Mirrors in ice

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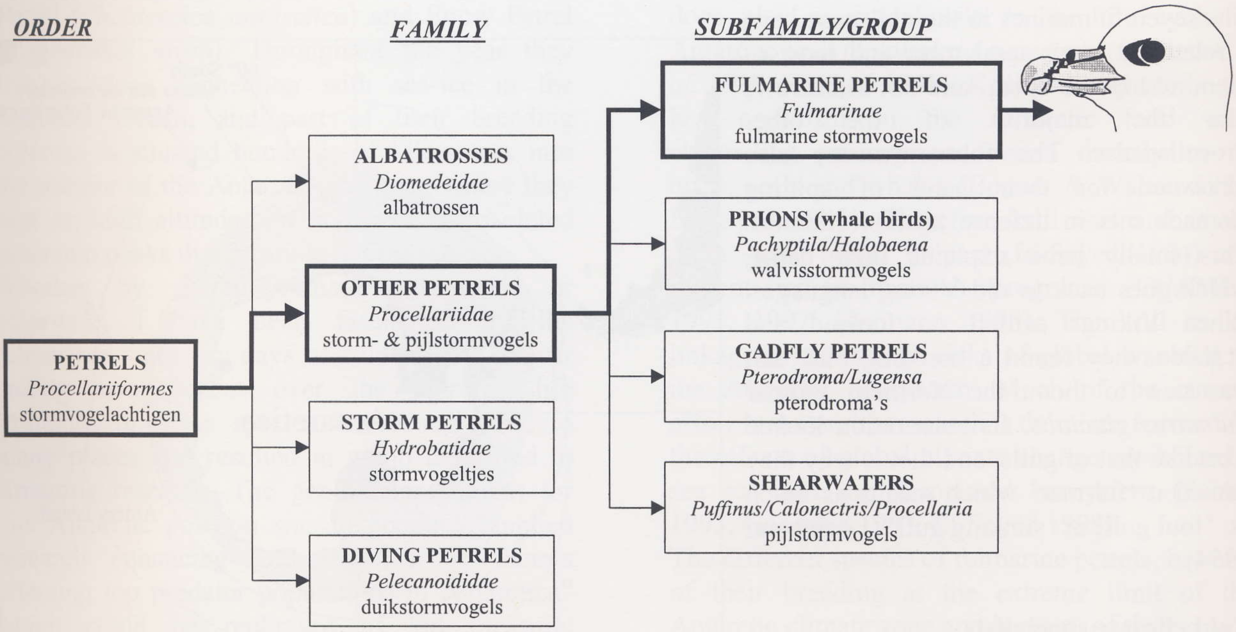
1. INTRODUCTION AND OUTLINE

Fulmarine petrels

Petrels are seabirds that are characterised by the possession of one or two horny tubes on top of the bill covering their nostrils. The petrels, or tubenosed seabirds (Order: Procellariiformes or Tubinares) are probably an old bird group that evolved in the southern hemisphere and that is related to the penguins (Order: Sphenisciformes). But unlike the penguins, petrels developed remarkable flying skills that enable them to utilize the most distant parts of the world's oceans. Four petrel families are distinguished (Warham 1990): the Diomedeidae (albatrosses), the Procellariidae (fulmarine petrels, gadfly petrels, prions and shearwaters), the Hydrobatidae (storm petrels), and the Pelecanoididae (diving petrels). There are considerable disagreements on evolutionary relationships (phylogeny) in the tubenoses, which leads to frequent changes in the systematics (the ordering in groups and related system of names that should be used). Followed here are the subdivisions and names as used by Warham in his extensive work on the petrels (Warham 1990, 1996).



FULMARINE PETRELS (Fulmarinae)

English name	mass (g)	scientific name	Dutch name	distribution
Northern Fulmar	725	*Fulmarus glacialis*	Noordse Stormvogel	Arctic
Southern Fulmar	850	*Fulmarus glacialoides*	Zuidelijke Stormvogel	Antarctic
Antarctic Petrel	690	*Thalassoica antarctica*	Antarctische Stormvogel	Antarctic
Cape Petrel	475	*Daption capense*	Kaapse Stormvogel	Antarctic
Snow Petrel	360	*Pagodroma nivea*	Sneeuwstormvogel	Antarctic
Northern Giant Petrel	4500	*Macronectes halli*	Noordelijke Reuzenstormvogel	Antarctic
Southern Giant Petrel	4500	*Macronectes giganteus*	Zuidelijke Reuzenstormvogel	Antarctic

Within the family of the Procellariidae, the fulmarine petrels seem a somewhat odd collection of seven species, in five genera. They lack unique morphological or anatomical group-characters and vary widely in size, shape coloration and habits. Neverheless, they have usually been grouped as a subfamily, the Fulmarinae (Warham 1990). In recent years mitochondrial DNA analyses have confirmed the common ancestry of these seven species (Nunn 1994). According to the same study, Blue Petrel (*Halobaena caerulea*), Prions (*Pachyptila* spp.) and surprisingly the Kerguelen Petrel (*Lugensa kerguelensis or Pterodroma kerguelensis*) are close relatives that could be included under a broader interpretation of the name fulmarines (Nunn 1994).

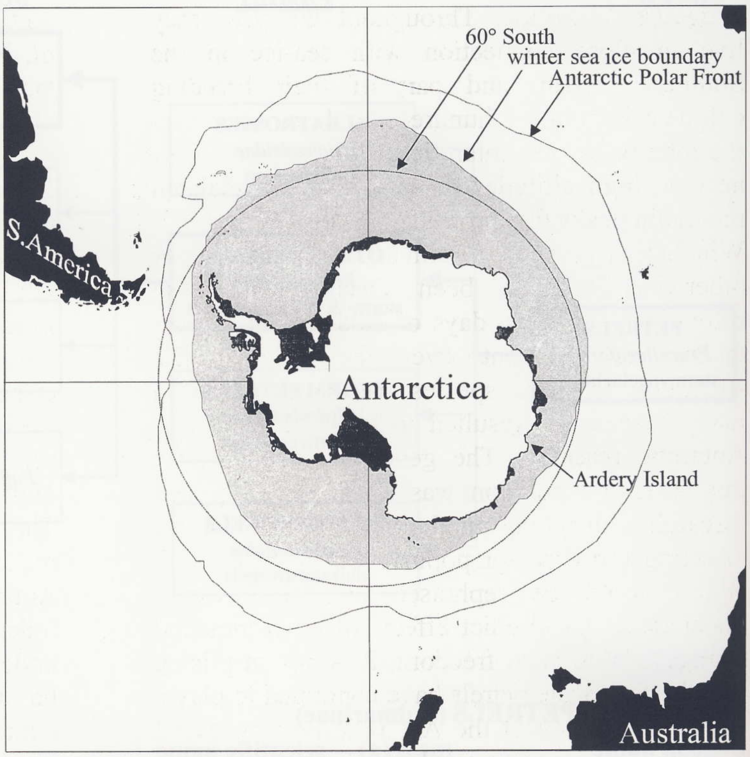
The seven fulmarines in the old sense have a relatively large nasal tube, and most of them nest in the open, and not in burrows like the majority of the other Procellariidae. The fulmarines are also renowned for their habit of spitting stomach oils in defense against enemies. This smelly habit explains their name, which goes back to old Viking languages. When Vikings settled on Iceland and St.Kilda, they found a breeding bird that was new to them, the Northern Fulmar *Fulmarus glacialis.* Its colouration looked a bit like that of gulls, and that is why they named it 'ful-mar' which means as much as 'foul gull' or 'stinking gull' (Lockwood 1954).

Cold climate specialists

A pronounced characteristic of all fulmarine petrels is that they are adapted to the coldest of the world's environments. They breed from extreme high-Arctic places in the northern hemisphere, to the inland mountains of the Antarctic. No other bird group breeds beyond 80° of latitude on both poles. They are so highly specialised to the cold, that they are unable to live in subtropical and tropical climate zones. Only over cold currents, some of the fulmarines occasionally venture into warmer climate zones during the non-breeding seasons. The single northern hemisphere species, the Northern Fulmar, is thought to be an offspring of ancestral Southern Fulmars (*Fulmarus glacialoides*) having reached the north Pacific using the cold Humbold Current in Pleistocene glaciation periods (Voous 1949). From the Pacific, Northern Fulmars have successfully colonized all of the Arctic and now have separate and morphologically highly variable populations in the North Pacific and North Atlantic (Fisher 1952; van Franeker & Wattel 1982).

All other fulmarines are restricted to the cold climate zones of the southern hemispere (Watson *et al.* 1971).

The name of the Northern Giant Petrel (*Macronectes halli*) is somewhat confusing, as it is a subantarctic southern hemisphere bird. Its



ANTARCTICA. The Antarctic Polar Front is the zone where cold Antarctic surface water and warmer subantarctic water bounce against each other and submerge. It creates a sharp temperature gradient all around the Antarctic, conveniently used as the natural northern border of the the Antarctic area. Politically, the Antarctic is defined as the area south of 60° of latitude. The light grey area shows the extent of sea ice during winter, which melts to about 20% of that size in mid summer. Dark areas along the Antarctic coast show ice shelves, the floating outer margins of the Antarctic icecap.

range overlaps with that of the Southern Giant Petrel (*M. giganteus*) but the northern species extends into more temperate zones, whereas breeding locations of the southern one include locations along the continental coasts of Antarctica (Bourne & Warham 1966).
The Cape Petrel, also known as Cape Pigeon or Pintado Petrel (*Daption capense*), has a wide breeding distribution from many subantarctic islands down to the Antarctic coast and disperses widely during winter, reaching the coasts of New Zealand, South Africa and South America.
The Southern Fulmar has a true Antarctic distribution, as it does not breed out of the area enclosed by the Antarctic Polar Front. During the non breeding seasons, part of its populations disperses to the north of the Polar Front.
The real cold climate champions are the Antarctic Petrel (*Thalassoica antarctica*) and Snow Petrel (*Pagodroma nivea*). Throughout the year they live in close connection with sea-ice in the Southern Ocean, and part of their breeding colonies is situated hundreds of kilometers into the interior of the Antarctic continent where they nest on high altitudes on nunataks, the isolated mountain peaks that protrude out the icecap.
Whether by shared climatic preference or otherwise, I have been fascinated by the fulmarines since my days of studenthood. Never ending astonishment over the extreme life strategies of these species has brought me to many places and resulted in a job dedicated to Antarctic research. The general assignment for this Antarctic position was to conduct “applied research enhancing understanding of factors affecting top predator populations in Antarctica” which could be rephrased as “to measure, understand, and predict effects of environmental change”. With such freedom, it is not surprising that the fulmarine petrels have continued to play a key role in many of the Antarctic projects that I have been allowed to conduct. This thesis brings together the major results of those Antarctic studies in order to demonstrate that fulmarine petrels are not an isolated study-object, but provide a powerful tool in understanding Antarctic ecosystems.

Mirrors in ice

Populations of Antarctic fulmarine petrels number many millions of individuals (e.g. Ainley *et al.* 1984; Woehler 1997; Croxall *et al.* 1984; Croxall *et al.* 1995) that depend entirely on the small bits of ice-free land for breeding and largely or completely on the Southern Ocean marine environment for their food.
The most striking feature of the Antarctic marine system is the seasonal sea ice cover (Bonner & Walton 1985, SCAR 1993). In late winter, sea ice in the Southern Ocean grows to a surface of more than 20 million km^2. That is more than half of the Antarctic waters (38 million km^2 south of the Antarctic Polar Front) and effectively doubles the ice surface of the continent itself. During summer, the sea ice melts to a residual surface of about 4 million km^2. The ecological importance of the continuous waxing and waning of this huge sea ice zone is probably still underestimated and poorly understood (Legendre *et al.* 1992). Sea ice does play a critical role in the life cycle of Antarctic krill (*Euphausia superba*) (Smetacek *et al.* 1990, Hempel 1991). Krill is thought to be the key organism in the Antarctic food web, channeling primary production directly to all birds, seals and whales (Bonner & Walton 1985, El-Sayed 1985). Therefore krill was and is the main study object in past (El-Sayed 1994) and current major research programs (CCAMLR 1991, 1997; Hofmann 1998). The krill to ice linkage suggests high risks of global warming to the Antarctic ecosystem. Much of the current effort in Antarctic research is therefore focused on the effects of global climate change on Antarctic sea ice and the associated ecosystem (SCAR 1993, Goodwin 1997, El-Sayed 1998).
The different species of fulmarine petrels, because of their breeding at the extreme limit of the Antarctic climate zone and because of their strong linkage to the seasonal sea ice system, will undoubtedly be among the very first organisms to be affected by climate change. Changes in climate and ice conditions will be ‘mirrored’ by variations in petrel breeding success, survival, and shifts in distribution ranges. By simultaneously studying the different species of fulmarines, each of them with different ecological adaptations to the Antarctic environment, one obtains a number of sensitive and early indicators for a wide range of potential changes in the Antarctic environment and the way in which ecosystems are functioning. This thesis aims to show that such a mirror function is not just a theoretical assumption.

Research question

It would be incorrect to suggest that the environmental indicator or mirror function of fulmarines above has been the key research question on which all projects for this thesis have sharply focused.

My original interest in the fulmarines concerned the rather academic question on the taxonomy and zoogeography of the fulmarine petrel group. Having studied morphological variation of the Northern Fulmar in detail (van Franeker & Wattel 1982), the hope for resolving phylogenetic relationships in the fulmarines using just morphological characters was small. As ecological characteristics could hold additional clues on phylogeny, my first Antarctic project aimed at a comparative study of the ecology of the four smaller species of Antarctic fulmarines (Southern Fulmar, Antarctic-, Cape- , and Snow Petrel). The comparative aspect was best served by studying these birds simultaneously on a location where they co-occurred and shared nest locations and foraging areas. Such location was found on Ardery Island and the Australian Antarctic Division was prepared to support the project. Research question, from a phylogenetic background, for the project was thus: "What are the ecological adaptations that allow four related and similar species of petrels to breed on the same location and to exploit the same environment?" Such a research question actually requires the same type of data collection as what is needed for the environmental indicator function, with the only difference that the latter more explicitly needs to look into possible changes over time in relation to environmental variability. Being employed to conduct applied Antarctic research, the emphasis of follow up projects on Ardery Island shifted to the indicator aspect. This was enhanced by the structure of the Netherlands AntArctic Program NAAP (CAO 1994) which does not operate its own research station or ship. This means that any project has to adapt to the objectives of foreign programs to obtain their logistic support. The Australian commitment to the Ardery project has increasingly been based on the Ecosystem Monitoring Program of CCAMLR (Commission on the Conservation of Antarctic Marine Living Resources). CCAMLR aims to collect information on potential or actual effects of (krill-) fisheries on prey-stocks and predator populations and has Cape Petrel and Antarctic Petrel among the target species for its monitoring program (CCAMLR 1991, 1997).

Further projects used in this thesis were not sharply or exclusively focused on the research question of fulmarine petrel ecology, but were more a matter of adapting to political preferences or taking advantage of logistic opportunities. A comparative study on Cape Petrels in the Peninsula area could be included because of the Dutch Antarctic Expedition 1990/91 to King George Island (Anonymous 1990). Further knowledge on Cape Petrels in that area was achieved by supporting data analyses of a Tsjechian research project. My first ship-based project was, to be honest, mainly started to flag Dutch presence in international coordinated research efforts. The cruise was not specifically focused on top predator research, let alone fulmarine petrel research. However, the study proved to be extremely productive and was followed up by further projects on the German icebreaker Polarstern. Most of these were conducted as part of the Joint Global Ocean Flux Study JGOFS (IGBP & SCOR 1992) which aims to quantify carbon fluxes in marine environments in relation to atmospheric CO_2 levels and global climate change. By bits and pieces, the combined results of studies at sea have considerably improved my understanding of the marine ecology of fulmarine petrels, crucial to the interpretation of study results obtained on land. The marine projects also provided me with a much broader awareness of how Antarctic top predators mirror the ecosystems hidden below the surface and how important the sea ice system is. For this reason, parts of the thesis deviate from the central question on the fulmarines.

Outline of the thesis

The thesis consists of two sections, the first part (Chapters 2-7) dealing with results from ship based research, and the second part (Chapters 8-14) with results of land-based studies of the fulmarine petrels.

Considerable proportions of my time, I have been wrestling with methodological issues to ensure or search for comparability of data in larger frameworks. Chapters 2, 9 and large parts of chapter 11 are attempts to clarify methods or to unite different methods from published literature.

Ship-based studies. Chapters 2 and 3 concern the first marine science project, the European Polarstern Study (EPOS 1988-89). My breaking with old study methods from the BIOMASS program necessitated an explanation of why new methodology was needed, and how results compared to those collected by old methods (BIOMASS = Biological Investigations of Marine Antarctic Systems and Stocks). EPOS results are discussed in chapter 3 and focus on distributions of the whole top predator community and the comparison between their food requirements and primary productivity measured in the water. Chapter 4 continues on this issue by comparing top predator requirements with primary production data from more research cruises. Chapters 5 and 6 deal with pelagic distributions and ecology of separate species. Chapter 5 investigates the links between frontal physics in the Antarctic Polar Front (APF) and prions *Pachyptila* sp. The bird species and the area may seem a bit out of the focus of this thesis. However, according to Nunn (1994) prions are also fulmarines, and the paper was included to demonstrate the mirror function of seabirds on the small spatial and temporal scales that occur in dynamic oceanic frontal systems. Chapter 6 makes the first step to the real fulmarines, by combining various data into a description of the pelagic ecology of the Antarctic Petrel and an estimate of the size of a regional population. Chapter 7 is a species review paper on the Antarctic Petrel population, integrating knowledge from landbased and sea-going research from literature and my own data. This paper is one in a series on populations of Antarctic seabirds, compiled by members of the SCAR Bird Biology Subcommittee as a prerequisite to the subcommittees task in providing advise in conservation and management issues (SCAR=Scientific Committee on Antarctic Research).

Land-based studies. Chapter 8 describes and maps the bird populations in the study area on Ardery Island and on the nearby Odbert Island with which it forms a Specially Protected Area under the Antarctic Treaty. Chapter 9 is a methodological paper dealing with methods for sexing live fulmarine petrels on the basis of their measurements. Many studies on petrel ecology require sex identification in the field, but the sexes lack distinguishing characters. Using all data from Northern Fulmars and the southern fulmarines we searched for a method that can be used in any fulmarine petrel population without the need to kill birds for sexed reference material. Chapter 10, first authored by Karel Weidinger, gives and example of applicability of the method and refines it for Cape Petrels from different populations.

The large chapter 11 is the link between marine and landbased research and extensively discusses foods and foraging ecology of the fulmarines of Ardery Island, and compares the species in detail. Diet study methods are extensively discussed in order to integrate our data with published information. Chapter 12, first authored by Sophie Creet, gives valuable comparative data on the diets of Cape Petrels on King George Island. Chapter 13 is also related to diets, but discusses the non-food plastic items that are ingested by petrels. It was included to show that the 'mirror' function of petrels in our studies extends to the signalling and measuring of global levels of man-made pollutants. The best example of this latter function is of course the completed study of Nico van den Brink on monitoring organochlorine pollutants (van den Brink 1997). Finally, chapter 14 demonstrates the importance of long term ecological and environmental data collection in a spectacular 'mirror' example of effects of environmental change on birds.

The thesis concludes with a short English summary with concluding remarks, an extensive Dutch summary and finally acknowledgements.

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