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Abstract

White-chinned petrels, *Procellaria aequinoctialis*, are one of the most abundant pelagic seabirds in the Southern Ocean and have the highest incidental mortality rate by long-line fisheries in the region. Tracking results on this population have shown that their foraging areas cover the waters around South Georgia, Scotia Sea and sub-Antarctic waters to the Patagonian shelf. However, much information on their diet and activity patterns is needed to better understand their foraging ecology in relation to fisheries and thus provide valuable information for the conservation of this species. The diet has been broadly characterized previously using breeding birds caught at the colonies, however, no diet information is available from white-chinned petrels caught out at sea, caught accidentally by fishing vessels, including the cephalopod part of the diet. As cephalopods are poorly known in the Southern Ocean, and they have no Antarctic fisheries targeting them, understanding their importance in the diet of these seabirds can contribute to our understanding of how white-chinned petrels catch prey (in this case cephalopods) naturally. The diving and activity patterns of white-chinned petrels, related to their feeding ecology, are, also, poorly understood. This species possibly feed by seizing live prey from the surface, by surface plunging and they are also excellent divers. As they are also scavengers, potentially feeding on bait and discards from longline fishing vessels, they may become vulnerable species due to possible attraction to fishing vessels and are known to being caught accidentally by longline hooks. The objectives of this study will be to characterize the diet of white-chinned petrels caught in South Georgian waters onboard of longline fishing vessels, in two different years (2002 and 2004), assess diving patterns of white-chinned petrels, from colonies on Bird Island, South Georgia, from December 2009 and January 2010, and evaluate the implications of the impact of accidental by-catch on white-chinned petrels populations by longline fisheries in the study region. Warmer waters cephalopod species *Gonatus antarcticus*, *Taonius* sp. B (Voss) and *Illex argentinus* (a typically species from the Patagonian shelf) were more abundant in the diet of 2004 than in 2002 (*Martialia hyadesi* was the most important species in 2002). Our results from the activity patterns showed that white-chinned petrels could dive up to 14 metres deep, slightly more than previously thought. In terms of conservation, my results reinforce the need for the implementation of integrated weights in longlines in order to reduce white-chinned by caught. Mitigation measures of precaution and conservation need to also be implemented for the night periods (i.e. so that white-chinned petrels do

not see the longlines being deployed), as white-chinned petrels are both diurnal and nocturnal species.

Keywords: Conservation, diet, diving patterns, incidental mortality, South Georgia, white-chinned petrel.

Resumo

Os painhos de queixo branco, *Procellaria aequinoctialis*, são uma das aves pelágicas mais abundantes no Oceano Antártico e tem a maior taxa de mortalidade acidental por pesca de palangre. Resultados de rastreamento via satélite desta população têm mostrado que as áreas de alimentação e de procura de alimento cobrem as águas ao redor de South Georgia, Mar de Scotia e das águas sub-antárticas até à costa da Patagónia. No entanto, muita informação sobre a sua dieta e padrões de actividade é necessária para entender melhor sua ecologia alimentar em relação à pesca e, portanto, fornecer informações valiosas para a conservação desta espécie. A dieta tem sido amplamente caracterizada anteriormente usando aves que se estão a reproduzir (amostras obtidas nas colónias), mas não há informação disponível da sua dieta destas aves capturadas no mar, quando apanhadas acidentalmente por barcos de pesca, especialmente em relação ao componente de cefalópodes. Como os cefalópodes são pouco conhecidos no Oceano Antártico, e não são pescados de forma intencional neste oceano, compreender a sua importância na dieta destas aves marinhas podem contribuir para um melhor conhecimento de como estes painhos capturam, de forma natural, as suas presas (neste caso cefalópodes). Os padrões de mergulho e actividade dos painhos de queixo branco, relacionados com a sua ecologia alimentar, também são mal compreendidos. Esta espécie possivelmente alimenta-se, ou apanhando presas vivas à superfície da água, ou através do mergulho a partir da superfície, sendo estas aves marinhas também excelentes mergulhadores. Como eles também são *scavengers*, alimentando-se provavelmente, dos iscos e dos restos deixados pelos navios de pesca de palangre, estas aves podem se tornar espécies vulneráveis devido à provável atracção a estes navios de pesca e serem apanhadas acidentalmente pelos anzóis. Os objetivos deste estudo consistem em caracterizar a dieta dos white-chinned petrels capturados em águas de South Georgia a bordo dos navios de pesca de palangre, em dois anos diferentes (2002 e 2004), avaliar os padrões de mergulho dos white-chinned petrels, a partir de colónias em Bird Island, Geórgia do Sul, de Dezembro de 2009 e Janeiro de 2010, e avaliar as implicações do impacto acidental “*by-catch*” destes painhos através da pesca de palangre. Espécies de cefalópodes de águas mais quentes, como *Gonatus antarcticus*, *Taonius* sp. B (Voss) e *Illex argentinus* (uma espécie tipicamente proveniente da costa Patagónica) foram mais abundantes na dieta de 2004 do que em 2002 (*Martialia hyadesi* foi a espécie mais importante em 2002). Os meus resultados dos padrões de actividade mostraram que os

painhos de queijo branco podem mergulhar até 14 metros de profundidade, pouco mais do que se pensava anteriormente. Em termos de conservação os resultados reforçam a necessidade de implementação de pesos integrados nas linhas de pesca. Medidas de mitigação, de precaução e de conservação também precisam de ser implementadas para os períodos da noite (isto é, para impedir que estas aves marinhas não vejam os aparelhos a serem postos na água), devido a estes painhos serem uma espécie activa tanto de dia como de noite.

Palavras-chave: Conservação, dieta, mortalidade acidental, padrões de mergulho, painhos-de-queixo-branco, South Georgia.

Chapter 1

INTRODUCTION

1. Introduction

Marine systems provide many “goods” and services to Mankind. Living marine resources are a source of food, used for compounds for medical usage and cosmetics. Marine resources are also used in aquaculture, agriculture and research in many disciplines. These ecological services that the sea provides, include land buffering from storms, global nutrient cycle contribution and coastal stabilization (Knox 1994). These are just some of the invaluable services that the Ocean provides to the whole biosphere. These marine habitats contain various resources and each species has their own value. Due to much human interference, many of these resources are being drastically depleted. This depletion constitutes a range of ecosystem imbalances and the impairment of ecological processes, which will in turn affect human necessities in the future. To try to curtail these challenges, which our planet is facing, conservation and protection of marine biodiversity is becoming more and more important and making these as a main topic of research in many disciplines.

1.1 Seabirds in the Southern Ocean

Marine birds, or seabirds, in the Southern Ocean have been studied in depth since the 1950's, providing valuable information on the “ecosystem approach to marine management” of the Southern Ocean, particularly in the region of South Georgia (54°20'S and 37°W; Prince and Croxall 1983, Figure 1). Seabirds are marine top predators that may be used as indicators of changes in the marine environment and are useful as flagship species for the conservation of the pelagic marine ecosystems (Knox 1994). These seabirds belong mainly to the two most marine-adapted of all groups, the Procellariiformes, including albatrosses and petrels (amongst others), and the Sphenisciforms (penguins) (Croxall 1984).

Many seabirds are globally threatened because of impacts both at sea and at their breeding sites (BirdLife International, 2008). Threats contributing to seabird population decreases at breeding sites may be attributed to introduced predators (e.g. rodents), human exploitation and disturbance. In trawl fisheries, waste from fishing and fish processing is attractive to foraging seabirds (Jackson 1988; Cartard and Weimerskirch 1999; Weimerskirch *et al.* 1999; Bertellotti and Yorio 2000; Weimerskirch *et al.*, 2000). This waste can change ecosystem dynamics by providing unnatural feeding opportunities for

seabirds. These indirect effects of fisheries discharge on seabird populations may be positive or negative; for example, influencing the dispersal of breeding adults (Oro *et al.*, 2004), changes in their prey (Votier *et al.* 2004), and affecting chick mortality due to the ingestion of low quality prey food from fishery waste (Grémillet *et al.* 2008). However, seabirds that are feeding behind vessels can be injured and killed when they run into nets and vessels, and can be captured in the meshes of these nets (Weimerskirch *et al.* 2000; Wienecke and Robertson, 2002; Munro 2005; Sullivan *et al.* 2006a). Furthermore, due to overfishing and accidental by-catch (usually getting hooked, after being attracted to the bait, and drown), many seabird species are being directly affected and their populations are being reduced drastically (Robertson and Gales 1998; Melvin and Parrish 2001). There is increasing conservation concern about unsustainably high levels of by-catch in many marine fisheries, with several previously abundant species of turtles, sharks and seabirds experiencing serious population declines as a direct result of incidental mortality (Spotila *et al.* 2000; Baum *et al.* 2003; Lewison *et al.* 2004; Gerrodette and Forcada 2005).

The major concerns of conservation are directed especially to albatrosses and petrels in the Southern ocean, as these long-lived seabirds are killed in the tens of thousands, by overfishing, while wintering in the sub-tropics (Brothers 1991; Alexander *et al.* 1997; Catard and Weimerskirch 1999). Large numbers of Procellariiform seabirds are killed each year when they swallow baited hooks set by longline fishing vessels and drown (Brothers 1991; Murray *et al.* 1993; Cherel *et al.* 1996; Hedd *et al.* 1997). Population decreases of several albatross species have been reported from Southern Ocean breeding sites (Weimerskirch & Jouventin 1987; Gales 1993; Weimerskirch *et al.* 1997) and have been linked to the high mortality rates caused by longlining operations (Croxall & Prince 1990; Brothers 1991; Murray *et al.* 1993).

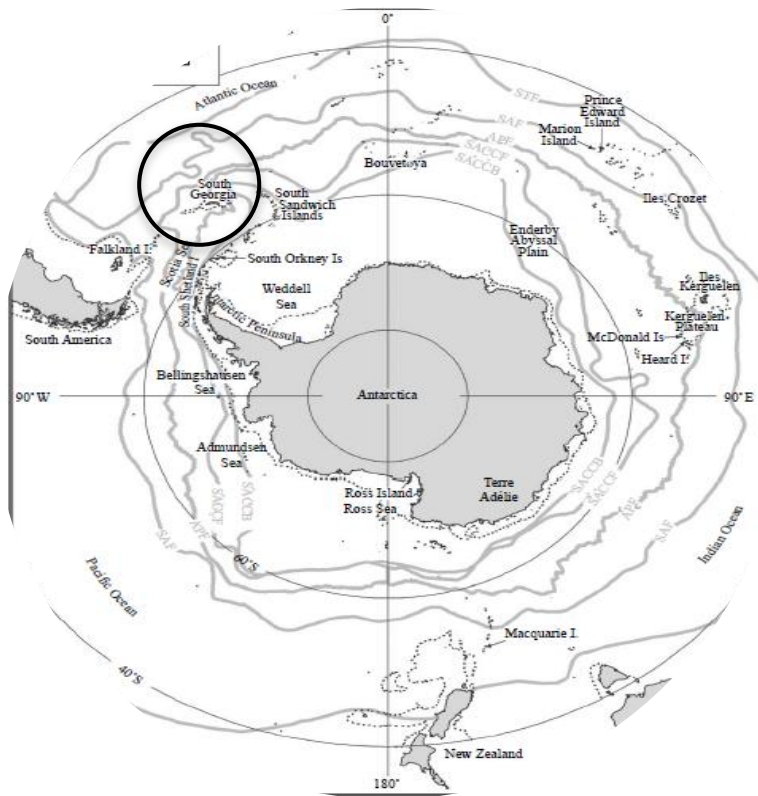


Figure 1: Map of Antarctica (circle around South Georgia). STF – Subtropical front, SAF – Sub Antarctic front, APF - Antarctic polar front, SACCF - South Antarctic circumpolar current front, SACCB - South Antarctic circumpolar current boundary.

For example, the white-chinned petrel, *Procellaria aequinoctialis* Linnaeus 1758, the study seabird species of this thesis, is the seabird killed accidentally as by-catch, in largest numbers by fisheries, mainly by long-line fisheries targeting hake, ling, and toothfish, in the Southern Ocean (Barnes *et al.* 1997; Weimerskirch *et al.* 1999; Berrow *et al.* 2000; Kock 2001; Ryan *et al.* 2002; Nel *et al.* 2003; Tuck *et al.* 2003; Petersen *et al.* 2007; Robertson *et al.* 2006). With up to 80,000 birds killed annually, and listed as Vulnerable (BirdLife International, 2008), the white-chinned petrel is one of the most threatened Antarctic seabird species (Berrow *et al.* 2000).

In order to estimate the impact of fishing mortality on populations, it is necessary to identify foraging ranges for each population as well as their mortality in different fisheries. In order to understand the role and estimate the impact of fishing mortality on populations of white-chinned petrels, and seabirds in general, in the marine environment a good knowledge of foraging behavior, their diet and feeding ecology is important.

1.2. Foraging ecology and diet of seabirds

Information on diet of seabirds, their diving patterns and performance will enable us to understand how they exploit the marine environment (Hedd *et al.* 1997). Physical laws and cost/benefit relations not only fix the limits of seabird sizes, but also determine the size range of animals eaten by seabirds. The ecology of the Southern Ocean, particularly in the southwest Atlantic sector, is dominated by Antarctic krill *Euphausia superba* (hereafter referred as krill), which is considered the keystone species that links primary production to top predators (Knox 1994). Rodhouse and White (1995) proposed an alternative oceanic food web, due to the importance of squid in the Antarctic system. This oceanic food web consists of the linkage between planktivorous mesopelagic fish to squid and predators. More than 70 species of cephalopods (that includes squid and octopods) have tremendous value in the diet of numerous pelagic seabirds in the Antarctic (Cherel and Klages 1998; Collins and Rodhouse 2006; Xavier and Cherel 2009).

The various methods available to determine seabird diet were reviewed by several studies (Duffy and Jackson 1986; Rodway and Montevecchi 1996; Carss *et al.* 1997; González-Solís *et al.* 1997; Andersen *et al.* 2004). Initially, the primary means of assessing diet composition were examining stomach contents; catching generally breeding birds and collecting food samples resulting from either spontaneous or forced regurgitation; collecting prey samples dropped near nest sites; and visually identifying prey carried in the bill, usually during the delivery of prey by adults to chicks. Another method involves stable isotope analysis; it is used to make inferences regarding trophic positions of seabirds in marine food webs (e.g. Cherel and Hobson 2005). Each method has its own associated limitations and biases, and methods chosen must depend on the goals of the study.

Regurgitated food samples collected by stomach lavage or other techniques can provide useful information about the diets of many seabirds. However, analysis of regurgitations and stomach samples may be biased because of the differential digestibility of certain prey types (Jackson and Ryan 1986). For example, squid beaks are not readily digested and can stay for weeks or months in the stomachs of predators (Xavier and Cherel 2009).

Most seabird species are visual predators and forage most actively during daylight hours. However, several species may forage regularly at night. In the Southern Ocean, 13 of 20 species from three different orders (Procellariiformes, Pelacaniformes,

Charadriiformes) were directly observed feeding at night, and five species were exclusive nocturnal feeders (Harper 1987). Some species that are present at the breeding colony by day, leave at night, and return at dawn are presumed to be feeding mostly at night. Diet studies indicating prey that are more likely to be available at or near the surface at night (such as bioluminescent myctophid fish or vertically migrating euphausiids) can also be used to infer nocturnal foraging behaviour (Collins *et al.* 2008).

Various studies on diving behaviour have been done throughout the years on numerous seabird species such as penguins, albatrosses, alcids and cormorants (Prince, *et al.* 1994). There are few data on the depths to which other seabirds dive although some species are known to have considerable abilities for diving and swimming underwater, such as shearwaters (Kuroda 1954; Brown *et al.* 1978), diving petrels (Prince and Jones 1992) and gannets (Adams and Walter 1993). Some more examples of diving studies are the Shy Albatross, *Diomedea cauta*, in Tasmania (Hedd *et al.* 1997), the diving behaviour of the grey-headed albatross, *Diomedea chrysostoma*, (Huin and Prince 1997), the diving ability of blue petrels, *Halobaena caerulea*, Thin-billed prions (Chastel and Bried 1996) and the maximum dive depths attained by South Georgia diving petrel, *Pelecanoides georgicus*, at Bird Island, South Georgia (Prince and Jones 1992).

According to Prince *et al.* (1994), the mean maximum depths attained by the Wandering albatross is 0.3m, the Black-browed albatross is 2.5m, the Grey-headed albatross is 3.0m and the Light-mantled sooty albatross corresponds to 4.7m. The maximum dive depths attained by South Georgia diving petrels range from 17.1 to 48.6 m (Prince and Jones 1992). The maximum diving depths of Blue Petrels and Thin-billed Prions, at Kerguelen Islands, range from 1.0 to 6.2m, and 3.8 to 7.5m, respectively (Chastel and Bried 1996).

Awareness of by-catch issues has led to the use of tracking data to try and identify where and when the greatest potential exists for negative interactions between albatrosses, and petrels, with fisheries (Nel *et al.* 2000, 2002b; Anderson *et al.* 2003; BirdLife International 2004b; Cuthbert *et al.* 2005). The diving behaviour of various seabird species has been extensively investigated and researched mostly in the last two decades, mainly as a result of the increased use of maximum depth gauges (MDGs) and more recently the miniaturization of the time-depth recorders (TDRs) (Hedd *et al.* 1997). Over the last decade, specifically, the development of light-weight satellite transmitters and other types of miniaturized electronic devices have revolutionized the ability to (1) map breeding and wintering foraging ranges of seabirds, (2) investigate relationships between

their at-sea distribution and environmental characteristics, and (3) quantify overlap with commercial fisheries (e.g. Weimerskirch *et al.* 1997, Berrow *et al.* 2000, Catard *et al.* 2000, Fernández *et al.* 2001, Hedd *et al.* 2001).

Effects of deployment of miniaturized transmitters and loggers have been well studied in penguins, but not so much in flying seabirds. As a result, there have been many studies that have examined that topic in penguins, emphasizing the problems and stimulating discussion on ways to minimize hydrodynamic drag and thereby reduce detrimental effects by modifications to tag design (Culik *et al.* 1994). Comparing this to flying seabirds, much less attention has been given even though device mass and attachment method are also of great importance (Massey *et al.* 1988, Wanless *et al.* 1988). From the start, researchers were aware that devices could have a potentially detrimental influence on foraging behaviour, particularly on diving species (Wilson *et al.* 1986). Some studies indicated no significant adverse effects of PTT (Platform terminal transmitters) deployment on foraging trip duration or chick survival of Black-browed and Grey-headed albatrosses, nor on meal mass or adult return rates of Black-browed albatrosses (Phillips *et al.* 2003). On the other hand, there could be intra-specific variation in susceptibility to the effect of tagging, suggesting that deployments for multiple trips are acceptable, but that adults should be monitored closely and PTTs removed if there is any evidence of disadvantageous effects (Phillips *et al.* 2003). There are other studies that show notable differences on trip duration or breeding success in albatrosses and petrels (Klomp and Schultz 2000, Söhle *et al.* 2000). There are many ways of satellite transmitter placement on breeding birds may interfere with the viability of the nesting attempt or the validity of the concluding data. There may be a short-term effect of handling, such as nest desertion, which with a few exceptions tends to affect only a very small proportion of birds tagged (Phillips *et al.* 2003).

Seabird foraging ecology can be better understood when joined with the knowledge of their diving patterns and dietary information. Studies of this nature have included penguins (Whitehead 1989, Seddon and van Heezik 1990), alcids (Burger and Powell 1990, Burger 1991), gannets (Adams and Walter 1993), petrels (Prince and Jones 1992) and albatrosses (Prince *et al.* 1994). Besides the very specialized Pelacanoididae, the Procellariidae (i.e. petrels and shearwaters), are the best adapted of the Procellariiformes for diving, reaching depths of about 20 m (Huin 1994, Skira 1979). Foraging areas and diving behaviour have mostly been studied respectively with GPS loggers and time-depth records that are attached to the birds.

1.3. Diet and Diving patterns of White-chinned petrels

The white-chinned petrel possibly feeds by seizing live prey from the surface, by surface plunging, and they are also excellent divers (Huin 1994, Harper *et al.* 1985). They are also considered scavengers, feeding on bait and discards from long-line fishing vessels, thus making them an extremely vulnerable species (Cherel *et al.* 1996, Barnes *et al.* 1997, Weimerskirch *et al.* 1999). Despite the fact that many benefit from the easy access of these discards and offal, which can form a major dietary component (Jackson 1988, Catard *et al.* 2000), incidental mortality currently represents an enormous threat to long-term population viability.

The main diet of white-chinned petrels generally consists of Antarctic krill, fish and squid, 41%, 34% and 22%, respectively (Croxall and Wood 2002). In a study by Berrow and Croxall (1999) krill (41-42 % by weight) was the single most important prey item, followed by fish (29-39%) and squid (19-25%). This species is the third most important consumer of krill at South Georgia because of its extensive breeding population (Prince and Croxall 1983, Croxall and Wood 2002), and is the most important avian piscivore in the region (Croxall *et al.* 1995). Krill is the most important prey for white-chinned petrels at South Georgia, even though it varies inter-annually in quantity and availability (Berrow and Croxall 1999). However, the diet of white-chinned petrels has only been studied from regurgitations collected at the breeding colonies (Berrow *et al.* 2000) and there are no dietary studies on birds captured at sea. In this innovative study we wish to address this issue and also contribute for the understanding of diet patterns and, consequently for the long-term conservation of this species.

White-chinned petrel diving patterns time-depth recorders (TDR) and geo-locator systems (GLS) were attached to individuals while travelling from Bird Island, South Georgia to the Patagonian Shelf, Argentina. The data obtained by these devices have a huge interest in the study of the feeding ecology and the diving capability of white-chinned petrels, which is particularly important when assessing the susceptibility of this species to incidental capture in long-line fisheries as well as when designing appropriate mitigation measures (Brothers 1991).

Satellite-tracking studies have provided a good indication of the at-sea distribution of breeding white-chinned petrels from the Crozet Islands and South Georgia during chick-rearing, and to a limited extent during incubation (Weimerskirch *et al.* 1999,

Berrow *et al.* 2000b, Catard *et al.* 2000). In contrast, there is little information on winter distribution beyond observations that densities increase in northern sub-Antarctic and subtropical regions (Marchant and Higgins 1990, Olmos 1997).

1.4. Objectives

The main objectives of this study were: a) To characterize the diet of white-chinned petrels in two different years (2002 and 2004), discussing whether diet differs in these two years, b) compare this study with past diet studies, c) assess diving patterns of white-chinned petrels, and d) assess the implications of our results in the conservation of white-chinned petrels.

Chapter 2

MATERIAL AND METHODS

2. Material and Methods

2.1. Study species

The white-chinned petrel is one of the most abundant pelagic seabirds in the Southern Ocean, alongside the Sooty Shearwater, *Puffinus griseus*, (Duffy *et al.* 1987). This species is medium-sized, approximately 55 cm in length, with a pale bill and a variable amount of white on its throat and chin (Berrow *et al.* 2000). This intermediate size between the small petrels (e.g. Blue petrel and Antarctic prion, *Pachyptila desolata*) and the albatrosses (especially the light-mantled sooty albatross, *Phoebastria palpebrata*, and the smaller *Diomedea* sp. species) contributes to its unique position at South Georgia (Hall 1987).

The white-chinned petrel breeds in the sub-Antarctic region, in burrows, grassland areas, in colonies on many scattered islands, including South Georgia, Crozet Islands, Auckland Islands, Antipodes Island and Falkland Islands (Murphy 1936, Jouventin *et al.* 1984, Williams 1984, Berrow *et al.* 2000, Figure 2).



Figure 2: White-chinned Petrels in a grassland area. Photograph by Ben Phalan (Cambridge University).

They breed from September to May on ten different islands in the Southern Ocean, migrating North to the sub-tropics outside the breeding season (Berrow *et al.* 2000). These petrels fly very fast and for long distances during the breeding period for long foraging trips (Croxall 1984).

White-chinned petrels are aggressive in competing for fishing bait, offal and

discards, and have a disproportionately high chance of being hooked in relation to the number attending vessels (Barnes *et al.* 1997, Bertellotti and Yorio 2000, Weimerskirch *et al.* 2000). At South Georgia there are two million pairs of White-chinned petrels (Prince and Croxall 1983), i.e., 40% of the world population inhabits this island (Berrow *et al.* 2000). A 2004 estimate placed the adult bird population at 7,000,000 with an occurrence range of 44,800,000 km² from the Southern Oceans to as far north as South Australia, Peru and Namibia. The current global population estimate for mature adult white-chinned petrels is around about 3,000,000 (Brooke 2004).

An overall decline in population is inferred by a drop in burrow occupancy rates on various islands, with data from Bird Island indicating a decrease of 28% in only two decades (Berrow *et al.* 2000a). This decline in the population maybe the result of environmental changes such as erosion of large coastal grasslands, including those at Bird Island, by Antarctic fur seals *Arctocephalus gazella* Peters 1875 which has increased from a few thousand in the 1960s to an estimated 1.6 million by 1991 (Boyd 1993). This species has the highest incidental mortality rate by long-line fisheries in the Southern Ocean in comparison to other seabirds in the region (Phillips *et al.* 2005), and it is not only caught during its breeding period but also during its non-breeding period (Cherel *et al.* 1996, Barnes *et al.* 1997, Catard and Weimerskirch 1999, Weimerskirch *et al.* 1999, CCAMLR 1999). Accidental by-catch is the reason for such a high mortality rate, due to unintentional long-line fisheries (Cherel *et al.* 1996, Barnes *et al.* 1997, Weimerskirch *et al.* 1999).

This incidental mortality in long-line fisheries is recognized as a key threatening process for seabird species (Tuck *et al.* 1999). More recently trawl fisheries were also found to be huge threats to both petrels and albatrosses (Lokkeborg *et al.* 2003). There have been management regimes for addressing seabird by-catch by the Regional Fishery Management Organizations (RFMOs) (Hunt 2006), but these have not been efficient. In the case of the long-line fisheries managed under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), monitoring of the effectiveness of measures at reducing seabird captures, implementation of the measures and ecological risk assessment (ERA) for seabirds have also been used. CCAMLR has been highly effective at reducing seabird by-catch in its long-line fisheries (Waugh *et al.* 2007).

This species was included in the IUCN's red list as Vulnerable (BirdLife International 2005, *Procellaria aequinoctialis* In: IUCN 2007).

2.2. Study area

The study site extends from Bird Island in South Georgia to the Patagonian Shelf, Argentina (Figure 3).

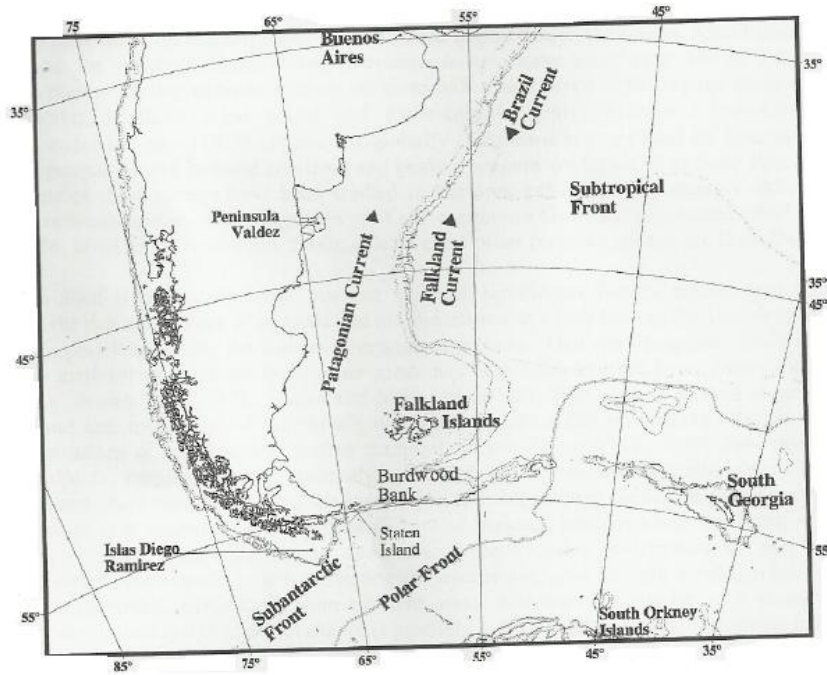


Figure 3: Southwest Atlantic, showing main frontal and current systems and principal locations.

South Georgia and its islands have an oceanic climate, which is influenced by high levels of precipitation (1200-2000mm/year, Laws 1978). The main ocean currents around South Georgia are the Antarctic Circumpolar Current and the Northerly range of the Polar Front. The biota in the waters of South Georgia is therefore cold water Antarctic species (Barnes 2008, Smith *et al.* 2010). South Georgia's waters are highly nutrient rich with some of the highest nutrient values in the Southern Ocean with silicon at 25-30, phosphate at 0.75 and nitrate levels at 5 millimoles per cubic meter (Whitehouse *et al.* 1996, Priddle *et al.* 1998). The high nutrient levels provide a rich and productive frontal shelf environment around South Georgia, which provides abundant prey for a great number of predatory species, like the white-chinned petrel.

One of the important factors of the Patagonian Shelf for top predator species breeding at South Georgia is due to the very rich zooplankton, fish and squid resources that sustain substantial populations of largely resident seabirds and marine mammals

(Croxall and Wood 2002). Recent studies, using satellite-tracking to determine foraging ranges and feeding areas of seabirds and mammals breeding at South Georgia, have shown that these species make use of the Patagonian Shelf's waters (Croxall and Wood 2002). White-chinned Petrels mainly visit during incubation and post-breeding, particularly to the Falklands Current and to upwelling areas around the southern shelf-break (Croxall and Wood 2002).

2.3. Methods

For this study, we used individuals of white-chinned petrels caught accidentally by long-line fishing vessels, along the South Georgia shelf, for the years 2002 and 2004. Exact locations are missing for quite a few of the birds, but they will have been caught in roughly the same areas. To analyze their diet, the material in their stomachs was identified and measured when possible. For each sample, squid beaks were counted, separated and upper beaks were differentiated from lower beaks, with the lower beaks identified, measured and allometric equations used (to extrapolate to size and weight) following Xavier and Cherel (2009); this work was carried out at Institute of Marine Research (IMAR-CMA), University of Coimbra. The otoliths from the 2002 stomachs were not identified due to extensive erosion.

Frequency of occurrence, number of individuals of each species divided by the total number of identified individuals, and number of individuals of each species divided by the total number of individuals (identified plus unknown species) were calculated from the measurements obtained (Jackson 1988).

The diving and activity patterns of white-chinned petrels breeding at Bird Island, South Georgia were analyzed in Cambridge at the British Antarctic Survey: the diving patterns of 14 deployments of 14 different birds (Figure 4). The analysis was based on TDR (time- depth recorders) and GLS (geo-locator system) data, they collect diving and time-budget information and wet and dry period information, respectively. The GLS-immersion loggers were Mk19 (Figure 5). They record the timings of all changes of state (from wet to dry, and vice-versa) of 6 seconds or more, allowing the reconstruction of detailed activity patterns. From December 2009 to January 2010 this information was obtained by Richard Phillips and his team at the British Antarctic Survey (Cambridge, UK).

The *Divemove* software (Luque 2010), that is one of the packages belonging to R, was used to obtain the various characteristics of each dive during each deployment. After obtaining the various dive characteristics using this software, bird number 4 really stood out. After repeating the *Divemove* software various times it was decided to eliminate the deployment of bird number 4, due to consistently demonstrating these dubious results, i.e, extremely high maximum depth (approximately 46 m) and a huge amount of dives (918).



Figure 4: White-chinned Petrel and a Wandering Albatross, Drake Passage, (birdtours.co.uk).

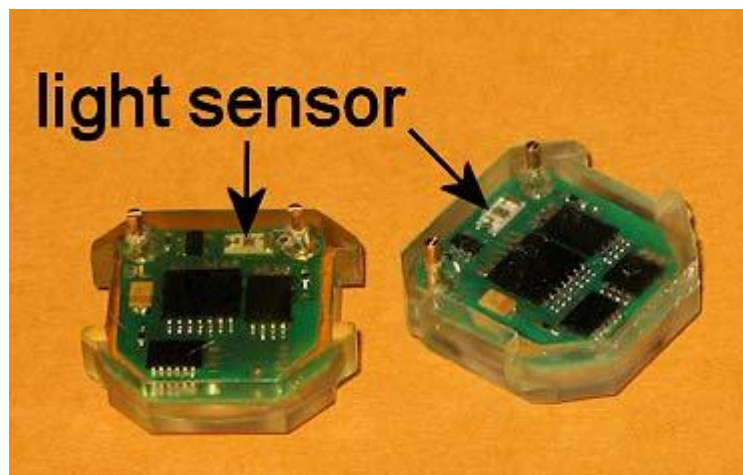


Figure 5: Mk 19 Geolocator, where wet/dry activity in saline water is recorded (<http://www.birdtracker.co.uk>).

Chapter 3

RESULTS

3. Results

3.1. Diet results

3.1.1. Squid component of the diet of white-chinned petrels

The cephalopod component of white-chinned petrels was characterized for the years 2002 (n= 20 samples) and 2004 (n= 38 samples). The total number of upper beaks in 2002 is 156 and the total number of lower beaks is 449, and in 2004 the total number upper and lower beaks are 80 and 1803, respectively.

3.1.1.1. Year 2002

In 2002, the main cephalopod species identified by frequency of occurrence (FO) was *Martialia hyadesi* (65%), followed by *Gonatus antarcticus* (Figure 7) (45%), *Galiteuthis glacialis* (35%), *Histioteuthis eltaninae* (35%) and *Taonius* sp. B (Voss) (35%). By Number of individuals (N) the order of importance is the following: *Martialia hyadesi* (Figure 8) (21.3%), *Galiteuthis glacialis* (12.2%), *Histioteuthis eltaninae* (6.3%), *Gonatus antarcticus* (5.5%) and *Taonius* sp. B (Voss) (4.2%). In relation to the percentage of mass of each species (M), *Martialia hyadesi* (26%), *Moroteuthis knipovitchi* (22.8%) and *Gonatus antarcticus* (13.2%) (Table 1 and Appendix 1). The total number of eroded lower beaks in 2002 was 32.5 % (Table 1).

The average lower rostral lengths (LRL) (Appendix 1) for 2002 in mm that stand out belong to *Taonius* sp. B (Voss) (6.7 mm), *Moroteuthis knipovitchi* (6.2 mm) and *Gonatus antarcticus* (5.2 mm), each one's range being 5.8-7.7 mm, 5.9-6.5 mm and 3.2-8 mm, respectively. This shows that *Taonius* sp. B (Voss) has the biggest beaks in the diet of white-chinned petrels in 2002, followed by *Moroteuthis knipovitchi* and *Gonatus antarcticus*.

The average mantle lengths (ML) (Appendix 1) in mm for the same year that must be noted belong to *Taonius* sp. B (Voss) (399 mm ML), *Moroteuthis knipovitchi*, (286 mm ML) *Martialia hyadesi* (200 mm ML), *Galiteuthis glacialis* (191 mm ML) and *Gonatus antarcticus* (180 mm ML), for each species the ML ranges from 344-461 mm, 253-316 mm, 153-290 mm, 94-300 mm and 135-245 mm, respectively (Appendix 1).

3.1.1.2. Year 2004

In 2004, the main cephalopod species in terms of frequency of occurrence, number and mass was *Gonatus antarcticus* (Table 1 and Appendix 2). According to FO in the diet was *Gonatus antarcticus* (79%), followed by *Taonius* sp. B (Voss) (47%) and *Histioteuthis eltaninae* (29%), *Galiteuthis glacialis*, *Illex argentinus*, *Psychroteuthis glacialis* and *Slosarczykovia circumantarctica*, all with 24% FO. Regarding N, the most important species include *Gonatus antarcticus* (13.4%), *Slosarczykovia circumantarctica* (7.1%) and *Taonius* sp. B (Voss) (6.9%). In relation to M the following the following species are in order of importance: *Gonatus antarcticus* (36.9%), *Taonius* sp. B (Voss) (20.8%), *Moroteuthis knipovitchi* (10.4%) and *Illex argentinus* (10.1%) (Table 1 and Appendix 2). The total number of eroded lower beaks in 2004 was nearly half of all lower beaks (48.9 %; Table 1).

In 2004 the average LRLs (Appendix 2) that are important to mention are those of the species *Taonius* sp. B (Voss) (7.4), ranging from 5.4-9.7 mm, *Mastigoteuthis* A (6.6), *Gonatus antarcticus* (5.7), it's range being 4-7.5 mm, *Chiroteuthis veranyi* (5.0) ranging from 3.4-6 mm. This means that *Taonius* sp. B (Voss) has the longest beak for the year 2004.

The average Mantle lengths (ML) (Appendix 2) in mm for the same year that must be noted belong to *Taonius* sp. B (Voss) (442 mm ML) 319-584 mm, *Mesonychoteuthis hamiltoni* (289 mm ML), *Moroteuthis knipovitchi* (232 mm ML) 0.2-327 mm and *Illex argentinus* (219 mm ML) 196-234 mm.

3.1.1.3. Comparison between years

Interesting to note that *Illex argentinus* only occurred in 2004 (Table 1, Appendices 1 and 2). The main cephalopod consumed in 2002 and 2004 were different, with *Martialia hyadesi* being the most important species (in terms of FO, N and M) in 2002 and *Gonatus antarcticus* in 2004 (Table 1). The FO of the species *Martialia hyadesi* decreases from 2002 to 2004 (from 65% to 13%), in relation to N this species also diminishes (from 21.3% to 4.7%) and concerning M there was a huge decrease from 2002 to 2004 (26% to 2.1%). Another species that must be noted is *Taonius* sp. B (Voss), increasing from 35% to 47% of FO from 2002 to 2004. Concerning N, this species went up from 4.2%

to 6.8% in 2004 and in relation to M it also increased from 8.7% to 20.8%. Comparing the 2 species *Galiteuthis glacialis* and *Gonatus antarcticus* (Figure 7), FO, N and M all decreased from 2002 to 2004, except for M for the species *Gonatus antarcticus*, which increased from 13.2% to 36.9% (Table 1, Appendices 1 and 2).

Table 1: Cephalopod component of white-chinned petrels caught accidentally as by-catch around South Georgia in 2002 and 2004. FO = Frequency of Occurrence; N = Number of individuals (number of individuals of each species/ total number of individuals, including unknown individuals, multiplied by 100 to obtain the percentage) and M is the percentage of mass of each species. Only species with FO > 20% and N > 2 % are displayed; a detailed version of these results are in appendix.

Species	2002			2004		
	FO (%)	N (%)	M (%)	FO (%)	N (%)	M (%)
<i>Galiteuthis glacialis</i>	35	12.2	9.3	24	2.6	4.1
<i>Gonatus antarcticus</i>	45	5.5	13.2	79	13.4	36.9
<i>Histioteuthis eltaninae</i>	35	6.3	1.9	29	3.9	5.3
<i>Illex argentinus</i>	0	0	0	24	5.4	10.1
<i>Martialia hyadesi</i>	65	21.5	26	13	4.7	2.1
<i>Moroteuthis knipovitchi</i>	30	3.4	22.8	11	1.1	10.4
<i>Psychroteuthis glacialis</i>	20	2.1	1.3	24	2.4	1.9
<i>Slosarczykovia circumantarctica</i>	25	8.9	0.8	24	7.1	0.9
<i>Taonius</i> sp. B (Voss)	35	4.2	8.7	47	6.9	20.8
Unknown (eroded) lower beaks	85	32.5		84	48.9	

There were no significant differences in mass, LRL and ML, between the years 2002 and 2004, in eight of the ten species of squid compared (Table 2). The squid species *Galiteuthis glacialis* and *Taonius* sp. B (Voss) showed significant differences of LRL, Mass and ML between years (Table 2). For both of these squid species, their beaks were bigger in 2004. It can also be noted that in 2004 these species have a bigger mantle length and higher mass values. *Slosarszikovia circumantartica* shows the lowest mean LRL and

ML in both 2002 and 2004, 2.8 (ranges from 2-3.9 mm) and 73 mm (ranges from 57-95 mm) and 2.5 (ranges from 1.7-3.6 mm) and 67 mm (ranges from 51-89 mm), respectively (Table 2, Appendices 1 and 2). The range LRL of all the species in 2002 is from 1.9 mm to 8.9 mm. In 2004 the LRL range from 1.7 mm to 9.7 mm (Table 2, Appendices 1 and 2).

Table 2: Average values of LRL (Lower Rostral length), Mass and ML (Mantle length) of species of squids identified in the diet of white-chinned petrels captured in 2002 and 2004, that occurred in both years and had more than 3 lower beaks in given year. Differences in mass, LRL and ML, between years were assessed using the statistical t-test. The minimum number of beaks considered for the t-test is 3.

Species	2002	N for 2002	2004	N for 2004	t-test
<i>Ancistrocheirus lesueurii</i>					
LRL (mm)	4.7 ± 1.3		3.8 ± 0.4		t(9)=1.71; p=0.12
Mass (g)	260.8 ± 198.1	4	102.8 ± 36.1	7	t(9)=2.13; p=0.06
ML (mm)	152.2 ± 54.2		115.3 ± 14.7		t(9)=1.71; p=0.12
<i>Galiteuthis glacialis</i>					
LRL (mm)	4.4 ± 0.7		4.9 ± 0.5		t(29)=-2.22; p=0.03
Mass (g)	68.6 ± 24.6	20	86.8 ± 18.3	11	t(29)=-2.14; p=0.04
ML (mm)	191.4 ± 28.1		212.4 ± 18.4		t(29)=-2.22; p=0.03
<i>Gonatus antarcticus</i>					
LRL (mm)	5.2 ± 1.5		5.7 ± 0.8		t(55)=-1.72; p=0.09
Mass (g)	162.5 ± 147.8	12	189.8 ± 92.3	45	t(55)=-0.80; p=0.43
ML (mm)	179.5 ± 62.2		203.1 ± 35.5		t(55)=-1.72; p=0.09
<i>Histioteuthis eltaninae</i>					
LRL (mm)	3.6 ± 2.2		3.3 ± 0.3		t(22)=0.48; p=0.64
Mass (g)	144.9 ± 252.9	8	77.7 ± 18.0	16	t(22)=1.08; p=0.29
ML (mm)	65.2 ± 49.7		59.3 ± 7.3		t(22)=0.48; p=0.64
<i>Martialia Hyadesi</i>					
LRL (mm)	3.6 ± 1.2		4.0 ± 0.1		t(27)=-0.54; p=0.59
Mass (g)	149.4 ± 121.7	26	162.4 ± 9.1	3	t(27)=-0.18; p=0.86
ML (mm)	197.9 ± 36.4		209.5 ± 2.9		t(27)=-0.54; p=0.59
<i>Moroteuthis knipovotchi</i>					
LRL (mm)	6.2 ± 0.2		5.7 ± 1.3		t(9)=0.97; p=0.36
Mass (g)	562.1 ± 67.2	6	479.5 ± 258.0	5	t(9)=0.76; p=0.47
ML (mm)	286.2 ± 22.5		231.8 ± 136.5		t(9)=0.97; p=0.36
<i>S. circumantarctica</i>					
LRL (mm)	2.8 ± 0.7		2.5 ± 0.5		t(48)=1.98; p=0.05
Mass (g)	7.6 ± 2.5	17	6.4 ± 1.9	33	t(48)=2.00; p=0.05
ML (mm)	73.4 ± 13.1		66.6 ± 10.7		t(48)=1.98; p=0.05
<i>Taonius sp. B (Voss)</i>					
LRL (mm)	6.7 ± 0.7		7.4 ± 0.9		t(34)=-2.20; p=0.03
Mass (g)	142.9 ± 31.1	9	178.2 ± 45.4	27	t(34)=-2.15; p=0.04
ML (mm)	399.3 ± 40.2		441.6 ± 52.7		t(34)=-2.20; p=0.03
All species					
LRL (mm)	4.3 ± 1.5		4.8 ± 1.8		t(285)=-2.43; p=0.02
Mass (g)	133.3 ± 160.0	111	131.4 ± 115.6	176	t(285)=0.12; p=0.91
ML (mm)	178.2 ± 95.4		196.5 ± 127.4		t(285)=-1.30; p=0.19



Figure 7: *Gonatus antarcticus*, Richard E. Young.



Figure 8: *Martialia hyadesi*, Paul G. K. Rodhouse.

3.1.2. Fish component of the diet of white-chinned petrels

The other component of the white-chinned petrel diet that was analysed was the fish species component (Table 3). The most important fish in the diet in 2004 was *Champsocephalus gunnari* (Figure 9); 66 % FO, 55.2 % N and 95.6 % M) (Table 3). The FO of the latter is 66% and N is 55%, there are no results for 2002, due to extremely high erosion of fish otoliths, hence the impossibility to identify fish species for this year.



Figure 9: Mackerel icefish, *Champsocephalus gunnari*, from South Georgia (Photo courtesy of Reyes, P.).

The percentage of mass and average total length that really stands out are of *Champocephalus gunnari*, approximately 95.6% and 268.4mm, respectively (Table 3). *Electrona antarctica* is the smallest species of fish, 0.3% of mass and 72.5 mm long. Due to the fact of not being able to measure the otolith length for the species *Dissostichus eleginoides*, *Gymnoscopelus* sp. and *Sio nordenskjoldii* (due to otolith erosion), it is not possible to determine the mass and percentage of mass for these species.

Table 3: Fish component of the diet of white-chinned petrels in 2004 (no otoliths were analyzed in 2002 samples due to the high level of erosion). Frequency of occurrence (FO), Number of individuals (N), percentage of mass (M).

Species	2004			Total length (mm)
	FO (%)	N (%)	M (%)	
<i>Chanocephalus aceratus</i>	2	0.7	0.4	178.4
<i>Champocephalus gunnari</i>	66	55.2	95.6	268.4
<i>Dissostichus eleginoides</i>	0	0.7	-	-
<i>Electrona antarctica</i>	7	2.8	0.3	72.5
<i>Electrona carlsbergi</i>	12	4.2	0.4	83.0
<i>Gymnoscopelus nicholsi</i>	10	2.8	0.7	
<i>Gymnoscopelus</i> sp.	2	1.4	-	149.5
<i>Gymnoscopelus</i> sp. (eroded)	2	0.7	-	-
<i>Lepidonotothen larseni</i>	2	0.7	0.3	123.0
<i>Protomyctophum choriodon</i>	20	18.2	2.3	87.8
<i>Sio nordenskjoldii</i>	2	0.7	-	-

3.2. Diving patterns of white-chinned petrels

A total of 14 white chinned petrels were handled to evaluate their activity patterns. The white-chinned petrels dived, on average, approx. to 4 m deep on their foraging trips, reaching up to 14 m deep (Table 4). As the Table 4 shows, bird number 6 has an

excessive amount of number of dives (188 to be exact). Birds 1, 7, 10, and 13 indicate that they made more than 50 dives each. Bird number 10 has the deepest dive, to approximately 14 m deep. 4 birds did not demonstrate any diving or depth (28.6% of the individuals studied). Bird 6 stands out in the percentage of dryness during the deployment: 83.64% dry. The bird that has the highest percentage of wetness is bird number 1: 51.43% wet. This last bird shows an even percentage of dryness and wetness, 48.57% and 51.43%, respectively. The biggest difference in percentages of dry and wet is noted in bird 6, 83.64% and 16.36%, respectively. Bird 6 also stands out in relation to the number of days of the trip duration, approximately 30.5 days. The shortest deployment is 10.26 days and belongs to bird 7.

Overall the average of the number of dives per foraging trip is 39.15. The average percentage of dryness is much higher than the average percentage of wetness as seen on the table above, 66.33% and 33.67%, respectively. The average number of days of the trip duration is approximately 15 (Table 4).

Table 4: Diving characteristics and analysis. The maximum depth (in metres) is mean \pm SD.

Bird	ID	Departure date	Arrival date	Trip duration (days)	Dry (%)	Wet (%)	TDR time on	Nr dives	Max Depth (m)	
1	A05496	05/12/09 20:21	20/12/09 23:32	15.13	48.57	51.43	6.67	52	2.2 \pm 1.4 (1.0-7.4)	
2	A05498	11/12/09 00:23	25/12/09 20:14	14.83	70.46	29.54	0	0	0	
3	A05504	07/12/09 11:27	18/12/09 22:53	11.48	59.68	40.32	6.69	28	2.4 \pm 2.7 (1.0-12.1)	
5	A05502	07/12/09 04:47	19/12/09 22:49	12.75	64.77	35.23	1.19	0	0	
6	A05497	06/12/09 05:06	05/01/10 16:30	30.47	83.64	16.36	9.04	188	1.64 \pm 0.74 (1.0-7.33)	
7	A05499	17/12/09 17:37	27/12/09 23:53	10.26	72.51	27.49	9.04	55	1.4 \pm 0.37 (1.0-2.8)	
8	A05500	06/12/09 03:28	19/12/09 20:57	13.73	63.92	36.08	6.66	25	1.57 \pm 0.68 (1.0-4.5)	
9	A05505	06/12/09 03:38	18/12/09 19:16	12.65	66.44	33.56	6.7	18	2.19 \pm 0.87 (1.03-3.72)	
10	A05503	18/12/09 00:44	01/01/10 10:23	1.4	64.09	35.91	9.04	65	2.89 \pm 2.45 (1.0-13.95)	
11	A05517	01/01/10 13:13	14/01/10 20:01	13.28	56.91	43.09	1.19	0	0	
12	A05511	26/12/09 00:30	10/01/10 12:51	15.51	66.5	33.5	21.04	18	1.5 \pm 0.5 (1.0-2.6)	
13	A05508	24/12/09 03:49	12/01/10 12:07	19.35	81.51	18.49	21.04	60	1.91 \pm 0.58 (1.00-3.18)	
14	A05513	28/12/09 04:39	08/01/10 23:21	11.78	63.33	36.67	21.04	0	0	
				Average overall	15.05 \pm 5.16	66.33\pm 9.38	33.67\pm 9.38	9.18 \pm 7.41	39.15 \pm 50.85	3.93 \pm 1.14

Bird 7 stands out being 80% wet during the day. Birds 1 and 2 also have high percentages of wetness during the day, reaching 76.86% and 71.84%, respectively. Birds 5 and 8 both reach approximately 75% of dryness during the day. Birds 6 and 14 really stand out being the birds with the least percentage of dryness during the day (Table 5 and Figure 10).

Table 5: Percentage of wet and dry periods during the day.

Bird	Dry (%)	Wet (%)
1	64.42	76.86
2	69.72	71.84
3	63.80	68.06
5	74.90	64.84
6	18.08	56.90
7	64.29	79.84
8	74.61	69.02
9	70.81	66.09
10	49.50	62.37
11	67.60	66.54
12	49.35	64.63
13	47.50	65.26
14	15.71	57.99
Total	56.18±19.72	66.94±6.52

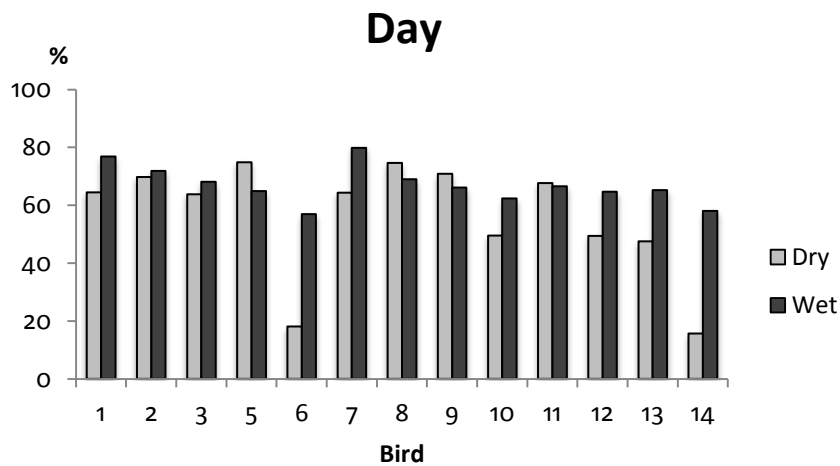


Figure 10: Percentage of wet and dry periods during the day

Bird 6 has 43.10% wetness during the night and Bird 14 reaches 42.01% wetness at night. Birds 1 and 7 represent the least percentage of wetness during the night, 23.14% and 20.16%, respectively. Birds 6, and 14 stand out due to their higher percentage of dryness during the night, reaching more than approximately 80% each. Bird 5 is only 25.10% dry and bird 8 is only 25.39%, both during the night (Table 6 and Figure 11).

Table 6: Percentage of wet and dry periods during the night.

Bird	Dry (%)	Wet (%)
1	35.58	23.14
2	30.28	28.16
3	36.20	31.94
5	25.10	35.16
6	81.92	43.10
7	35.71	20.16
8	25.39	30.98
9	29.19	33.91
10	50.50	37.63
11	32.40	33.46
12	50.65	35.37
13	52.50	34.74
14	84.29	42.01
Total	43.82±19.72	33.06±6.52

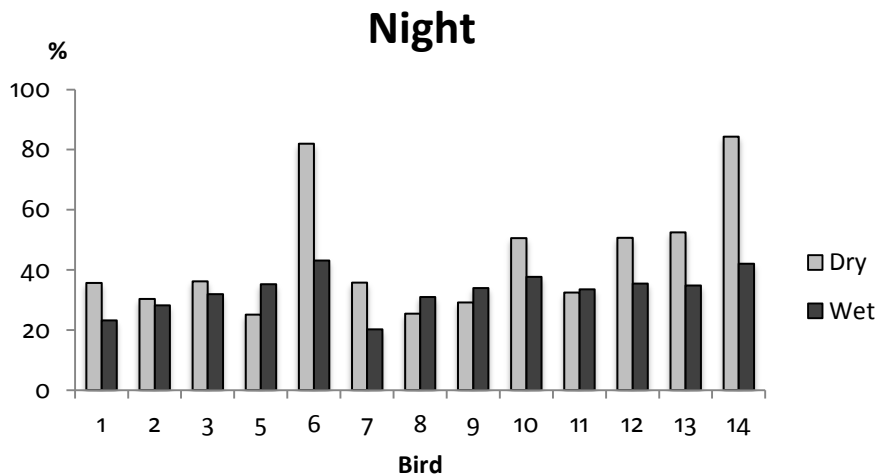


Figure 11: Percentage of wet and dry periods during the night

The average percentage of wetness overall is higher during the day than at night and the average percentage of dry periods overall is higher during the day than at night.

The number of dives is directly proportional to the % of dry periods and inversely proportional to the % of wet periods. Both the graphics are symmetrical, thus only presenting the graphic of the correlation in relation the dry periods (Figure 12).

This correlation presents an r^2 of 0.311 (thus explains 31% of the variation) and p equals 0.047, thus presenting a significant relationship between the number of dives and the percentage of dry periods.

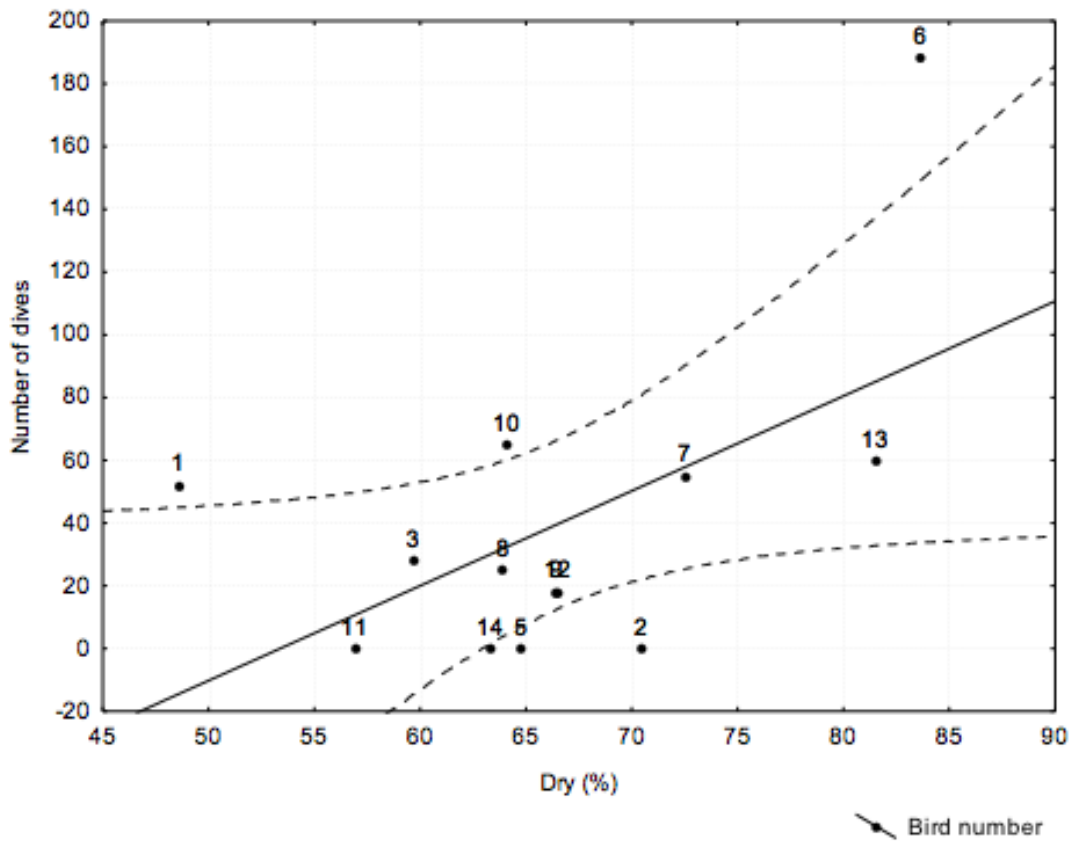


Figure 12: Correlation with % of dry periods and number of dives of the different birds (Number of dives= $-161.4 + 3.0233 * \text{Dry} (\%)$, $r^2 = 0.311$; $p = 0.047$). The dots with associated numbers represent the bird's numbers.

Chapter 4

DISCUSSION

4. Discussion

4.1. The diet of White-chinned petrel

The diet of white-chinned petrels has been broadly characterized on previous occasions from breeding birds (Jackson 1988; Ridoux 1994; Croxall *et al.* 1995; Berrow and Croxall 1999; Berrow *et al.* 2000). These studies show that white-chinned petrels can change their diets according to krill abundance and because of that, and unlike other seabirds, can keep the birth rates constant, despite feeding rates of the offspring could decrease, as shown in Berrow and Croxall (1999). However, there is only diet information taken from regurgitations from breeding white-chinned petrels and no information was provided for white-chinned petrels caught at sea by fishing vessels. This study shows the first description of the cephalopod component of the diet of white-chinned petrels that were caught accidentally by fisheries around South Georgia, allowing a comparison between both.

In the current study the diet of white-chinned petrels varied between years, with the sub-Antarctic squid species *Martialia hyadesi*, a species known to occur at the Antarctic Polar Front, north of South Georgia, as the most important (its FO being 65% and M equaling to 26%) in 2002. This was also verified before in a study by Croxall *et al.* (1995), where it was stated that this species, *Martialia hyadesi*, was the most commonly taken cephalopod in 1986 by white-chinned petrels breeding at South Georgia (accounting for one half of the mass of the squid consumed), contrary to another study by Berrow and Croxall (1999) carried out at South Georgia, where it did not occur at all in both the years of the study, being *Brachioteuthis ? picta* the most frequently recorded squid species, occurring in one third of the samples (but, by % of mass, it was only 3% of the diet). Moreover, the squid species *Illex argentinus* was registered by Berrow and Croxall (1999) in both 1996 and 1998, but was not recorded at all in the study realized before by Croxall *et al.* (1995). These results suggest that white-chinned petrels might have foraged more in these waters and on the Patagonian shelf (where *Illex argentinus* is known to occur).

The warmer waters species *Gonatus antarcticus*, *Taonius* sp. B (Voss) and *Illex argentinus* (the latter typically from the Patagonian shelf) were more abundant in 2004 than in 2002 (these species have the higher % of FO, N and M in 2004 than in 2002), confirming the inter-annual variation. Therefore, our diet data from white-chinned petrels

caught accidentally by fisheries around South Georgia from 2002 to 2004 suggest that the foraging ranges of this bird moved further north, into warmer waters in 2004, due to the fact that the prey consumed in 2004 are typically found in these warmer waters. However, more data is required, particularly from tracked animals with diet samples collected after foraging trips.

Our results suggests that white-chinned petrels from around South Georgia may vary their foraging effort between years and forage in Antarctic and sub-Antarctic waters, particularly in the Patagonian shelf waters, as demonstrated in tracking studies carried out by Berrow *et al.* (2000). White-chinned petrels breeding at South Georgia were found foraging from over a huge area from the waters of South Georgia and the South Orkney Islands to the Patagonian shelf. This widespread area exposes them to long-line fisheries. Breeding white-chinned petrels are amongst the widest foraging ranging of seabirds, thus minimizing competition with other Procellariiformes in the South Atlantic (Berrow *et al.* 2000).

In the current study the component of the diet of the white-chinned petrel constituted by fish was only visible for the year 2004 and not 2002, due to extremely high otolith erosion. The species of fish most frequent was *Champscephalus gunnari*, from the family Channichthyidae, accounting for more than half of the fish component of the diet and more than 95 % of mass. This last species, *Champscephalus gunnari*, has been the target species of the trawl fishery around South Georgia (Kock 1991) and is known to depend on krill and not copepods, amphipods or hyperiids (Kock *et al.* 1994, Berrow and Croxall 1999). The Myctophidae *Protomyctophum choriodon*, *Electrona calisbergi*, *Gymnoscopelus nicholsi* and *Electrona antarctica* were the most frequent fish species in the current study, contrasting with the study of Berrow and Croxall (1999), where the species *Lepidonotothen Larseni* and *Patagonotothen guntheri*, from the Notothenidae family, were more frequent. This last species of fish did not even occur in the current study.

Except for the species *Electrona calisbergi*, a species known to be found in warmer waters, north of the Antarctic Polar front (APF), which depends on copepods and hyperiids (Berrow and Croxall 1999), all the above species referred to as more frequent in the current study are dependent on krill. White-chinned petrels depend greatly on krill when they are breeding, and there are other components of prey, like some squid species (e.g. *Gonatus antarcticus*, *Martialia hyadesi* analyzed in South Georgia) and fish that also depend on krill (Berrow and Croxall 1999). Therefore, when white-chinned petrels are

feeding on *Illex argentinus*, they are foraging more in warmer northern waters (north of the APF, say for example to the Patagonian shelf) whereas when feeding on krill (or krill dependent squid and fish species), they are more distributed further south (south of the APF). As seen in the study by Collins and Rodhouse (2006), the squid fauna can be divided into species that are entirely Antarctic, like *Psychroteuthis glacialis* and *Alluroteuthis antarcticus* (the last species is not seen either of the years of the current study) and those that cover the APF. The species that cross the APF are either mobile migratory species that undertake feeding migrations (*Martialia hyadesi*, *Moroteuthis ingens*) or deepwater species to which the APF is not such a distinct barrier (*Chiroteuthis veranyi*) (Collins and Rodhouse 2006). These migrations are linked to the major current systems and the success of a generation influenced by oceanographic variability (O'Dor 1992, Anderson and Rodhouse 2001). The migrations of *Martialia hyadesi* are not fully understood, and this species occasionally appears on the eastern edge of the Patagonian shelf (Gonzalez *et al.*, 1997; Anderson and Rodhouse 2001) and has been taken at the APF (southwest Atlantic) and northwest of South Georgia. Xavier *et al.* (2003a,c) have shown inter-annual variability in the availability of *Martialia hyadesi* to predators, like the white-chinned petrel, at South Georgia, which may be a consequence of oceanographic variability influencing migration patterns.

In the current study, as shown previously, the squid *Champsoccephalus gunnari*, which depends preferably on krill (Kock 1991), is found in the waters north of the APF, in warmer waters. Probably the white-chinned petrels were found foraging further north also due to this fact.

4.2. Analysis of diving patterns of white-chinned petrels from South Georgia

The activity patterns showed that white chinned petrels can dive up to 14 metres deep, slightly more than previously thought (13 m depth recorded by Huin (1994)). The overall maximum depth average of the 13 birds in the current study was approximately 4 metres, so when comparing this study with that of Huin (1994), the maximum depth value has increased by 33%. The distribution of maximum depths of white-chinned petrels is similar to the range of depths measured for the light-mantled sooty albatross (Prince *et al.* 1994), which is the most similar species to white-chinned petrels in relation to body proportions (Pennycuick 1982; Pennycuick *et al.* 1984). Another comparison can be made with Wandering albatrosses, which according to Prince *et al.* (1994), rarely or never dive

at all. The maximum dive depths recorded by the TDRs state that grey-headed albatrosses dive to 3 metres deep and occasionally 6 metres (Huin and Prince 1997), and species like *Diomedea cauta*, the shy albatross, present in the waters of Tasmania, dives to at least 7 metres deep (Hedd *et al.* 1997); the maximum depths of both these studies are less than in the current study. On average, white-chinned petrels can dive 4 metres deep and the maximum depth registers at 14 metres, and the regularity of the dives is high, on average the number of dives during the various deployments was 39. The number of dives recorded (by TDR) showed that diving is common when foraging, just as seen in a study of diving behaviour of the grey-headed albatross by Huin and Prince (1997). Our data leads us to hypothesised that the amount of dives and diving depth by white-chinned petrels may be higher than that of other seabirds.

The average percentage of wetness registered overall was higher during the day than at night (67% and 33%, respectively), and the average percentage of dry periods overall was higher during the day than at night (56% and 44%, respectively). This could mean that white-chinned petrels prefer to keep dry during the night, meaning that probably they were less active during this period. Possibly, during the night this species rests or sleeps, on land, or are busy feeding the offspring (Warham 1996) or alternatively they may also rest or sleep on the surface of the water (Huin and Prince 1997). Other seabirds in the region like, for example, the grey-headed albatross (study by Huin and Prince in 1997) dived mostly during the day, suggesting that at night birds are mainly resting on the water. Despite an apparent preference to forage during the day, white-chinned petrels do also forage to a significant extent at night and therefore are considerably more versatile than albatrosses (particularly Black-browed albatross) in this respect. In fact, our study and that of Berrow and Croxall (1999) shows that White-chinned petrels seem to forage both by day and night (as seen also in Phillips *et al.* (2008)), and dive to greater depths and over larger areas than other seabird species in the region.

This study shows that the diving depths of the white-chinned petrel are influenced by prey availability (as shown by the inter-annual variations in the diet). As they are more active during the day than at night, this could be due to prey availability or to the fact that at night the visibility of the prey is slightly impaired. The white-chinned petrels could dive (in order to forage) at night due to the fact that many fish species come closer to the water surface during this period, as shown by the studies of Collins *et al.* (2008) and Collins *et al.* (2011). This is the reason why these seabirds can be related to the vertical

distribution of various species of fish, specifically from the family Myctophidae, that are abundantly found in the waters of South Georgia. The vertical distribution or migration, as seen in Collins *et al.* (2008) and Collins *et al.* (2011), explains why fish species during the day are at a certain depth and at night at another, generally during the day the fish would inhabit deeper waters than at night.

Also, there is a connection between the number of dives and the time that loggers are dry. In other words, birds that dive more are those that remain dry the longest period of time. This result suggests that birds that dived more frequently come out of the water immediately after the dive and stay dry longer. Moreover, our results also seem to indicate that the birds that spend more time out of water, may require diving more times in order to forage more efficiently.

4.3. Conservation of white-chinned petrels

The longline fisheries is the major problem, because, concerning other problems, like global warming (for example) and the rise of ocean temperature, white-chinned petrels probably are not as affected by that as other seabirds are. Due to their varied and versatile feeding methods, together with their greater diving ability, capacity to feed at night and extensive foraging range, white-chinned petrels can minimize the effects of the absence of food resources, like krill shortage, that could be caused by the warming of the ocean waters. Despite Atkinson *et al.* (2004) showing that it is probably the existence of sufficient quantities of krill throughout the year in the Southwest Atlantic, Parkinson (2002) adds that this region of the globe is one of the fastest warming regions and that krill inhabits regions that are very sensitive to environmental changes.

Several analyses have addressed fisheries overlap for single species during the breeding season (Nel *et al.* 2000; Nel *et al.* 2002; Anderson *et al.* 2003; Xavier *et al.* 2004). Unlike most albatrosses, white-chinned petrels feed during both darkness and daylight, compete aggressively for bait, and have the unfortunate distinction of the highest incidental mortality rates of any seabird in most Southern Ocean fisheries (Cherel *et al.* 1996). Previous tracking studies highlighted a high degree of overlap with South American fisheries (on both Atlantic and Pacific coasts) (Phillips *et al.* 2008).

The majority of fatal interactions occur when white-chinned petrels scavenge discards or fisheries offal, but are also attracted by baits from longliners, and can become hooked or entangled in the gear and drown (Catard and Weimerskirch 1999). Evidence

from demersal longline fisheries indicates that increasing the sink rate of baited hooks substantially reduces seabird mortality (Agnew *et al.* 2000; Robertson *et al.* 2006). Longlines with integrated weight (IW) sink faster than normal, unweighted (UW) longlines, and have the potential to reduce the numbers of these species killed, as seen in the study by Robertson *et al.* (2006) for 2002 and 2003, which compared the UW lines with IW lines, obtaining a reduced mortality of white-chinned petrels by 98.7% and 93.5%, respectively.

Under CCAMLR (Commission for the Conservation of Antarctic Marine Life Resources) regulations, longline fishing vessels in the Antarctic must sink longlines at more than 0.3 m/s to 10 m depth to minimise seabird mortality (Robertson *et al.* 2006) but elsewhere is according to national regulations. As white-chinned petrels, can dive 4 metres deep and the maximum depth registers at 14 metres and the regularity of the dives is high, they might still be likely to be affected. These results reinforce the need of the implementation of integrated weight in longlines, which will enable the longlines to sink faster (Robertson *et al.* 2006) in order to potentially reduce the numbers of white-chinned petrels being killed.

Overall capture rates of seabirds have gradually declined in many areas with introduction of better observer coverage and improved mitigation, and around South Georgia has been virtually eliminated by effective implementation of mitigation measures and restriction of longline fishing to the winter period (Klaer and Polacheck 1997; Nel *et al.* 2002c; Croxall and Nicol 2004; Phillips *et al.* 2006). However, mitigation includes restriction of line setting to hours of darkness, which is less effective for white-chinned petrels that are active by both night and day (Murray *et al.* 1993; Weimerskirch *et al.* 2000; Nel *et al.* 2002c). As white-chinned petrels are very active during the day and the night, during both these periods they forage for food, because of this it is very important to take note of this unique characteristic and try to find and develop measures of precaution and conservation also for the night periods.

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APPENDICES

Appendix

Appendix 1: Squid diet of 2002. Frequency of occurrence (FO), Number of individuals (N), Mass (M), percentage of mass (M), Lower Rostral length (LRL), Mantle length (ML) and upper beaks (N).

Species	2002						
	FO (%)	N (%)	M (g)	M (%)	LRL (mm)	ML (mm)	N (upper beaks)
<i>Ancistrocheirus lesueuri</i>	5	0.4	1043	7.1	4.7 (3-6)	151 (81-203)	12
<i>Batoteuthis skolops</i>	5	0.4	33	0.2	4 (4-4)	109 (109-109)	0
<i>Brachioteuthis linkovskyi</i>	5	0.4	13	0.1	4.1 (4.1-4.1)	99 (99-99)	0
<i>Chroteuthis veranyi</i>	5	0.4	35	0.2	4.1 (4.1-4.1)	112 (112-112)	14
<i>Galiteuthis glacialis</i>	35	12.2	1372	9.3	4.4 (2.8-5.7)	191 (135-245)	12
<i>Gonatus antarcticus</i>	45	5.5	1949	13.2	5.2 (3.2-8)	180 (94-300)	6
<i>Histioteuthis atlantica</i>	5	0.8	286	1.9	4.3 (4.2-4.4)	82 (80-84)	
<i>Histioteuthis eltaninae</i>	35	6.3	1160	7.8	3.6 (1.9-8.9)	65 (29-184)	1
<i>Illex argentinus</i>	0	0.0	0	0	-	-	1
<i>Kondakovia longimana</i>	0	0.0	0	0	-	-	0
<i>Martialia hyadesi</i>	65	21.5	3849	26.0	3.6 (2-6.7)	200 (153-290)	0
<i>Mastigoteuthis A</i>	0	0.0	0	0.0	-	-	0
<i>Mastigoteuthis psychrophila</i>	5	0.4	65	0.4	4 (4-4)	118 (118-118)	
<i>Mesonychoteuthis hamiltoni</i>	0	0.0	0	0	-	-	0
<i>Moroteuthis ingens</i>	0	0.0	0	0	-	-	0
<i>Moroteuthis knipovitchi</i>	30	3.4	3372	22.8	6.2 (5.9-6.5)	286 (253-316)	0
<i>Psychroteuthis glacialis</i>	20	2.1	198	1.3	3.7 (3.1-4.4)	127 (103-161)	4
<i>Slosarszikovia circumantarctica</i>	25	8.7	130	0.9	2.8 (2-3.9)	73 (57-95)	0

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Taonius sp. B (Voss)	35	4.2	1287	8.7	6.7 (5.8-7.7)	399 (344-461)	30
Unknown	85						

Appendix 2: Squid diet of 2004, Frequency of occurrence (FO), Number of individuals (N), Mass (M), percentage of mass (M), Lower Rostral length (LRL), Mantle length (ML) and upper beaks (N).

Species	2004						
	FO (%)	N (%)	M (g)	M (%)	LRL (mm)	ML (mm)	N (upper beaks)
<i>Ancistrocheirus lesueuri</i>	0	0	720	3.1	3.8 (3.4-4.5)	115 (97-142)	12
<i>Batoteuthis skolops</i>	3	0.2	23	0.1	3.5 (3.5-3.5)	97 (97-97)	0
<i>Brachioteuthis linkovskyi</i>	0	0	0	0.0	-	-	0
<i>Chiroteuthis veranyi</i>	13	1.1	266	1.2	5.0 (3.4-6)	134 (95-158)	14
<i>Galiteuthis glacialis</i>	24	2.6	954	4.1	4.9 (4.1-5.5)	212 (179-236)	12
<i>Gonatus antarcticus</i>	79	13.4	8542	36.9	5.7 (4-7.5)	203 (128-278)	6
<i>Histioteuthis atlantica</i>	0	0	0	0.0	-	-	0
<i>Histioteuthis eltaninae</i>	29	3.9	1243	5.4	3.3 (2.7-3.9)	59 (46-73)	1
<i>Illex argentinus</i>	24	5.4	2335	10.1	3.9 (2.5-4.8)	219 (196-234)	1
<i>Kondakovia longimana</i>	5.3	0.4	16	0.1	5 (5-5)	156 (156-156)	0
<i>Martialia hyadesi</i>	13	4.7	487	2.1	4 (3.9-4.1)	210 (207-213)	0
<i>Mastigoteuthis A</i>	3	0.2	128	0.6	6.6 (6.6-6.6)	173 (173-173)	0
<i>Mastigoteuthis psychrophila</i>	0	0	0	0.0			
<i>Mesonychoteuthis hamiltoni</i>	3	0.2	17	0.1	4.9 (4.9-4.9)	289 (289-289)	0
<i>Moroteuthis ingens</i>	3	0.4	530	2.3	4.8 (3.7-5.8)	132 (21-242)	0
<i>Moroteuthis knipovitchi</i>	11	1.1	2398	10.4	5.7 (3.5-6.6)	232 (0.2-327)	0
<i>Psychroteuthis glacialis</i>	24	2.4	440	1.9	4.4 (3.5-5.4)	161 (121-206)	4

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<i>Slosarszikovia circumantartica</i>	24	7.11 21	210	0.9	2.5 (1.7-3.6)	67 (51-89)	0
<i>Taonius</i> sp. B (Voss)	47	6.9	4810	20.8	7.4 (5.4-9.7)	442 (319-584)	30
Unknown	84						