies. No long-term terrestrial phenological studies are in progress at the time of writing.

7.2.4 British Antarctic Survey

The British Antarctic Survey (BAS, http://www.antarctica.ac.uk) has been responsible for the majority of the United Kingdom's Antarctic research for more than 60 years.

BAS has five research stations in the Antarctic (summer-only since 1996 at Signy, South Orkney Islands), two on South Georgia: Bird Island (continuously since 1982) and King Edward Point and Halley and Rothera, Antarctica.

Phenology fits within one of BAS's key challenges, "*understanding how Southern Ocean species respond to climate change*". Several long-term monitoring programs have been established and contribute to CCAMLR-CEMP, including seabird and seal research at Bird Island and penguin, seabird and seal biology at Signy research station. Signy research station also hosts long-term collaborative studies with the Japanese National Institute for Polar Research and the Netherlands Polar Programme.

7.2.5 Chilean Antarctic Institute

The Chilean Antarctic Institute (INACH, http://www.inach.cl) was established in 1963. It operates scientific stations on King George Island, Greenwich Island and Cape Shirreff (South Shetland Islands) and on the Palmer and Antarctic Peninsulas. Long-term monitoring programs investigate Antarctic flora, benthic communities, fur seals and seabirds. Recent initiatives include research on the impacts of regional climate change on marine and terrestrial systems.

7.2.6 French Polar Institute

France has had research bases in the Antarctic since 1950. The French Polar Institute Paul-Emile Victor is responsible for the implementation of research programs in polar and subpolar regions in both hemispheres.

The territory of the French Southern and Antarctic Lands (Terres Australes et Antarctiques Françaises) administers several island groups in the southern Indian Ocean and part of Antarctica (Adélie Land). The subantarctic territories include the Crozet and Kerguelen Archipelagos, St. Paul and Amsterdam Islands.

There are two continental stations (Dumont d'Urville and Concordia, which is managed in conjunction with Italy) and three subantarctic stations: Alfred Faure on the Crozet Archipelago, Port aux Français on the Kerguelen Archipelago and Martin-de-Viviès on Amsterdam Island.

Scientific research of relevance to phenology includes the project, "*penguins as indicators of climate anomalies in the Southern Ocean*". One of the longest phenological Antarctic and subantarctic projects (extending for more than 50 years), this study monitors the first arrival and first egg laying dates in Adélie Land, Crozet and Kerguelen Archipelagos and on Amsterdam Island (Table 7.2).

Table 7.2 Published long-term (at least 10 years) phenological studies from the Antarctic many of these studies are on-going

Location	Species	Phenological variable	Time period	Summary	References
Dumont d'Urville Station, Adélie Land, East Antarctica	Emperor Penguin *Aptenodytes forsteri*	First arrival date	1950–2004	No trend over time or relationship with sea ice extent	Barbraud and Weimerskirch (2006)
	Adélie Penguin *Pygoscelis adeliae*				
	Southern Giant Petrel *Macronectes giganteus*				
	Snow Petrel *Pagodroma nivea*		1970–2004		
	Southern Fulmar *Fulmarus glacialoides*	First arrival date	1950–2004	Later arrival over time; negative relationship with sea ice extent	Barbraud and Weimerskirch (2006)
	Cape Petrel *Daption capense*				
	South Polar Skua *Stercorarius maccormicki*				
	Wilson's Storm Petrel *Oceanites oceanicus*		1960–2004		
	Antarctic Petrel *Thalassoica antarctica*	First arrival date	1980–2004	Later arrival over time; no relationship with sea ice extent	Barbraud and Weimerskirch (2006)
	Adélie Penguin	Laying date: first eggs	1950–2004	Later laying over time; negative relationship with sea ice extent	Barbraud and Weimerskirch (2006)
	Cape Petrel				
	Emperor Penguin	Laying date: first eggs	1950–2004	No trend over time; negative relationship with sea ice extent	Barbraud and Weimerskirch (2006)
	Snow Petrel	Laying date: first eggs	1950–2004	No trend over time or relationship with sea ice extent	Barbraud and Weimerskirch (2006)
	South Polar Skua	Laying date: first eggs	1960–2004	Earlier laying over time; no relationship with sea ice extent	Barbraud and Weimerskirch (2006)

(continued)

Table 7.2 (continued)

Location	Species	Phenological variable	Time period	Summary	References
Béchervaise Island, East Antarctica	Adélie Penguin	Arrival date: first and average	1995–2008	No trend over time; later arrival when near-shore ice extensive and maximum temperatures lower	Emmerson et al. (2011)
	Adélie Penguin	Laying date	1990–2003	No trend over time; earlier laying when Southern Angular Mode positive and later when winds more southerly	Emmerson et al. (2011)
	Adélie Penguin	Hatching date	1990–2005	No trend over time	Emmerson et al. (2011)
	Adélie Penguin	Créching date	1992–2006	No trend over time	Emmerson et al. (2011)
	Adélie Penguin	Fledging date	1991–2004	No trend over time	Emmerson et al. (2011)
Casey, East Antarctica	Snow Petrel	Breeding success (7 years of laying and hatching dates)	1984–2003	Breeding success linked to sea ice extent, no relationship with Southern Oscillation Index (SOI) or Antarctic Circumpolar Wave	Olivier et al. (2005)
Cape Crozier, Ross Island, Ross Sea, Antarctica	Adélie Penguin	Dates of first arrival and first eggs	1962–1975	No long-term trend, inter-annual variability from sea-ice extent	Ainley et al. (1983)
Admiralty Bay, King George Island	Adélie Penguin Gentoo Penguin *Pygoscelis papua*	Laying date	1991–2006	Earlier egg laying when mean October temperatures warmer; overall trend in egg laying shared by all 3 species 0.15 days year^{-1} earlier	Lynch et al. (2009); Lynch et al. (2012a)
Cape Shirreff, Livingston Island	Chinstrap Penguin *Pygoscelis antarcticus*	Laying date	1997–2006	Earlier egg laying when mean October temperatures warmer; overall trend in egg laying shared by all 3 species 0.15 days year^{-1} earlier	Lynch et al. (2009); Lynch et al. (2012a)

Possession Island, Crozet Archipelago	King Penguin *Aptenodytes patagonicus*	Arrival date	1998–2008	Did not measure trend over time; difference in timing between banded and non-banded birds; banded birds arrived later at colonies	Saraux et al. (2001), Gauthier-Clerc et al. (2004), Le Bohec et al. (2008)
	King Penguin	Laying date	1998–2008	Did not measure trend over time; difference in timing between banded and non-banded birds	Saraux et al. (2001)
Marion Island	Macaroni Penguin *Eudyptes chrysolophus* Rockhopper Penguin *Eudyptes chrysocome*	Arrival date	1994–2005	Did not measure trend over time; mean and range vary by gender	Crawford et al. (2006)
	Macaroni Penguin Rockhopper Penguin	Fledging date	1994–2005	Did not measure trend over time	Crawford et al. (2006)
Macquarie Island	Royal Penguin *Eudyptes schlegeli*	Laying date	1960s (6 years), 1990s (5 years)	Earlier laying over time (-0.108 days^{-1}); lay later in years of high SOI (lower productivity)	McMahon and Hindell (2009)
	Southern Elephant Seal *Mirounga leonina*	Peak haul out date	1950–1959	Did not measure trend over time; mean and range according to age and breeding status	Hindell and Burton (1988)
	Leopard Seal *Hydrurga leptonyx*	First and last sighting dates	1949–1979	Irruption of seals onshore, cyclic haul out numbers. Cycles considered to be related to sea-ice proximity	Rounsevell and Eberhard (1980), Rounsevell (1988)

(continued)

Table 7.2 (continued)

Location	Species	Phenological variable	Time period	Summary	References
Bird Island, South Georgia	Antarctic Fur Seal *Arctocephalus gazella*	Birthing date	1984–2004	Later timing with extreme positive SST anomalies	Forcada et al. (2005)
	Gentoo Penguin	Laying date: first egg	Not provided	First egg ~10 days earlier than 18 years ago; advance in date when 75 % of eggs laid	Trathan and Agnew (2010)

7.2.7 New Zealand

Antarctica New Zealand is responsible for New Zealand government activities in the Southern Ocean and Antarctica. New Zealand manages the research station Scott Base, in Victoria Land, and has an operational presence in the Ross Dependency (http://www.antarcticanz.govt.nz/).

Research of relevance to phenology includes a long-term project investigating the population dynamics of the Adélie Penguin of the Ross Sea and its use as a biological indicator of local and broad-scale changes.

The Department of Conservation has long-term population and phenological studies established for New Zealand Sea Lions (*Phocarctos hookeri*) on Enderby Island. Long-term population and demographic studies of albatrosses at Campbell Island commenced in the 1940s (Waugh et al. 1999).

7.2.8 Norwegian Polar Institute

Norway operates a year round base in Dronning Maud Land and has conducted regular expeditions to the Antarctic since 1976 (http://www.npolar.no). Biological and climate-change related studies are conducted at their field station, Tor, and opportunistic studies on the island of Bouvetøya in the South Atlantic Ocean.

7.2.9 Russian Antarctic Expedition

Russia has had a research presence in the Antarctic since 1956 when Mirnyy station was established. The Russian Antarctic Expedition (http://www.aari.aq) currently maintains four other active stations: Vostok, Novolazarevskaya, Bellingshausen and Progress (summer only). Long-term monitoring of seabird populations has been undertaken at Mirnyy since the 1950s (Barbraud et al. 2011).

7.2.10 South African Antarctic Programme

The South African National Antarctic Programme (http://www.sanap.org.za/) maintains bases on Antarctica and on Marion and Gough Islands. The first Antarctic Expedition in 1959 established a permanent South African presence on Antarctica. Research themes include the response of biodiversity to earth system variability, and programs of phenological relevance include seabirds at Marion Island and individual variation in albatross reproduction.

7.2.11 United States Antarctic Program

The United States has had a research presence (including 3 year-round research stations) in Antarctica since 1956, with an aim to understand the region's ecosystems and its responses to global processes, including climate (http://www.nsf.gov/od/opp/antarct/usap.jsp).

Long-term biological studies are undertaken at Palmer Station on Anvers Island (Antarctic Peninsula), Admiralty Bay and King George Island, in the South Shetland Islands. This includes the breeding biology and demography of the Pygoscelid penguins. Long-term studies of Adélie Penguins are also conducted in the Ross Sea region on Beaufort and Ross Islands (Cape Crozier, Cape Bird and Cape Royds), and a long-term population study of Weddell Seals (*Leptonychotes weddellii*) in Erebus Bay, Ross Island.

7.2.12 National Institute of Polar Research (Japan)

Japan has had a research presence in the Antarctic since the 1950s, with Syowa Station, East Antarctica, opening in 1957 (http://www.nipr.ac.jp). Long-term biological studies are undertaken at Syowa Station and, until 1991, at Asuka Station. Since 1997, there has been an emphasis on monitoring for biological change.

7.3 Recent Phenological Research

Although low in number compared to many Northern Hemisphere regions, a number of long-term (at least 10 years of data) studies have been conducted in the Antarctic (Fig. 7.1, Table 7.2). The most notable being the 50+ year study of all seabird species in the East Antarctic (Barbraud and Weimerskirch 2006).

Most long-term phenological research has been conducted on birds (84 % of 45 data series); the balance has been conducted on mammals (16 %). Studies of breeding and migration phenology were equally represented.

7.3.1 Plants

Limited phenological studies have been conducted on terrestrial plants in the Antarctic and phenology (spelling was incorrect on line 221) on the subantarctic islands and most are short-term studies. Bryophyte and lichen phenology in particular, is significantly neglected as a topic of study. Many mosses and some lichens do not produce reproductive structures such as capsules or apothecia in the Antarctic or

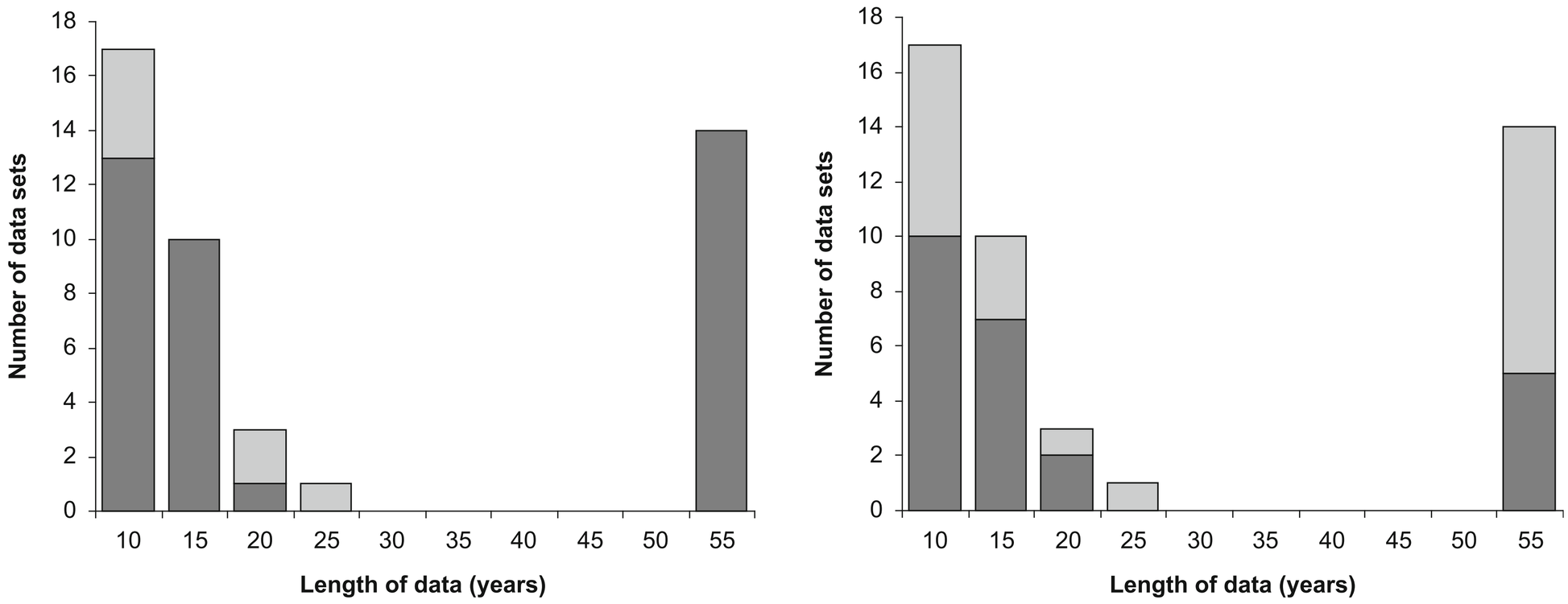

Fig. 7.1 Typical duration of long-term phenological data sets in the Antarctic. Broken down into (*left*) bird data sets (*dark grey*, n = 38) and mammal data sets (*light grey*, n = 7); (*right*) according to breeding data (*dark grey*, n = 24) and migration data (*light grey*, n = 21)

subantarctic (see Seppelt 2004; Olech 2004; Ochyra et al. 2008). In terrestrial areas of the extreme zone (continental Antarctica), only one third of the bryophyte flora (5 of 15) species have been observed fruiting. In the southern maritime Antarctic (68–72°S), this increases to 47 % at Marguerite Bay, 51 % at the South Shetlands, but decreases again on subantarctic islands (37 % South Georgia, Smith and Convey 2002; 33 % Macquarie Island [mosses data only], Bergstrom and Selkirk 1987). Reasons for failure to sexually reproduce include disjunct patterns in male and female plants, lack of one gender at a locality and failure for gametangial initiation (Smith and Convey 2002).

Phenology in flowering plants in the region is cued to seasonality in the light regime. Two species, the small cushion plant Antarctic Pearlwort *Colobanthus quitensis* and the grass Antarctic hair grass *Deschampsia antarctica* can be found along a latitudinal gradient from South Georgia extending to the cold Antarctic zone along the Antarctic Peninsula, to as far south as Alexander Island (69°22′0S, 71°50′7W). They have both been noted to flower most years and produce mature seed along their entire latitudinal range (Holtom and Greene 1967; Convey et al. 2011). Flower initiation for the species is in early to late summer and both species can produce seed within a single year but, with increased (southward) latitude, rates of development were observed to become lower and less predictable. Flower primordia for *D. antarctica* develop late in the previous summer season (Holtom and Greene 1967; Edwards 1974). In many years, seeds failed to reach maturity. With climate warming, however, seed maturation appears to be increasing (Convey 1996; Convey and Smith 2006).

In the subantarctic, flowering onset generally occurs in spring and is triggered by day length, but variation in the timing of stage development (e.g., flower bud opening, fruit ripening, seed shedding) can be found across the floras and is often associated with life history strategies. Small herbs generally have rapid development and some long-lived perennial stayers often do not complete a sexual reproductive cycle in a single year, with both preformation of flower buds the season previous and post winter ripening (see: Dorne 1977; Walton 1982; Bergstrom et al. 1997;

Table 7.3 Key plant phenological studies across the subantarctic region

Island	Author	Notes (number of species)
Kerguelen	Dorne (1977)	Floral phenology and germination (7)
	Frenot and Gloaguen (1994)	Reproductive biology (7)
	Hennion and Walton (1997)	Germination (8)
	Chapius et al. (2000)	Reproductive biology (1)
Macquarie	Taylor (1955)	Autecology including phenological notes (39)
	Bergstrom et al. (1997)	Phenology and reproductive behaviour (10)
	Tweedie (2000) and Shaw (2005)	Phenology and germination (6, 26)
Marion	Huntley (1970)	Phenology and distribution (12)
	Mukhadi (2010)	Vegetative and reproductive phenology (15)
South Georgia	Callaghan and Lewis (1971)	Reproductive performance (1)
	Tallowin (1977)	Phenology and reproductive biology (1)
	Walton (1977, 1979, 1982)	Phenology, germination, and hybridization (19)

Hennion and Walton 1997; Shaw 2005). Some non-native species, such as *Poa annua* and *Cerastium fontanum* exhibit longer reproductive seasons (Bergstrom et al. 1997; Mukhadi 2010). Table 7.3 summarises major studies on subantarctic vascular plant phenology.

Phenological patterns have been noted in some marine algae, with development finely tuned to seasonal light regimes. "Seasonal anticipators" become fertile in late autumn to winter, in contrast "seasonal responders" reproduce in summer under suitable irradiance, nutrient, and temperature conditions (see Wiencke et al. 2011 for review).

7.3.2 Birds

On a whole, more research has been conducted into seabirds than other taxa of the Antarctic region (Korczak-Abshire 2010). As these seabirds are long-lived (in some cases for more than 50 years), and thereby integrate environmental signals over multiple time and space scales, this research may provide useful insights into ecosystem status and processes (Trathan et al. 2007).

Many Antarctic seabirds have high degrees of breeding synchrony (e.g. Black-browed Albatross (Croxall et al. 1988), Cape Petrel (Weidinger 1997), Snow Petrel (Amundsen 1995; Barbraud et al. 2000)). For species that require snow-free areas for breeding, the amount of time available to breed can be relatively short and may lead to more breeding synchrony (and is broadly correlated with latitude); sea ice seasonality and photoperiod may also reduce the time available for breeding. Synchronous breeding may also result in predator swamping, thereby increasing the likelihood of individuals surviving the breeding period (but see Kharitonov and Siegel-Causey 1988; Siegel-Causey and Kharitonov 1990 for reviews of seabird coloniality).

Many Antarctic seabird species show strong latitudinal gradients in time of breeding, for example Lynch et al. (2009) found that *Pygoscelis* penguins breed approximately 4.77 days later per degree latitude south, later revised to 5.2 days per degree south (Lynch et al. 2012a). But despite this, not all species show a high degree of flexibility in phenology (e.g., Adélie and Emperor Penguins, Forcada and Trathan 2009).

Although species that are reliant on snow-free areas for breeding may advance their breeding in response to higher temperatures (e.g., Lynch et al. 2009), the rate of change is not always consistent among species, e.g., Gentoo Penguins advanced their breeding at more than twice the rate of either Adélie or Chinstrap Penguins (Lynch et al. 2009). Gentoo Penguins forage close to the breeding colonies during winter, potentially giving them the competitive advantage of local knowledge of prey distribution, compared to the dispersive Adélie and Chinstrap penguins (Lynch et al. 2012b).

Since the early 1950s, the community of nine species of Antarctic seabirds breeding at Dumont d'Urville on the East Antarctica coast have been monitored for their arrival dates and breeding chronologies (Barbraud and Weimerskirch 2006). Over the period of the study, this region saw no major warming or cooling events, but did experience a large reduction in sea ice extent. Although all nine species delayed their arrival over time (c. 9.1 days later than in 1950s), the only species with significantly later ($p < 0.05$) arrival dates were Southern Fulmars, Antarctic and Cape Petrels. The mean egg-laying dates for two species were also significantly delayed (Adélie Penguin and Cape Petrel). The combined delay in both arrival and egg-laying resulted in a c. 7 day compression of the pre-laying period (Barbraud and Weimerskirch 2006), possibly due to the birds requiring additional time to feed before returning to their colonies to commence breeding.

The extent of sea ice has been associated with the arrival timing of several species of Antarctic seabirds. For some penguin species at some colonies, years of extensive sea ice are associated with generally later arrival at breeding colonies, either due to longer travel times over the ice, penguins assessing the ice extent and delaying travel and/or the effect of the sea ice on prey availability and therefore the penguin's body condition (e.g., Ainley et al. 1983; Ainley 2002; Emmerson et al. 2011). For other seabird species, sea ice extent was either unrelated to arrival timing or resulted in earlier arrival when sea ice was more extensive (Olivier et al. 2005; Barbraud and Weimerskirch 2006). Changes in sea ice may not only affect the timing and success of breeding but, consequently, can have flow on effects to survival and population abundance (e.g., Fraser et al. 1992; Crawford et al. 2006; Korczak-Abshire 2010). In fact, changes in sea ice seasonality may explain many of the shifts observed in key phenological relationships in the Antarctic (Massom and Stammerjohn 2010).

Variation in body size has also been proposed as a means of explaining individual variation in laying date, at least in the case of the nest fidelity of Snow Petrels; with larger females having later laying dates (Barbraud et al. 2000). A higher proportion of larger females in larger colonies is also suggested as the main reason for laying occurring approximately 2 days later in larger breeding colonies

compared to small colonies or isolated nests of the same species. The presence of flipper bands on birds has also been shown to delay arrival and breeding of penguins which had negative implications for breeding success and survival (Froget et al. 1998; Saraux et al. 2001; Gauthier-Clerc et al. 2004; Le Bohec et al. 2008).

The breeding cycle of the King Penguin is unique among penguins in that it takes more than 1 year to complete. As the timing of initiation of breeding depends on the success of the previous season there can be considerable asynchrony in laying dates over the colony (du Plessis et al. 1984). Early breeding leads to generally higher breeding success with more chicks surviving to fledging compared with later laying (du Plessis et al. 1984; Weimerskirch et al. 1992; Jouventin and Lagarde 1995). In the Crozet Archipelago, late breeding almost always leads to breeding failure (Weimerskirch et al. 1992). Successful breeders tended to return to the colony earlier for either moult or displaying (Jouventin and Lagarde 1995). Moult duration in King Penguins was shorter for individuals that commenced moult later in the season (Jouventin and Lagarde 1995).

7.3.3 Mammals

Although the peak haul out date for Southern Elephant Seals tends to vary with latitude, Authier et al. (2011) found no corresponding latitudinal pattern in the level of breeding synchrony. However, within sites, breeding synchrony tended to be lower in the harems that formed earlier in the breeding season than those forming later and may be age related (breeding experience); older, more experienced, females tended to haul out later (Authier et al. 2011). The level of haul out synchrony in Antarctic Fur Seals has been shown to vary between genders, and also at the individual and population levels (Duck 1990; Slip and Burton 1999). Both genders vary the timing of haul out in relation to environmental conditions, but females appear to be more constrained in timing to ensure that offspring are born and raised during the brief summer period.

A long-term study of Antarctic Fur Seals in South Georgia (Forcada et al. 2005, 2008) found that they are more likely to "optimize" individual fitness by altering their phenology (particularly birthing dates) when faced with short-term changes in their environment. Although later mean birthing dates tended to correspond to periods of higher sea surface temperatures, the overall long-term variability in birthing dates was small (range of 4–15 days), indicating that their ability to alter their phenology may be limited (Forcada et al. 2005, 2008). A similar result was found for all major Southern Elephant Seal populations (Hindell and Burton 1988). Antarctic and Subantarctic Fur Seals *A. tropicalis* at Marion Island also show little year-to-year variation in pupping dates (Hofmeyr et al. 2007).

There has been some debate in the past as to whether Leopard Seals are migratory or not (see Rounsevell and Eberhard 1980) and hence exhibit migration phenology. Long-term sighting dates of Leopard Seal haul outs on Macquarie Island indicate that non-breeding seals will over-winter in subantarctic and

temperate oceans. The number of seals undertaking this northward movement varies from year to year, suggesting dispersion rather than migration, which may be driven by food shortages (Rounsevell and Eberhard 1980).

7.3.4 Other Species

Low thermal energy budgets in all three Antarctic zones results in reduced or zero growth rates in terrestrial invertebrates over winter (Convey 1996). This can lead to life-cycle events (such as moulting and oviposition) being synchronized following the winter period.

The onset of maximum production of Antarctic phytoplankton varies with latitude, from early spring in the northern zones (~50°S) to late summer or early autumn in the south (El-Sayed 1988). There is an inverse relationship between latitude and the length of the period of maximum production. The timing and magnitude of peak marine production, and the phytoplankton species associated with it, also varies inter-annually in association with oceanographic changes (El-Sayed 1988).

The timing, and intensity, of Antarctic Krill spawning is affected by a variety of environmental conditions including variation in the timing of sea ice formation and retreat, and by the amount and duration of sea-ice cover (Massom and Stammerjohn 2010). Spawning tends to be earlier when there is a longer duration of winter sea ice and delayed seasonal pack ice opening in spring. When spawning is delayed, larval production and or survival are generally poor, presumably due to larvae being less developed, and therefore less able to survive the food-limited winter sea ice conditions (Siegel and Loeb 1995).

Water temperature also influences moult in the sub-Antarctic dytiscid water beetle *Lancetes claussi* which delays moulting from its larval stage IV into pupa until surface water temperatures exceed 7.3 °C (Convey 1996). This delayed moulting results in early summer peaks of adult emergence and oviposition.

At subantarctic Heard and Kerguelen Islands, site, gender, and species differences have been observed in the timing of seasonal activity of Dipterans and, based on these data, earlier and longer lasting reproductive phases are expected in the future (Greenslade et al. 2011).

7.4 Conclusions

There are few long-term studies that collect phenological data for the Southern Hemisphere and our review draws heavily on information published on a limited number of species from a limited number of sites. For the few species with sufficient data to detect phenological changes, both over time and in response to climate variables, the responses varied by location and species. This highlights the need for

greater spatial coverage to assess and quantify regional and ecosystem-scale processes and patterns. The proposed Southern Ocean Observing System (http://www.scar.org/soos), based on sustained multi-disciplinary observations for the detection, interpretation and responses to change may assist this goal. The ideal monitoring system comprises long-term observations over multiple trophic levels (Griffiths 2010), enabling investigators to detect potential mismatches in temporal scales between response from populations/communities/species and rates of change in environmental parameters.

For species with less flexible life histories (e.g., many Antarctic mammals and seabirds) changes to critical components of their environment (e.g., sea ice) may result in population changes. These may take the form of range shifts or demographic change. Some of these changes have already been observed (e.g., Forcada et al. 2008).

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