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Review of diseases (pathogen isolation, direct recovery and antibodies) in albatrosses and large petrels worldwide

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Summary

Albatrosses (*Diomedeidae*) and large petrels (*Macronectes* and *Procellaria* spp.) are among the world's most rapidly declining birds. Some of the most endangered species, Amsterdam Albatross *Diomedea amsterdamensis*, Indian Yellow-nosed Albatross *Thalassarche carteri* and Sooty Albatross *Phoebetria fusca*, are at risk from recurrent avian cholera outbreaks. Yet little is known about the overall impact of disease in this group. We compiled all available information on pathogens described in albatrosses and large petrel species listed under the Agreement on the Conservation of Albatrosses and Petrels (ACAP) (n = 31). Available reports (n = 53) comprise nearly 60% of ACAP species (18/31). However, only 38% of them focus on threatened species (20/53), and 43% solely report macroparasite findings (23/53). Black-browed Albatross *Thalassarche melanophrys* (Near Threatened) and Southern Giant Petrel *Macronectes giganteus* (Least Concern) are the two species with higher number of publications (29/53, 55% of all papers). Conversely, seven species on the IUCN Red List have three papers or less each. Most existing research has resulted from disease or mortality investigations and baseline studies (28 and 32%, respectively). Pathogens reported in the subset of ACAP species, included bacteria in seven species (39%), viruses in five (28%), protozoa in four (22%), helminths in nine (50%), ectoparasites in 13 (72%) and fungi in one species (5%). Avian cholera, caused by the bacterium *Pasteurella multocida*, appears as the most severe threat to ACAP species. Infections by poxvirus are the most common viral finding, yet entail lower population level impact. Few serosurveys report pathogen exposure in these species, but add valuable baseline information. There are numerous obvious gaps in species and geographical coverage and likely under-reporting due to remoteness, accessibility and sporadic monitoring. This insufficient knowledge may be hampering effective protection and management of populations at risk. Attention to species currently affected by avian cholera is of utmost priority.

Introduction

Seabirds are globally declining (Croxall *et al.* 2012). Particularly, albatrosses (*Diomedeidae*) and large petrels (*Macronectes* and *Procellaria* spp.) have increasingly roused concerns about their sustainability (Croxall and Gales 1998, Woehler *et al.* 2001, Cooper *et al.* 2006). This group comprises some of the world's most endangered species of birds, with rapidly decreasing populations and their conservation status markedly deteriorating in recent years (Paleczny *et al.* 2015, Phillips *et al.* 2016). Incidental mortality in fisheries (hereafter "bycatch") has been well documented and identified as a major threat to these species (Tuck *et al.* 2001, Baker *et al.* 2002, Lewison *et al.* 2004, Rolland *et al.* 2009, 2010, Jimenez *et al.* 2014). However, invasive alien species, degradation or loss of nesting habitat, human disturbance, and marine pollution or plastic ingestion are also significant factors in population declines (Phillips *et al.* 2016).

Notably, less is known about the threat that albatrosses and petrels face from infectious disease, even though pathogens have the potential to cause rapid declines and extinction in vulnerable vertebrate populations (Smith *et al.* 2009, Delahay *et al.* 2009, Heard *et al.* 2013). It is likely that most albatross and large petrels are immunologically naïve to infectious diseases due to evolutionary and current geographic isolation (Phillips *et al.* 2016). This, coupled with their highly gregarious breeding habits, make them particularly susceptible to opportunistic pathogens and disease epidemics (Descamps *et al.* 2012). Dramatic evidence of this are the recurrent chick mortalities and reproductive failure from avian cholera presently affecting two albatross species from Amsterdam Island in the Indian Ocean, and threatening the 'Critically Endangered' and endemic Amsterdam Albatross *Diomedea amsterdamensis* (Weimerskirch 2004, Demay *et al.* 2013, Jaeger *et al.* 2013, 2015). Furthermore, the avian cholera agent *Pasteurella multocida* is closely linked to poultry and human dispersion, and has caused the most significant epizootics in locations as isolated as Antarctica (Woods *et al.* 2009).

As pathogen transmission dynamics evolve rapidly with globalisation and climate change (Morse 1995, Altizer *et al.* 2013, Wang *et al.* 2014), threats from disease will likely increase exponentially. Moreover, the synergistic effects of disease with other highly negative impact factors, such as interactions with fisheries and environmental pollution, may become determinants for species extinction and further accelerate this irrevocable process (Rolland *et al.* 2009, Demay *et al.* 2013). An additional concern is that albatrosses and large petrels spend most of their life at sea and return to land only to breed, thus the impact of diseases is perhaps more difficult to detect than in coastal species (Weimerskirch 2004).

The Agreement on the Conservation of Albatrosses and Petrels (ACAP) has recognized the potential impact of diseases on this group of seabirds, and has rightfully encouraged actions to improve knowledge and management of diseases of concern; i.e. "*…review evidence for impacts of pathogens and parasites on ACAP species and effectiveness of mitigation measures*" (ACAP AC7 2013); "*… implement long-term disease surveillance programs*" and "*…thoroughly investigate albatross disease/mortality events when they occur*" (ACAP AC8 2014).

Here we provide a compilation of all available pathogen and health-related information in albatross and large petrel species listed under ACAP as a starting point to enable a thorough evaluation of the overall threat posed by disease. In order to expand the utility of this information, we also summarised meaningful context for data interpretation (e.g. location of studies, study type, potential reservoirs, vectors or modes of transmission). Finally, we discuss the significance of findings and when possible, suggest recommendations for filling current knowledge gaps.

Methods

Literature review

The species-level taxonomy and nomenclature used in our review is based on BirdLife checklist v. 8.0 (http://www.birdlife.org/datazone/info/taxonomy). We used Google Scholar and Pubmed databases to conduct an extensive search of peer-reviewed journal papers on any types of pathogen and/or clinical disease reported in albatross and large petrel species included in ACAP (henceforth ACAP species). We also included health assessments reporting exposure as evidenced by blood antibodies, as well as detection of pathogen DNA/RNA by molecular methods. In addition, we provide data from unpublished "grey" literature (including presentations at scientific conferences) reporting on any of the above when peer-reviewed data were not available. Finally, existing disease information in ACAP database (available at www.acap.aq) and in ACAP Population and Conservation Status Working Group meetings (http://acap.aq/en/working-groups/population-and-conservation-status-working-group) was likewise collated. Weblinks to these online documents are provided in the references section.

To provide meaningful context for data interpretation, we extracted information about geographical distribution of pathogen reports, tissues tested, tests performed and, when available,

whether studies were conducted on apparently healthy animals or on individuals with signs of disease. Author comments or hypothesis on potential reservoirs, vectors or modes of transmission for reported pathogens were also included.

Results

Publications and species covered

We identified a total 53 studies reporting on pathogen isolation, molecular identification (e.g. by PCR) or pathogen-specific antibody searches (including those which yielded negative results) in 18 of the 31 (58%) albatross and large petrel species listed under ACAP. Henceforth, all results and discussion refer to these 18 species (ACAP species subset). Summarised information includes references for 10 (56%) species considered as threatened (Critically Endangered, Endangered or Vulnerable) by IUCN. The remaining species in this review are categorised as 'Near Threatened' (four) or have a 'Least Concern' status (three) (BirdLife International 2015) (Tables 2–7).

Publications cover six genera, namely *Diomedea* (two species): *exulans, amsterdamensis; Macronectes* (two species): *giganteus, halli; Thalassarche* (five species): *melanophrys, chrysostoma, cauta, carteri, chlororhynchos; Phoebastria* (four species): *albatrus, immutabilis, irrorata, nigripes*; *Phoebetria* (two species): *fusca, palpebrata;* and *Procellaria* (three species): *aequinoctialis, cinerea, parkinsoni*.

The number of publications per species was highly variable. Black-browed Albatross *Thalassarche melanophrys* (Near Threatened) and Southern Giant Petrel *Macronectes giganteus* (Least Concern) with 15 and 17 papers, respectively, were the two species with a higher number of health or pathogen-related publications. In contrast, Amsterdam Albatross, Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos*, Black Petrel *Procellaria parkinsoni*, Grey Petrel *Procellaria cinerea*, Short-tailed Albatross *Phoebastria albatrus*, Sooty Albatross *Phoebetra fusca*, Indian Yellow-nosed Albatross *Thalassarche carteri*, Waved Albatross *Phoebastria irrorata*, Black-footed Albatross *Phoebastria nigripes* and Northern Giant Petrel *Macronectes halli* had three publications or less each, and with exception of the last two species, are all included in the IUCN Red List (BirdLife International 2015).

Type of study

Most research on pathogens or pathogen-specific antibodies in the ACAP species subset has resulted from disease/mortality investigations (15/53) and baseline studies (17/53) (28% and 32%, respectively). Three additional studies investigated the role of ACAP species as vectors or dispersers of pathogens of human origin (e.g. gastrointestinal bacteria), and five others were targeted pathogen searches (*Borrelia* sp., *Edwardsiella sp., Chlamydophila sp.*, Poxvirus avium and influenza A virus). On the other hand, the information on type of study was not inferable in 13 studies of the reviewed literature.

Temporal and spatial distribution of reports

The number of studies reporting on pathogens or health assessments in ACAP species has increased over time. Referenced publications go as far back as the 1940s (Johnston and Mawson 1942, Lent and Freitas 1948). Up to 1970 there were nine publications, 14 were added from 1981 to 2000, and 30 from 2001 to the present.

The location of studies surveying (including antibodies, isolation, recovery and molecular characterization of DNA or RNA) pathogens in the ACAP species subset is diverse, and covers circumpolar as well as tropical locations. In Table 1 we summarise the number of studies reporting on different pathogen taxa by site, classified as Antarctic (> 61°S), Subantarctic (48–61°S) and "other" locations (those not included in the two previous categories). Overall, there are fewer

Table 1. Number of studies in ACAP species reporting on specific pathogen findings by geographic region. Studies reporting indirect evidence of exposure (i.e. antibodies) between brackets. Note that some papers report on more than one pathogen group, therefore the total pathogen findings (65) differ from the total number of reports collated (53).

Pathogen type	Location		
	Antarctic*	Subantarctic**	Other***
Bacteria and fungi	5(0)	8(1)	6(2)
Virus	3(1)	2(1)	7(3)
Protozoa	2	0	0
Helminths	3	0	4
Ectoparasites	7	4	10
Total	20	14	27

*Antarctic region: extends from the South Pole to the Antarctic Convergence (higher than 61°S latitude).
**Subantarctic region: located immediately north of the Antarctic region and adjacent to the Antarctic Convergence (48-61°S latitude).
***Other: locations not included in the other two categories (i.e. lower latitudes, such as Hawaii and Galápagos islands).

studies in Subantarctic areas (Table 1). Distribution of reports is likely reflective of albatross and petrel reproductive site location (BirdLife International 2004), as this is where most sampling has occurred for all species.

Isolation of pathogens, direct detection (i.e. pathogen DNA or RNA) and indirect evidence of exposure (i.e. antibodies)

Detailed results separated by pathogen group (viruses, bacteria and fungi, protozoa, gastrointestinal parasites and ectoparasites) and host species are provided in tables 2–6. In addition, for viral, bacterial and fungal isolations and direct detection via PCR, we present data on type of sample tested and diagnostic tests performed in Table 7.

In summary, pathogens found in the subset of ACAP species (including isolation, recovery and molecular characterisation of DNA or RNA) included bacteria in seven species (39%), viruses in five (28%), protozoa in four (22%), helminths in nine (50%), ectoparasites in 13 (72%) and fungi in one species (5%). For some species (39%, 7/18), pathogen descriptions are limited to parasites. Namely, ectoparasites in Northern Giant Petrel, Grey Petrel and White-chinned Petrel *Procellaria aequinoctialis*; ectoparasites plus helminths in Light-mantled Albatross *Phoebetria palpebrata* and Atlantic Yellow-nosed Albatross; protozoa, ectoparasites and helminths in Wandering Albatross *Diomedea exulans;* and only helminths in Short-tailed Albatross.

Regarding bacterial and viral isolation, 17 different bacteria were reported in six species, most commonly *Pasteurella multocida* (six reports in four different species) (Weimerskirch 2004, 2016, Leotta *et al.* 2003, Demay *et al.* 2013, Jaeger *et al.* 2013, 2015) and *Salmonella* sp. (four strains in two different species) (Work *et al.* 1998, Palmgrem *et al.* 2000). Only two viruses were isolated from the ACAP species subset, namely pox viruses (six reports in five different species) (Sileo *et al.* 1990, Young and Vanden Werf 2008, Shearn-Boschler *et al.* 2008, Woods 2004, Bell *et al.* 2007, Munro 2007) and a newly discovered Phlebovirus (HIGV) in *Ixodes eudyptidis* ticks collected from Shy Albatrosses *Thalassarche cauta* from the Hunter Island Group in Tasmania (Wang *et al.* 2014).

Bacterial DNA for *P. multocida* and *E. rhusiopathiae* was found via Polymerase Chain Reaction (PCR) in cloacal and oropharyngeal swabs of apparently healthy Amsterdam Albatross chicks in 2011–2012 by Jaeger *et al.* (2013, 2015). Information on total number of chicks sampled, number of positives, age of chicks at sampling, and type of PCR performed are not included in the reports. An unclassified *Chlamydiaceae*-like bacteria was identified by real-time PCR from fresh Southern

Table 2. Summary of reports on viral pathogens (exposure antibodies, viral isolation and/or direct detection), including those yielding negative results, in albatrosses and large petrels in ACAP species subset. References in brackets. Location: SA: Subantarctic, A: Antarctic, Other (see Table 1 for definitions). NA: not available or not applicable.

Host species IUCN Red list (2015)[a]	Antibodies		Isolation or direct detection		Location	Study type	Potential reservoir/vector
	positive	negative	positive	negative			
Black-browed Albatross *Thalassarche melanophrys* (NT)	Adenovirus (46)	Avian Encephalomyelitis virus, Infectious Laryngotracheitis virus, Influenza A virus, Reovirus, Infectious Bursal Disease virus, Infectious Bronchitis virus, Avian Paramyxovirus types 1, 2, and 3, Marek's disease (46)	*Avipoxvirus* (34)		SA (34, 46)	Mortality event (34), baseline (46)	Phylogenetic proximity with an Avipoxvirus found in penguins in Argentina suggests a long-term circulation of seabird Avipoxviruses in the Southwest Atlantic; possibility of transmission between colonies by tourists/visitors, researchers, or dispersion by fomites (34), NA (46)
Laysan Albatross *Phoebastria immutabilis* (NT)			Avian pox virus (*Poxvirus avium*) (15, 37)		other (15, 37)	Effects of pox on fledging rates and post-fledging survival of chicks (15), NA (37)	Introduced mosquito, *Culex quinquefasciatus*, humans create conditions for mosquito breeding (15), NA (37)
Waved Albatross *Phoebastria irrorata* (CR)	Adenovirus, Avian Encephalomyelitis virus (16)	Influenza A virus, Avian Paramyxovirus types 1, 2, and 3, Marek's disease, Infectious Bursal Disease virus, Infectious Bronchitis virus Conn and Mass strains (16)			other (16)	Baseline (16)	NA (16)

Table 2. Continued.

Host species IUCN Red list (2015)[a]	Antibodies		Isolation or direct detection		Location	Study type	Potential reservoir/vector
	positive	negative	positive	negative			
Southern Giant Petrel *Macronectes giganteus* (LC)	Influenza A virus (18); Adenovirus (22)	Avian Encephalomyelitis virus, Infectious Laryngotracheitis virus, Influenza A virus, Reovirus, Infectious Bursal Disease virus, Infectious Bronchitis virus, Avian Paramyxovirus types 1, 2, and 3 (22)	Avian poxvirus (21); Influenza A virus RNA (31)		A (18, 21, 31), other (22)	NA (18), diseased chicks (21), baseline (22) targeted Influenza A surveillance (31)	Migratory birds though antibodies in chicks suggest locally acquired infection (18), chicks from parental feeding, ticks? (21), NA (22, 31).
Shy Albatross *Thalassarche cauta* (NT)	Avian Paramyxovirus type 1 (42)	Influenza A virus, Infectious Bursal Disease virus, Fowlpox virus (42)	Avian poxvirus (30), Hunter Island Group virus I, seq (HIGV, new tick-borne Phlebovirus) (42)	common Bunyaviruses (Orthobunyavirus, Phlebovirus, and Nairovirus) (42)	other (30, 42)	Disease investigation (chick mortality and low breeding success) (30), mortality event investigation (42)	NA (30), HIGV closely related to 2 newly discovered tickborne zoonotic phleboviruses (SFTSV and HRTV) causing severe disease and death in humans in Asia and N. America. Possible vectors (e.g., phlebotomine sandflies, mosquitoes, ticks) (42)
Black Petrel *Procellaria parkinsoni* (VU)			Avian poxvirus (32)		Other (32)	NA (32)	NA (32)

[a]IUCN Status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern. <www.iucnredlist.org>.

Table 3. Summary of reports on bacterial and fungal pathogens (exposure antibodies, isolation, direct detection), including those yielding negative results, in albatrosses and large petrels in ACAP species subset. References in brackets. Location: SA: Subantarctic, A: Antarctic, Other (see Table 1 for definitions). NA: not available or not applicable.

Host species IUCN Red list (2015)[a]	Antibodies		Isolation or direct detection		Location	Study type	Potential reservoir/ vector
	positive	negative	Positive	negative			
Black-footed Albatross *Phoebastria nigripes* (NT)				*Borrelia spp.* (6)	Other (6)	NA (6)	NA (6)
Black-browed Albatross *Thalassarche melanophrys* (NT)	*Chlamydophila psittaci* (46)	*Salmonella pullorum* (46)	*Salmonella newport* (7), *Borrelia garinii DNA* (11)	*Salmonella Havana*, *S. typhimurium*, *S. enteriditis* (7); Rickettsia-like microorganism ("Mayes agent") (41)	SA (7, 11, 41, 46)	Baseline (7, 41), targeted global distribution of Lyme disease (11), NA (41), baseline (46)	Human visitors, migrating sp., scavenger sp. (skuas) (7); *Borrelia* DNA in *Ixodes uriae* ticks, marine enzootic cycle (11); not found in BBA chicks but isolated from *I. uriae* ticks collected from penguins in nearby colonies (41), NA (46)
Grey-headed Albatross *Thalassarche chrysostoma* (LC)			*Aspergillus flavus-oryzae group*, *Proteus spp.* (43)	*Salmonella havana* (7) *S. typhimurium*, *S. enteriditis*, *S. newport* (7)	SA (7), other (43)	Baseline (7), moribund animals (43)	NA (7), Domestic poultry? (43)
Laysan Albatross *Phoebastria immutabilis* (NT)			*Salmonella ohio*, *S. oranienburg*, *S. san-diego* (14); *Nocardia asteriodes* (37)		other (14, 37)	Chick mortality (14), extensive and regular epizootic mortality of chicks (37)	Necrotizing enteritis possibly sequela of dehydration. Lesions compatible with salmonellosis but isolation in only 4/10 birds makes diagnosis suspect (14), NA (37)

Table 3. Continued.

Host species IUCN Red list (2015)[a]	Antibodies		Isolation or direct detection		Location	Study type	Potential reservoir/ vector
	positive	negative	Positive	negative			
Waved Albatross *Phoebastria irrorata* (CR)		avian cholera (16)*		*Chlamydophila psittaci* (16)	other (16)	Baseline (16)	NA (16)
Southern Giant Petrel Macronectes giganteus (LC)	*Salmonella pullorum* (22); *Psittacosis-Lymphogranuloma group* (27)**	*Aspergillus spp., Chlamydophila spp.* (22); *Mycoplasma gallisepticum, Mycoplasma synoviae, Salmonella gallinarum, S. pullorum* (25)	*Pasteurella multocida subsp. gallicida* (17), *Escherichia coli* (17, 20), *Enterococcus faecalis, Bacillus subtilis, Brevibacterium brunneum, Alcaligenes faecalis* I, *Plesiomonas sp* (20); *Clostridium perfringens* (21); *Edwardsiella tarda* (26); *Chlamydiacea-like bacteria DNA* (50)	*Chlamydophila psittaci, Mycoplasma spp* (17); *Campylobacter lari, Campylobacter jejuni, Salmonella spp., Yersinia spp.* (28)	A (17, 20, 21, 25, 26, 28, 50), other (22, 27)	During surveillance, mortality one adult (17), role as reservoirs or vectors (20,25), disease investigation (chicks, with multiple proliferative nodules on bills and skin) (21), baseline (22, 26, 27), role of tourism in introduction of pathogens (28), targeted *Chlamydophila* surveillance (50)	During migration, eating diseased animals (penguins, gulls, skuas) (17, 20, 22), feeding on waste from scientific stations (20, 25), clostridia overgrowth in gut triggered by pox infections (21), spread by scavenger birds such as gulls (22), trophic chain link of transmission (26), NA (27, 28, 50)
Indian Yellow-nosed Albatross *Thalassarche carteri**** (EN)			*Pasteurella multocida* (12, 44, 52, 53); *Erysipelothrix rhusiopathiae* (12, 44, 52, 53)		SA (12, 44, 52, 53)	Population and breeding success declines: chick and adult mortality	Scavenging skuas on Amsterdam Island could disperse pathogens between colonies (12, 44, 52). *Erysipelas* maybe introduced through pigs or naturally, present in fish

Table 3. Continued.

Host species IUCN Red list (2015)[a]	Antibodies		Isolation or direct detection		Location	Study type	Potential reservoir/ vector
	positive	negative	Positive	negative			
Amsterdam Albatross *Diomedea amsterdamensis* (CR)			*Pasteurella multocida DNA* (44, 51, 53); *Erysipelothrix rhusiopathiae DNA* (44, 53)		SA (44, 51, 53)	Mortality and low reproductive success investigation	Colony located near *T. carteri* infected colonies: skuas potential vectors (44, 51).
Sooty Albatross *Phoebetria fusca* (EN)			*Pasteurella multocida* (44, 53)		SA (44, 53)	Very low breeding success due to high mortality of chicks, similar to *T. carteri and D. amsterdamensis*	Skuas as potential vectors between infected *T. carteri* and *P. fusca* colonies (44)

*Padilla *et al*. (2003): Samples were tested for antibodies to avian cholera by microagglutination at the Diagnostic Laboratory of the University of Missouri–Columbia, College of Veterinary Medicine, Columbia, Missouri 65211, USA.

**Chlamydial bacteria underwent several taxonomic miss-classifications in the past. It is likely that the authors refer to the bacteria *Chlamydophila psittaci* a common avian pathogen, or another pathogen within the *Chlamydophila* genera (Nunes and Gomes 2014).

***Weimerskirch (2004, ref n°12) monitored 200 pairs of Yellow-nosed Albatrosses (*Diomedea chlororhynchos*) annually since 1979 at Pointe d'Entrecasteaux, on the western coast of Amsterdam Island (37°S, 70°E). *Diomedea chlororhynchos* (Sibley and Monroe 1990, 1993) has been divided into *chlororhynchos* and *carteri* and both placed in the genus *Thalassarche* (Brooke 2004). *T. chlororhynchos* or Atlantic Yellow-nosed Albatross breeds on Atlantic Ocean islands (Tristan da Cunha and Gough Island). *T. carteri* or Indian Yellow-nosed Albatross is the species that breeds in Indian Ocean (Amsterdam Island). Therefore we refer to the individuals included in reference No 12 (Weimerskirch 2004) as Indian Yellow-nosed Albatross (*Thalassarche carteri*).

[a]IUCN Status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern. <www.iucnredlist.org>.

Table 4. Summary of reports on Protozoa in albatrosses and large petrels in ACAP species subset. References in brackets. Location: SA: Subantarctic, A: Antarctic, Other (see Table 1 for definitions). NA: not available.

Host species IUCN Red list (2015)[a]	Pathogen	Location	Study type	Potential reservoir/vector
Wandering Albatross *Diomedea exulans* (VU)	*Hepatozoon albatrossi* (1)	A	NA	Vector may be *Ixodes uriae* or one of several species of mites commonly found in association with the host
Black-browed Albatross *Thalassarche melanophrys* (NT)	*Hepatozoon albatrossi* (1)	A	NA	Vector may be *Ixodes uriae* or one of several species of mites commonly found in association with the host
Grey-headed Albatross *Thalassarche chrysostoma* (LC)	*Hepatozoon albatrossi* (1)	A	NA	Vector may be *Ixodes uriae* or one of several species of mites commonly found in association with the host
Southern Giant Petrel *Macronectes giganteus* (LC)	*Sarcocystis sp.* (19)*	A	NA	NA*

*Ippen R. and Henne D. (1989). Information on source of pathogen (muscle, blood, other tissue) not available.

[a]IUCN Status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern. <www.iucnredlist.org>.

Giant Petrel faeces (1/6) in the Antarctic Peninsula (Isaksson *et al.* 2015). *I. uriae* ticks (3/41) from Black-browed Albatross breeding in Campbell Island, New Zealand, were positive for the vector-borne bacteria *Borrelia garinii* DNA by PCR (Olsen *et al.* 1995). Recently (2010/11 austral summer), Influenza A virus RNA was detected by Reverse Transcription PCR (RT-PCR) in swabs from one (1/299) male Southern Giant Petrel of undescribed age from Elephant Island, Antarctica (de Souza Petersen *et al.* 2015). It is unknown whether the isolate was from a cloacal or oral swab. No further characterisation (i.e. serotype) of the virus is provided by the authors.

According to indirect evidence of exposure, virus and bacteria-specific antibodies were reported in four (22.2%, Table 2) and two (11.1%, Table 3) of the ACAP species subset (n = 18), respectively. Southern Giant Petrel was the species with the highest exposure to infectious agents inferred by antibodies against four pathogens (Avian Adenovirus, Avian Influenza, *Salmonella spp.*, *Chlamydophila spp.*) (Munday 1972, Uhart *et al.* 2003), followed by Waved Albatross with antibodies to two viruses (Avian Encephalomyelitis virus and Avian Adenovirus) (Padilla *et al.* 2003).

Spatial distribution of pathogen isolates

Poxviruses were isolated in all but two cases from locations in the "other" category, mostly in the North Pacific (Sileo *et al.* 1990, Woods 2004, Bell *et al.* 2007, Young and Vanden Werf 2008). The remaining poxvirus isolates were recovered from a Southern Giant Petrel in Antarctica (Shearn-Boschler *et al.* 2008) and a Black-browed Albatross in a Subantarctic location (Malvinas/Falkland Islands; Munro 2007). A Phlebovirus (HIGV) was isolated from Shy Albatross ticks collected in Tasmania (Wang *et al.* 2014) and Influenza A virus RNA was found in a Southern Giant Petrel from Antarctica by PCR (de Souza Petersen *et al.* 2015) (Tables 1 and 2). Bacteria were recovered in all geographical sites in similar numbers (Tables 1 and 3). In addition, a single fungal isolate was recovered in an "other" type location, from Grey-headed Albatross *Thalassarche chrysostoma* (Tham *et al.* 1974). Helminths were mostly reported in "other" type locations (Tables 1 and 5), while ectoparasites were found in decreasing order in "other", Antarctic and Subantarctic sites (Tables 1 and 6).

Table 5. Summary of reports on helminths in albatrosses and large petrels in ACAP species subset. References in brackets. Location: SA: Subantarctic, A: Antarctic, Other (see Table 1 for definitions). NA: not available. Dx: diagnosis.

Host species IUCN Red list (2015)[a]	**Pathogen**	**Location**	**Study type**	**Potential reservoir/vector**
Black-browed albatross *Thalassarche melanophrys* (NT)	*Stomachus sp.* (8); *Anisakis sp., Seuratia shipleyi, Paryseria diomedeae, Anisakis diomedeae, Contracaecum pelagicum* (48); *Kathleena scotti* (49)	SA (8), Other (48), A (49)	NA	NA
Light-mantled Albatross *Phoebetria palpebrata* (NT)	*Seuratia shipleyi, Paranisakiopsis sp.* (8)	SA	NA	NA
Southern Giant Petrel *Macronectes giganteus* (LC)	*Capillaria convoluta* (8); *Stegophorus macronectes, Stegophorus arctowski* (23); *Stegophorus sp.* (21); *Anisakis sp., Seuratia shipleyi, Paryseria macronectes, Anisakis diomedeae, Phocascaris sp.* (48)	SA (8), A (21, 23), Other (48)	NA (8, 48), Baseline (23), Diseased chicks, with multiple proliferative nodules on their bills and skin (Dx poxvirus) (21)	NA (8, 23, 48), No pathological changes associated with these nematodes, and no other internal or external parasites found (21)
Wandering albatross *Diomedea exulans* (VU)	*Seuratia shipleyi, Paryseria diomedeae, Anisakis diomedeae* (48)	Other	NA	NA
Grey-headed Albatross *Thalassarche chrysostoma* (LC)	*Paryseria macronectes, Paryseria diomedeae, Anisakis diomedeae, Anisakis sp.* (48)	Other	NA	NA
Short-tailed Albatross *Phoebastria albatrus* (VU)	*Tetrabothrius sp., Stegophoms stellaepolaris* (45)	Other	NA	NA
Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos* (EN)	*Tetraeres diomedeae, Anisakis diomedeae, Contracaecum pelagicum* (48)	Other	NA	NA
Waved Albatross *Phoebastria irrorata* (CR)	*Contracaecum, Tetrabothrius, Cardiocephaloide* (47)	Other	baseline	fish, squid, and crustaceans serve as intermediate hosts for parasites from all three of these genera
Shy albatross *Thalassarche cauta* (NT)	*Anisakis diomedeae Contracaecum magnicollare* (48)	Other	NA	NA

[a]IUCN Status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern. <www.iucnredlist.org>.

Table 6. Summary of reports on ectoparasites in albatrosses and large petrels in ACAP species subset. References in brackets. Location: SA: Subantarctic, A: Antarctic, Other (see Table 1 for definitions). NA: not available.

Host species IUCN Red list (2015)[a]	Pathogen	Parasite type	Location	Study type	Potential reservoir/vector
Wandering Albatross *Diomedea exulans* (VU)	*Ixodes uriae* (13); *Naubates pterodromi, Austromenopon sp.* (3); *Pseudonirmus gurlti, Trabeculus hexacon* (4); *Austromenopon affine, Perineus concinnoides, Episbates pederiformis* (5); *Docophoroides brevis* (3, 4, 5); *Harrisoniella hopkinsi, Paraclisis hyaline* (3, 5); *Naubates fuliginosus* (4, 5); *Ixodes kerguelenensis* (39)	tick (13, 39), louse (3, 4, 5)	A (4, 13), SA (3, 5, 39)	Baseline (3, 4, 5, 13), targeted prevalence of *B. burgdorferi* in penguins (39)	NA (4, 5, 13), Close encounters between individuals of different host species are opportunities for lice to straggle. Also contamination by researchers from one colony to another (3), *Pelecanoides georgicus, D.exulans* and *P. aequinoctialis* are hosts for *I. kerguelenensis*, suggested as possible vector of *Borrelia burgdorferi* (39)
Black-footed Albatross *Phoebastria nigripes* (NT)	*Carios (Ornithodoros) capensis* (6)	tick	Other	NA	NA
Black-browed Albatross *Thalassarche melanophrys* (NT)	*Ixodes uriae* (9, 10, 11, 35); *Paraclisis diomedeae, Perineus circumfasciatus* (3, 5); *Docophoroides brevis* (4); *Austromenopon affine, Harrisoniella ferox, Docophoroides brevis* (5); *Parapsyllus longicornis* (35)	tick (9, 10, 11, 35), louse (3, 4, 5), flea (35)	A (4, 9, 10), SA (3, 5, 11), other (35, 11)	NA (9, 35), chick mortality (10), targeted global distribution of Lyme disease (11), baseline (3, 4, 5)	Close encounters between individuals of different host species are opportunities for lice to straggle. Also contamination by researchers between colonies (3); on species that nested in large and dense colonies, carried by bird's feet (9, 10). *I uriae* reservoir of *Borrelia garini*, marine enzootic cycle (11), NA (4, 5, 35).
Grey-headed Albatross *Thalassarche chrysostoma* (LC)	*Ixodes uriae* (9, 13); *Docophoroides simplex* (3); *Paraclisis diomedeae* (3, 5); *Austromenopon affine, Perineus circumfasciatus* (5)	louse (3, 5), tick (9, 13)	A (9, 13), SA (3, 5)	NA (9), baseline (3, 5, 13)	Close encounters between individuals of different host species are opportunities for lice to straggle. Contamination by researchers between colonies (3), NA (5), *I. uriae* only on species that nested in large, dense, persistent colonies, carried by bird's feet (9, 13)

Table 6. Continued.

Host species IUCN Red list (2015)[a]	Pathogen	Parasite type	Location	Study type	Potential reservoir/vector
Atlantic Yellow-nosed Albatross *Thalassarche chlororhynchos* (EN)	*Docophoroides brevis, Naubates fuliginosus* (4); *Ixodes diomedeae* I (35)	louse (4), tick (35)	A (4), Other (35)	Baseline (4), NA (35)	NA
Light-mantled Albatross *Phoebetria palpebrata* (NT)	*Paraclisis diomedeae, Perineus circumfasciatus* (3, 5); *Naubates fuliginosus* (4); *Ixodes uriae* (9, 13)	louse (3, 4, 5), tick (9, 13)	A (4, 9, 13), SA (3, 5)	NA (9), baseline (4, 3, 5, 13)	Close encounters between individuals of different host species are opportunities for lice to straggle. Contamination by researchers between colonies (3), *I. uriae* only on species that nested in large, dense, persistent colonies, carried by bird's feet (13), NA (4)
Laysan Albatross *Phoebastria immutabilis* (NT)	*Womersia midwayensis* (37, 8); *Myialges nudus* (38)	mite	Other	NA (8), chick mortality (37), mange caused by ectoparasite in dead chicks (38)	NA (8, 37), could have been introduced on hippoboscid flies, on canaries or common mynahs as pets (38).
Waved Albatross *Phoebastria irrorata* (CR)	*Aedes taeniorhynchus* (36)	mosquito	Other	desertion of eggs, apparently in response to ectoparasites	NA
Southern Giant Petrel *Macronectes giganteus* (LC)	*Perineus macronecti* (3); *Naubates fuliginosus* (4); *Austromenopon ossifragae, Perineus circumfasciatus* (5); *Docophoroides murphyi, Paraclisis obscura* (3, 5); *Ixodes uriae* (Neg) (21); *Glaciopsyllus antarcticus (Neg)* (24)	louse (3, 4, 5), tick (21), flea (24)	A (4, 21, 24), SA (3, 5)	Baseline (3, 4, 5, 24), diseased chicks (21)	Close encounters between individuals of different host species are opportunities for lice to straggle. Also contamination by researchers from one colony to another (3); no mites or ticks were found on the dead chick. The tick *Ixodes uriae* is ubiquitous in the area and commonly infests Adélie penguins (*Pygoscelis adéliae*), a seasonally important prey of Southern Giant Petrel (21), NA (4, 5, 24)

Table 6. Continued.

Host species IUCN Red list (2015)[a]	Pathogen	Parasite type	Location	Study type	Potential reservoir/vector
Northern Giant Petrel *Macronectes halli* (LC)	*Docophoroides murphyi, Paraclisis obscura, Perineus macronecti* (3)	louse	SA	Baseline	Close encounters between individuals of different host species are opportunities for lice to straggle. Also contamination by researchers from one colony to another (3)
White-chinned Petrel *Procellaria aequinoctialis* (VU)	*Docophoroides brevis, Pseudonirmus gurlti* (4); *Naubates fuliginosus, Trabeculus hexacon* (4, 5); *Ixodes kerguelensis I* (13, 39); *Zachvakinia robusta* (29)	louse (4, 5), tick (13, 39), mite (29)	A (4, 13, 29) SA (5, 39)	Baseline (4, 5, 13), NA (29), targeted prevalence of *B. burgdorferi* in penguins (39)	NA (4, 5, 29); *Pelecanoides georgicus, D.exulans* and *P.aequinoctialis* are hosts for *I. kerguelenensis,* suggested as possible vector for *Borrelia burgdorferi* (39)
Grey petrel *Procellaria cinerea* (EN)	*Zachvatkinia puffini* (2); *Naubates fuliginosus, Trabeculus hexacon, Halipeurus procellariae, Halipeurus diversus* (3)	mite (2), louse (3)	Other (2), SA (3)	Baseline	NA (2); close encounters between individuals of different host species are opportunities for lice to straggle. Also contamination by researchers from one colony to another (3)
Shy albatross *Thalassarche cauta* (NT)	*Docophoroides brevis* (4); *Ixodes spp.* (33); *Ixodes eudyptidis* (42)	louse (4), tick (33, 42)	A (4), Other (33, 42)	Baseline (4), mortality event discovered in a baseline study (33), mortality event (42)	NA (4); Shy albatross chicks are hosts for *Ixodes,* suggested as vector of avian poxvirus (33); vector of newly discovered tick-borne and potentially zoonotic phlebovirus HIGV (42)

[a]IUCN Status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern. <www.iucnredlist.org>.

Table 7. Details on type of sample tested and diagnostic method used for direct detection or identification of bacterial, viral and fungal isolates in albatrosses and large petrels in ACAP species subset. References in brackets.

Species IUCN Red list (2015)[a]	Pathogen	Diagnostic method	Type of sample
Black-browed Albatross *Thalassarche melanophrys* (NT)	*Salmonella newport* (7) *Borrelia garinii DNA* (11) *Avipoxvirus** (34)	Culture + isolates and serotyping (pulsed-field gel electrophoresis) (7); Culture spirochetes from ticks + PCR and sequencing (11); Macroscopic lesions + histology + PCR (DNA) and sequencing (34)	Fecal swabs from live birds (7), *Ixodes uriae* ticks (11), tissue samples from dead birds inferred (34)
Laysan Albatross *Phoebastria immutabilis* (NT)	*Salmonella ohio* (14) *Salmonella oranienburg* (14) *Salmonella san-diego* (14) Avian poxvirus (15, 37) *Nocardia asteriodes* (37)	Histopathology + culture and strain identification (14); Fibrolast culture + PCR (DNA from culture) and sequencing (15); Culture + identification + histopathology (skin lesions consistent with avian pox (37)	Intestines from carcasses (14); Epithelial tissue from skin lesions in live chicks (15); Nodules on foot webs or phalanges from dead chicks (avian pox), air sacs from dead chicks (*Nocardia asteroids*) (37)
Southern Giant Petrel *Macronectes giganteus* (LC)	Avian poxvirus (21) *Pasteurella multocida subsp. Gallicida* (17) *Escherichia coli* (17, 20) *Enterococcus faecalis* (20) *Bacillus subtilis* (20) *Brevibacterium brunneum* (20) *Alcaligenes faecalis* (20) *Plesiomonas sp* (20) *Clostridium perfringens* (21) *Edwardsiella tarda* (26) Influenza A virus RNA *Chlamydiaceae*-like bacteria DNA(50)	Culture (tissue homogenates) + electron microscopy + PCR, sequencing, and compared to fowlpox and canarypox (21); Culture + morphologic characteristics and biochemical tests (17, 20, 26); *E. coli* virulence markers by PCR (17, 20); Capsular serotype of *P. multocida* strain by multiplex PCR assay (17); Histopathology (17, 21); Culture for *Cl. perfringens* and alpha toxin by PCR (21); Reverse Transcription PCR (31); Real-time PCR targeting the 23S rRNA gene and designed to detect *Chlamydiaceae* species (50)	Tissues collected at necropsy. *E. coli* from pericardial sac and air sacs, *P. multocida* from heart, liver, lung, air sacs, pericardial sac (17); Samples of multiple cutaneous nodules from dead chicks (21); Cloacal swabs from live birds (20, 26); Ileon (21); Swabs (unknown if cloacal or oropharyngeal) (31); Fresh feces (50)
Shy albatross *Thalassarche cauta* (NT)	Avian poxvirus (30, 33) Hunter Island Group virus I, seq (HIGV, new tick-borne *Phlebovirus*) (42)	NA (30, 33); Culture (pooled tick homogenates) + random PCR amplification (RNA from cultures) + next-generation sequencing (42)	NA (30, 33); Ticks (*Ixodes eudyptidis*) from healthy and affected birds (42)
Black Petrel *Procellaria parkinsoni* (VU)	Avian poxvirus (32)	NA	NA
Grey-headed Albatross *Thalassarche chrysostoma* (LC)	*Aspergillus flavus-oryzae group* (43) *Proteus spp.* (43)	Microscope examination of kidney smears + culture + histopathology	*A. flavus* in kidney, *Proteus spp.* in kidneys, liver and spleen

Table 7. Continued.

Species IUCN Red list (2015)[a]	Pathogen	Diagnostic method	Type of sample
Indian Yellow-nosed Albatross *Thalassarche carteri*** (EN)	*Pasteurella multocida* Pm (12, 44, 52, 53) *Erysipelothrix rhusiopathiae* Er (12, 44, 52, 53)	Bacteriology and histopathology, for Pm and Er, and serotyping Er (12, 53); Bacterial culture and isolation for Pm (44, 53)	Undescribed tissues from chick and adult frozen carcasses isolation Pm (12); undescribed tissues from chick carcasses isolation Er (12), Pm (44, 52); NA (53)
Sooty Albatross *Phoebetria fusca* (EN)	*Pasteurella multocida* (44, 53)	Bacterial culture and isolation for Pm (44, 53)	Cloacal and oro-pharyngeal swabs from chicks in apparent good health + undescribed tissues from chick carcasses culture and isolation Pm (44), NA (53)
Amsterdam Albatross *Diomedea amsterdamensis* (CR)	*Pasteurella multocida* (44, 51, 53) *Erysipelothrix rhusiopathiae* (44, 53)	PCR for Pm and Er (44, 53), NA (51)	Cloacal and oro-pharyngeal swabs from chicks in apparent good health (44, 53), NA (51)

[a]IUCN Status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened, LC = Least Concern. <www.iucnredlist.org>.
NA: not available.
*Munro (2007) report on outbreak of avian poxvirus in Gentoo Penguins, but include unpublished data from BBA pox isolate from Malvinas/Falkland Islands.
**Weimerskirch (2004, ref n°12) monitored 200 pairs of Yellow-nosed Albatrosses (*Diomedea chlororhynchos*) annually since 1979 at Pointe d'Entrecasteaux, on the western coast of Amsterdam Island (37° S, 70° E). *Diomedea chlororhynchos* (Sibley and Monroe 1990, 1993) has been divided into *chlororhynchos* and *carteri* and both placed in the genus *Thalassarche* (Brooke, 2004). *T. chlororhynchos* or Atlantic Yellow-nosed Albatross breeds on Atlantic Ocean islands (Tristan da Cunha and Gough Island). *T. carteri* or Indian Yellow-nosed Albatross is the species that breeds in Indian Ocean (Amsterdam Islands). Therefore we refer to the individuals included in reference n° 12 (Weimerskirch 2004) as Indian Yellow-nosed Albatross (*Thalassarche carteri*).

References: (1) Peirce and Prince (1980), (2) Mironov and Stefan (2013), (3) Palma and Horning (2002), (4) Zlotorzycka and Modrzejewska (1992), (5) Clay and Moreby (1970), (6) Tsurumi *et al.* (2002), (7) Palmgrem *et al.* (2000), (8) Goff *et al.*(1989), (9) Bergstrom *et al.* (1999b), (10) Bergstrom *et al.* (1999a), (11) Olsen *et al.* (1995), (12) Weimerskirch (2004), (13) Wilson (1970), (14) Work *et al.* (1998), (15) Young and Vanden Werf (2008), (16) Padilla *et al.* (2003), (17) Leotta *et al.* (2003), (18) Baumeister *et al.* (2004), (19) Ippen and Henne (1989), (20) Jorge *et al.* (2002), (21) Shearn-Boschler *et al.* (2008), (22) Uhart *et al.* (2003), (23) Zdzitowiecki and Drozdz (1980), (24) Whitehead *et al.* (1991), (25) Leotta *et al.* (2001), (26) Leotta *et al.* (2009), (27) Munday (1972), (28) Bonnedahl *et al.* (2005), (29) Mironov (1991), (30) Woods (2004), (31) de Souza Petersen *et al.* (2015), (32) Bell *et al.* (2007), (33) Johnstone *et al.* (1975), (34) Munro (2007), (35) Murray *et al.* (2003), (36) Anderson and Fortner (1988), (37) Sileo *et al.* (1990), (38) Gilardi *et al.* (2001), (39) Gauthier-Clerc *et al.* (1999), (40) Woods *et al.* (2009), (41) Chastel *et al.* (1993), (42) Wang *et al.* (2014), (43) Tham *et al.* (1974), (44) Jaeger *et al.* (2013), (45) Iwaki *et al.* (2006), (46) Uhart *et al.* (2004), (47) Jiménez-Uzcátegui *et al.* (2015), (48) Johnston and Mawson (1942), (49) Lent and Freitas (1948), (50) Isaksson *et al.* 2015, (51) Demay *et al.* (2013), (52) Weimerskirch (2016), (53) Jaeger *et al.* (2015).

Discussion

Albatrosses and large petrels are among the world's most endangered birds, with their status dramatically deteriorating in recent years (Brooke 2004, Cooper *et al.* 2006, Croxall *et al.* 2012, Cherel *et al.* 2013, Paleczny *et al.* 2015). While disease has been identified as a substantial risk in some of the most vulnerable species (e.g. Amsterdam Albatross) (Phillips *et al.* 2016), information on pathogens and, more importantly associated morbidity and mortality, is limited. This review of pathogen and health-related information in albatross and large petrel species listed under ACAP will enable a thorough evaluation of the overall threat posed by disease, identifying critical gaps and facilitating targeted conservation actions.

Species coverage

Available reports comprise nearly 60% of the species listed in ACAP (18/31), with no information on the remaining 40%. A notable asymmetry exists in species focus, with the Black-browed Albatross (Near Threatened) and the Southern Giant Petrel (Least Concern), concentrating most health or pathogen-related publications. Furthermore, the Southern Giant Petrel is the species from which the highest number of pathogens has been recovered. However, most are gastrointestinal bacteria isolated from healthy adults during targeted surveys, and considered clinically insignificant (Jorge *et al.* 2002, Leotta *et al.* 2009). The only allegedly meaningful pathogens isolated from these two species are *Pasteurella multocida* in Southern Giant Petrel (Leotta *et al.* 2003) and avian poxvirus in both species (Munro 2007, Shearn-Boschler *et al.* 2008). Interestingly, both Southern Giant Petrel isolates are from Antarctica.

On the contrary, there are three or less publications per species for most (7/10) albatross and petrel species in critical conservation status. Yet in this case, some reports are highly relevant as they refer to the pathogenic bacteria *P. multocida* and *E. rhusiopathiae* in Amsterdam Island species (Sooty, Indian Yellow-nosed and Amsterdam Albatross) (Weimerskirch 2004, 2016, Demay *et al.* 2013, Jaeger *et al.* 2013, 2015); and avian poxvirus in Black Petrels breeding in New Zealand (Bell *et al.* 2007). Notwithstanding the vulnerable condition of these species, however, existing descriptions exclude relevant information to assess the extent to which these pathogens may be impacting their populations, such as number of animals dying from infection annually, numbers of survivors, sex and age categories affected, etc.

In the remaining threatened species within the ACAP subset, reports are limited to findings of parasites, namely protozoa, helminths and ectoparasites (with the exception of a serosurvey in Waved Albatross, see below). Included are reports of the tick *Ixodes kerguelenensis* in Wandering Albatross (Critically Endangered), and White-chinned Petrels (Vulnerable) (Gauthier-Clerc *et al.* 1999).

Finally, indirect evidence of pathogen exposure via bacteria and virus-specific antibodies is rarely reported in ACAP species (five studies in four species; Munday 1972, Uhart *et al.* 2003, 2004, Padilla *et al.* 2003, Wang *et al.* 2014). Only one of these studies was conducted in a Critically Endangered species (Waved Albatross; Padilla *et al.* 2003).

Pathogen isolation

Viruses

Avian pox is a relatively slow-developing disease, characterized by wart-like lesions on featherless areas of the body (i.e. feet, head). Infections are usually mild and rarely result in death, except when they affect the eyelids, mouth and upper respiratory tract (van Riper and Forrester 2007). All avian poxvirus reports in ACAP species subset relate to findings in clinically ill or dead animals, mostly chicks or fledglings, and were often associated with mortality or low fledging success. In some cases, the immediate cause of death was not poxvirus, but a secondary bacterial infection (i.e. *Clostridium perfringens*; Shearn-Boschler *et al.* 2008). Poxvirus outbreaks seem to be recurrent in some locations

and species (i.e. Laysan Albatross *Phoebastria immutabilis* on the Hawaiian Islands, and Shy Albatross on Albatross Island, Indian Ocean). In many cases, morbidity seems to have exceeded mortality, at least while chicks were under parental care (Sileo *et al.* 1990, Woods 2004, Young and Vanden Werf 2008). Adults appear, for the most part, to be immune or capable of overcoming infection. Recovery has been reported in sick chicks (Young and Vanden Werf 2008) and adults (Shearn-Boschler *et al.* 2008, Young and Vanden Werf 2008), and was found to be highly dependent on health status and exposure to additional stressors such as environmental conditions and parasitism (Woods 2004). Most reported cases refer exclusively to cutaneous pox (Sileo *et al.* 1990, Bell *et al.* 2007, Young and Vanden Werf 2008). The more severe form of the disease, diphtheritic pox, was only described in a Southern Giant Petrel chick that died during an outbreak in Antarctica (Shearn-Boschler *et al.* 2008). All these characteristics agree with what is observed in many avian species infected with pox viruses (van Riper and Forrester 2007, Kane *et al.* 2012), yet differs from some island birds for which avian pox has been a major driver of extinction (i.e. Hawaiian forest birds; van Riper *et al.* 2002). Notwithstanding, because the virus is transmitted mechanically by arthropod vectors or by contact with pox-infected particles, it is highly contagious (Woods 2004). This implies that outbreaks often occur in clusters within colonies, but also that it can be spread to remote locations through bird travels and migration, human visitors, and as importantly, reintroduction programmes (Gyuranecz *et al.* 2013). Therefore, strict biosecurity is recommended during outbreaks, and poxvirus-specific screening should be included in translocation and reintroductions risk assessments (Jacobs *et al.* 2014). Dispersal of poxvirus with translocated albatrosses to remote islands could threaten not only the reintroduced flock, but any native bird species there (van Riper and Forrester 2007). Furthermore, avian pox outbreaks often coincide with weather-induced increases in vector populations (van Riper *et al.* 2002, Young and Vander Werf 2008). Thus, monitoring the behaviour of this disease over time, particularly in areas subject to influences from global climate change, is recommended (Kovats *et al.* 2001).

The only other virus isolated from ACAP species subset is a novel tick-borne phlebovirus, named Hunter Island Group Virus (HIGV; Wang *et al.* 2014). It was identified recently by next-generation sequencing from samples collected during the investigation of a disease outbreak of Shy Albatrosses in Tasmania. The HIGV is closely related to two newly discovered tick-borne zoonotic phleboviruses (SFTSV and HRTV) that were responsible for severe disease and death in humans in four countries in Asia and North America (Wang *et al.* 2014). However, and as reported by the authors of the study, this is probably an incidental finding and not particularly related to the disease event in the Shy Albatrosses.

Bacteria

Due to their capacity to produce acute systemic disease followed by death, the most significant isolates from the ACAP species subset are *Pasteurella multocida* and *Erysipelothrix rhusiopathiae*. *P. multocida* is a contagious avian pathogen that is known to infect over 190 species of birds and causes major and recurrent epizootics of avian cholera in waterfowl in North America (Samuel *et al.* 2007). Transmission occurs from contact between birds and by ingestion or inhalation of bacteria within a contaminated environment. Diseased birds and rotting carcasses are important sources of contamination and the bacteria can be carried between infected sites by migrating or carrion scavenging birds (Botzler 1991, Friend 1999, Samuel *et al.* 2005, Wille *et al.* 2016). Therefore, removing carcasses is the recommended method for reducing environmental loads and controlling avian cholera outbreaks (Friend 1999, Samuel *et al.* 2005, Blanchong *et al.* 2006). On the other hand, *E. rhusiopathiae* typically appears to be a secondary pathogen affecting individuals, not populations (Wolcott 2007). When it is the primary pathogen, death occurs acutely from a septic process with few pre and post-mortem signs (Wolcott 2007). Therefore, it is probably under-detected and under-reported in wild birds. Potential sources or vectors of erysipelas are unclear but may include fish, marine mammals, human handlers and ectoparasites (Wolcott 2007).

At least two mortality events from *P. multocida* infections have affected several seabird species in Antarctica (Leotta *et al.* 2006) in addition to an isolated case in an adult Southern Giant Petrel

(Leotta *et al.* 2003). *P. multocida* and *E. rhusiopathiae* have been reported (including isolation and/or molecular detection) in three threatened albatross species breeding on Amsterdam Island, namely the Indian Yellow-nosed, Sooty and Amsterdam Albatross (Weimerskirch 2004, 2016, Demay *et al.* 2013, Jaeger *et al.* 2013, 2015). Mortality attributed to disease in Indian Yellow-nosed Albatross extends to the 1980s, and in Sooty and Amsterdam Albatross to the 2000s (Weimerskirch 2004, Demay *et al.* 2013). However, the first bacterial isolates from dead Indian Yellow-nosed Albatrosses were not obtained until 1996 (chicks - *E. rhusiopathiae*) and 1999 (adults and chicks - *P. multocida*) (Weimerskirch 2004). No co-infections were reported. More recently (in 2012–2013), *P. multocida* has been isolated from Indian Yellow-nosed and Sooty Albatross chick carcasses (Demay 2013, Jaeger *et al.* 2013, 2015, Weimerskirch 2016). Notably, Amsterdam Albatross chicks in apparent good health were PCR positive for *P. multocida* and *E. rhusiopathiae* in 2011–2012 (Demay *et al.* 2013, Jaeger *et al.* 2013, 2015). Notwithstanding, without information on the age of the positive chicks, and given recent studies demonstrating extended duration of maternal antibodies in a procellariform (Garnier *et al.* 2011), it is impossible to discern whether this implies survival due to resistance or to passive immunity. Some albatrosses might be resistant to, or able to overcome the disease, as has been seen in other species such as swans and Common Eiders *Somateria mollissima* (Samuel *et al.* 2005, Descamps *et al.* 2012). Or it may well be that, as was described in Cory's Shearwater *Calonectes diomedea*, the presence of maternal antibodies over the first 3-4 weeks of life enable chick survival (Garnier *et al.* 2011). In either case however, these asymptomatically infected birds could then serve as healthy carriers or reservoirs (long-term sources) for the bacteria and initiate new outbreaks (Botzler 1991, Samuel *et al.* 2005). Moreover, of additional high concern are *P. multocida* isolates obtained from co-inhabiting Subantarctic Skuas *Catharacta antarctica lonnbergi* (adults and chicks) at this location, during the same season (Jaeger *et al.* 2013, Demay *et al.* 2013, Weimerskirch 2016). Skuas scavenge in all albatross colonies, connecting otherwise isolated sections of the Island where the different albatross species breed (Demay *et al.* 2013, Weimerskirch 2016). Thus, the role of skuas as carriers/mechanical vectors of *P. multocida* and/or other pathogens in this confined island situation is likely to be significant (Demay *et al.* 2013, Jaeger *et al.* 2013, Weimerskirch 2016, Wille *et al.* 2016).

Recent studies show phylogenetic resemblance between *P. multocida* isolates from albatrosses at Amsterdam Island and poultry in Europe (Demay *et al.* 2013, Jaeger *et al.* 2015, Weimerskirch 2016). This suggests that the bacteria may have been introduced by live poultry kept at the island navy station, and spread to the albatross colonies via skuas, humans, rats or other means (Weimerskirch 2004, 2016, Demay *et al.* 2013, Jaeger *et al.* 2015). Strict biosecurity has been implemented since 2010 for the Amsterdam Albatross colony, and since 2013 for Yellow-nosed and Sooty Albatross colonies as well, to minimise disease spread between colonies and species by researchers (Demay *et al.* 2013, Jaeger *et al.* 2015, Wemerskirch 2016). Notwithstanding, spread by other means may still occur (e.g. skuas and rats). Of concern, due to the inaccessibility of most albatross colonies, and particularly that of Amsterdam Albatrosses, carcasses are not removed and remain as infectious foci. Vaccination trials using a *P. multocida* strain from Amsterdam Island are currently being conducted in-situ on Yellow-nosed Albatross chicks and adults (Bourret *et al.* 2016). Given the critical condition of Amsterdam Albatrosses and the epidemiological scenario on the Island, such interventions are timely. Their success, however, will be influenced by vaccine efficacy and the proportion of the population inoculated (Plumb *et al.* 2006). While this method is not practical for immunizing large numbers of free-ranging birds, it has been used successfully in smaller groups such as captive propagation flocks of Canada Goose *Branta canadensis* (Friend 1999).

Based on currently available information, several factors make the behaviour of *P. multocida* in albatrosses from Amsterdam Island unusual and merit further investigation. For example, its biased impact on recently hatched chicks, its apparent self-limitation, its somewhat erratic recurrence (i.e. random years with high or very low mortality), and the fact that albatrosses seem to be suffering proportionately greater mortality than other species on the island even though potentially susceptible waterfowl are also present (Botzler 1991, Friend 1999, Weimerskirch 2004, Demay *et al.* 2013, Wille *et al.* 2016). As has been indicated by Jaeger *et al.* (2013, 2015) and Weimerskirch (2016), the situation on Amsterdam Island requires urgent and detailed research on the epizootiology of *P. multocida* infection

to better understand the ecology of the disease and accordingly define mitigation and prevention methods. Future studies should include host-specific factors affecting susceptibility to infection (e.g. sex, age, genetic variation or behavioural differences, immunity, contact with other species at breeding and foraging grounds) and environmental factors influencing the occurrence of these epizootics (i.e. proximity to human dwellings, weather, presence of carrier species, etc.) (Botzler 1991, Descamps *et al.* 2009).

Beyond the pathogens described above, a number of additional bacterial infections have been implicated in chick mortalities of the subset of ACAP species. However, they do not seem to be extended or sustained problems. Three strains of *Salmonella sp*. and compatible histopathological lesions were described in Laysan Albatross chicks dying from necrotizing enteritis (Work *et al.* 1998). The authors suggest a similar problem may have caused earlier mortality in this species (Sileo *et al.* 1990). In both cases death was associated with dehydration, and potentially linked to lead poisoning. Infections with *Nocardia asteriodes* were reported in dead Laysan Albatross chicks with mild fibrinous airsacculitis (Sileo *et al.* 1990). Nocardiosis is uncommon in birds and was suggested by the authors to deserve further study. However, no follow-up studies have been published to date. Enterotoxemia from *Clostridium perfringens* toxins was the ultimate cause of death in a Southern Giant Petrel nestling with cutaneous and diphtheritic pox (Shearn-Boschler *et al.* 2008). Pox infections in this case were considered significant stressors triggering clostridial overgrowth in the gut. Finally, *Escherichia coli* (*E. coli*) was cultured from a single adult Southern Giant Petrel dying from *P. multocida* infection in Antarctica, but was considered a secondary finding (Leotta *et al.* 2003).

Given scant information available on morbidity and mortality triggers in ACAP species, accompanying pathogen isolation findings with histopathology, particularly when investigating disease or mortality, is highly recommended. This might be hindered, however, by the extended time lag between the onset of mortality and investigations, a common occurrence as inferred from this review. Furthermore, several reported mortality events in ACAP species remain undiagnosed, revealing weaknesses in current outbreak response and investigation capacities. This most likely reflects the remoteness and inaccessibility of albatross breeding sites, but also highlights the need for establishing early warning systems, particularly at sensitive locations (i.e. where critically endangered species congregate). Determining cause of death will improve knowledge on disease pathogenesis and virulence, allow for evaluation of the potential population-level impact of diseases, and enable adequate mitigation and preventative measures.

All other reported bacterial isolates in ACAP species were recovered during targeted assessments of contamination by human waste. In this context, gastro-intestinal bacteria were cultured from rectal swabs of apparently healthy Southern Giant Petrel adults (including *E. coli;* Jorge *et al.* 2002, Leotta *et al.* 2009) and one Black-browed Albatross chick (1/240) (*S. newport*; Palmgrem *et al.* 2000) and are likely of little clinical significance. These reports do however show that albatrosses regularly shed bacteria and can therefore act as carriers to distant locations. This might be particularly relevant in carrion-eating species such as the Southern Giant Petrel.

Fungi

Fungal nephritis caused by *Aspergillus flavus-oryzae group* was reported in a moribund and later euthanised Grey-headed Albatross (Tham *et al.* 1974). Based on the chronicity of histological lesions however, it was considered more likely that co-infection with *Proteus* sp., a common urinary tract bacteria (Guentzel 1996), was responsible for the debilitated condition of the animal. Of note, *Aspergillus* genus consists of several hundred species undergoing taxonomical changes with the advent of genome sequencing (Bennett 2010). Therefore, the classification of the fungus in Tham *et al.* (1974) might be presently inaccurate.

Parasites

The majority of parasite papers for the ACAP species subset are taxonomic reports, and very few provide information on pathology or impacts on host species. Papers reporting ectoparasites (20)

greatly outnumber those reporting helminths (7) and protozoa (2). This likely reflects visibility and ease of collection and preservation of external parasites. Only one hematozoan, *Hepatozoon albatrossi*, potentially transmitted by the tick *I. uriae* or a laelapid mite (Woods *et al.* 2009), was described in Grey-headed, Wandering and Black-browed albatross at Islas Georgias del Sur/South Georgia and not associated to clinical disease (Peirce and Prince 1980). Numerous helminths have been described, yet most are from opportunistic collections in Australia and Tasmania and confined to a single report by Johnston and Mawson (1942). The most relevant helminth report is a recent survey of faecal parasites from apparently healthy adult and juvenile Critically Endangered Waved Albatross in Galápagos Islands (Jiménez-Uzcátegui *et al.* 2015). Findings included a nematode, a cestode and a trematode, all in genera previously described in fish-eating birds, including albatrosses, and not considered particularly pathogenic (Jiménez-Uzcátegui *et al.* 2015). It is very likely that available reports are not at all comprehensive of the endoparasite biodiversity in albatrosses and large petrels, so much research remains to be done in this field. Similarly, the impacts of internal parasite burdens on their host's health remain to be explored.

Only infestations with ticks in Black-browed Albatross (*Ixodes uriae*; Bergstrom *et al.* 1999a, b) and Shy Albatross (*Ixodes spp.* and *I. eudyptidis*; Johnstone *et al.* 1975, Wang *et al.* 2014, respectively); and mites *Myialges nudus* (Gilardi *et al.* 2001) and *Womersia midwayensis* (Sileo *et al.* 1990) in Laysan Albatross have been linked to disease or death in the ACAP species subset. Harassment by *Aedes taeniorhynchus* mosquitoes (Anderson and Fortner 1988), on the other hand, was considered responsible for nest abandonment in the Waved Albatross. With the exception of ticks which have been described in numerous seabird species in circumpolar locations, most ectoparasite infestations seem to be restricted to "other" type sites (i.e. tropics), presumably due to warmer climate conditions at lower latitudes. Notwithstanding, changes in parasite and associated vector-borne pathogen distribution can be expected with variations in climate conditions (Kovats *et al.* 2001, Antoniazzi *et al.* 2011, Altizer *et al.* 2013), and should be a monitoring priority in the near future.

Pathogen-specific antibodies

Few studies report antibodies to viruses in ACAP species. Findings are restricted to antibodies specific for Adenoviruses in serosurveys involving Black-browed Albatross (Uhart *et al.* 2004), Waved Albatross (Padilla *et al.* 2003) and Southern Giant Petrel (Uhart *et al.* 2003), Avian Encephalomyelitis virus in Waved Albatross (Padilla *et al.* 2003), Avian Influenza virus in Southern Giant Petrel (Baumeister *et al.* 2004), and Paramyxovirus type 1 in Shy Albatross (Wang *et al.* 2014). Four different studies (Uhart *et al.* 2003, 2004, Padilla *et al.* 2003, Wang *et al.* 2014) explored a suite of additional viral diseases but were unable to find indication of exposure, even though in one occasion samples were collected from animals during a mortality event investigation (Wang *et al.* 2014).

In the case of antibodies to bacterial agents, two studies report positives for *Chlamydophila spp.* in Southern Giant Petrel (Munday 1972) and Black-browed Albatross (Uhart *et al.* 2004), and for *Salmonella spp.* in Southern Giant Petrel (Uhart *et al.* 2003). Given taxonomic misclassifications in the past and cross-reactivity of serological assays, it is unknown whether Munday (1972) refers to *Chlamydophila psittaci*, or another pathogen within the *Chlamydophila* genera (Nunes and Gomes 2014). While available serosurvey reports suggest albatrosses and large petrels are occasionally exposed to common avian viruses and bacteria, in the absence of sequenced sampling to examine change over time, or indication of clinical disease in the individuals sampled, their utility remains limited. Furthermore, in some cases they might represent cross-reactivity with other pathogens given the lack of validation of the serological tests used, a common limitation in disease surveillance via serology in wild species (Gardner *et al.* 1996). Notwithstanding, implementing long-term and adequately designed disease surveillance programmes via measurement of antibodies in blood is recommended because antibodies are typically easier to detect and persist longer than the inciting infectious agents (Gilbert *et al.* 2013). In addition, antibody prevalence data provide information about the cumulative exposure history of the population (Gilbert *et al.* 2013). This is particularly significant for risk assessments (i.e. serosurveys of source stock)

preceding reintroductions and translocations, an increasingly frequent conservation strategy for depleted ACAP species (Gardner *et al.* 1996, Jacobs *et al.* 2014). Finally, to ensure that reliable and meaningful data are obtained, serosurveys would benefit from modelling prior to field sampling, greater consideration of pathogenesis and age structure in the population, investment in longitudinal studies whenever possible, and standardized sample collection, storage and testing protocols (Gilbert *et al.* 2013).

Direct detection of pathogen DNA/RNA

There are three reports on pathogen shedding diagnosed by PCR. Two are based on swabs from apparently healthy chicks including Amsterdam Albatross (sample size unknown) for *P. multocida* and *E. rhusiopathiae* (Jaeger *et al.* 2013, 2015), and one Southern Giant Petrel for Influenza A virus (de Souza Petersen *et al.* 2015). The potential significance of the finding in apparently healthy Amsterdam Albatross chicks has been discussed above, yet without further details, it remains speculative at best. On the other hand, Influenza A-specific antibodies have previously been described in several Antarctic seabirds, including Southern Giant Petrels (Baumeister *et al.* 2004, Barbosa and Palacios 2009). To date however, disease or health impacts associated to this virus have not been reported in albatrosses and petrels. Seabirds, and particularly *Charadriiformes*, are natural reservoirs of influenza viruses, which have been described in more than 105 avian species in 13 orders worldwide (Olsen *et al.* 2006). The third study reported 1/6 Southern Giant Petrel positive for bacteria of the order Chlamydiales by real-time PCR targeting the 23S rRNA gene from fresh faeces collected in Antarctica (Isaksson *et al.* 2015). Knowledge about the diversity and distribution of Chlamydiaceae-like bacteria is limited and evolving, with reports in 460 wild and domestic avian species in 30 orders (Kaleta and Taday 2003). While commonly found in Sphenisciformes and Lariformes (Kaleta and Taday 2003), at this time, the ecological and health relevance of the finding reported by Isaksson *et al.* (2015) is unknown. In addition, DNA of vector-borne bacteria, *Borrelia garinii*, was found in *I. uriae* ticks from Black-browed Albatross breeding in Campbell Island, New Zealand (Olsen *et al.* 1995). It is now known that *B. garinii* is maintained in an enzootic cycle in seabirds by *I. uriae* at their nesting sites over a wide circumpolar area (Smith *et al.* 2006). The significance of this finding relates to public health as *B. garinii* causes neurologic Lyme disease in Europe. However, exchange between the marine enzootic cycle of *B. garinii* and *Borrelia spp*. terrestrial cycles has not been described to date (Smith *et al.* 2006).

Conclusion

In this summary we note that even though the number of health-related studies has increased in recent years, there are still obvious gaps in species and geographical coverage and likely underreporting due to remoteness, accessibility and sporadic monitoring. Deficiencies in investigations of disease and mortality events add to the mix. Current insufficient knowledge may be hampering effective protection and management of populations at risk. Specifically, the threat posed by avian cholera for the most vulnerable albatross species, merits urgent attention.

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