

## IDENTIFYING AREAS, SEASONS AND FLEETS OF POTENTIAL HIGHEST BYCATCH RISK TO SOUTH GEORGIA ALBATROSSES AND PETRELS

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### SUMMARY

*This paper presents an analysis of tracking data for 4 procellariiform seabirds from South Georgia, and calculates overlap with pelagic longline fisheries in the Southern Ocean for the period 1990-2009. We used an unusually comprehensive tracking dataset from all major life-history stages (including juvenile stages), weighted according to the proportion of the population they represented (based on demographic models), in order to generate population-level distributions by month. This analysis confirms that the IOTC area is important for grey-headed and wandering albatrosses, and to a lesser extent black-browed albatrosses, with hotspots of overlap with fisheries in the southwest Indian Ocean, between the Prince Edward Islands and South Africa, and in the southeast Indian Ocean. Overlaps were particularly high with fleets from Japan and Chinese Taipei, and to a lesser extent South Korea and Spain, and highest during winter months (May–September; when fishing effort south of 30°S is greatest). The areas identified here largely match areas where high rates of bycatch have been recorded, emphasizing the need for use of bycatch mitigation measures.*

**KEYWORDS:** *seabird, pelagic longline, population structure, by catch, fishery regulations, international waters, Diomedea exulans, Procellaria aequinoctialis, Thalassarche chrysostoma, Thalassarche melanophris*

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## 1. Introduction

Incidental mortality (bycatch) in fisheries is one of the primary causes of seabird population declines (Lewison et al. 2004, 2014, Phillips et al. 2016). Albatrosses and petrels are particularly vulnerable as they are long-lived, have high adult survival, delayed sexual maturity and low reproductive rates; as such, even small increases in adult mortality can greatly impact population trajectories (Croxall & Rothery 1991, Delord et al. 2008, Croxall et al. 2012). For many albatross species, their circumpolar distribution brings them into contact with a wide range of pelagic longline fisheries managed by Regional Fisheries Management Organisations (RFMOs), particularly fleets operating under the jurisdictions of the five tuna RFMOs (Western and Central Pacific Fisheries Commission [WCPFC], Commission for the Conservation of Southern Bluefin Tuna [CCSBT], International Commission for the Conservation of Atlantic Tunas [ICCAT], Indian Ocean Tuna Commission [IOTC] and Inter-American Tropical Tuna Commission [IATTC]) and the Commission for the Conservation of Antarctic Marine Living Resources [CCAMLR] (BirdLife 2004).

South Georgia in the southwest Atlantic Ocean is a globally important breeding site for grey-headed (*Thalassarche chrysostoma*), black-browed (*Thalassarche melanophris*) and wandering (*Diomedea exulans*) albatrosses, and white-chinned petrels (*Procellaria aequinoctialis*) supporting from 12-50+ percent of the global populations. These species have undergone major declines in population size, and in adult and juvenile survival (where data are available) since the 1990s; bycatch in longline vessels is suspected to be a critical factor, confirmed by direct observations on vessels (Weimerskirch & Jouventin 1987, Croxall & Prince 1990, Brothers 1991, Prince et al. 1994). The adoption of bycatch mitigation measures in demersal longline and trawl fisheries within waters close to South Georgia has resulted in substantial reductions in seabird bycatch over the last 20 years (Croxall 2008); however the South Georgia albatross populations continue to decline (Poncet et al. 2017). As a result, grey-headed albatross is listed as Endangered, and wandering albatross and white-chinned petrel as Vulnerable on the IUCN Red List (Phillips et al. 2016). The South Georgia populations of wandering, grey-headed and black-browed albatrosses are three of only eight breeding populations, globally, that are considered of the highest priority for conservation by the Agreement on the Conservation of Albatrosses and Petrels (ACAP; [www.acap.aq](http://www.acap.aq)).

The purpose of this paper is to identify areas of greatest overlap between pelagic longline fisheries in the Southern Ocean and four procellariiform species from South Georgia, all of which have been recorded as bycatch: black-browed, grey-headed and wandering albatrosses, and white-chinned petrels. We mapped the bird distributions using tracking data collected over a 25-year period, including from juvenile and immature birds. We aimed to fill in gaps in the knowledge of at-sea distributions and provide a holistic, population-level assessment of fisheries overlap, and, by inference, potential bycatch risk. More specifically, we identify 1) regions and fleets with greatest overlap 2) temporal (year and month) variation in overlap, and 3) variation in overlap between life-history stages.

## 2. Methods

### 2.1. Study site and tracking data

Demographic and tracking data were obtained from long-term individual-based monitoring studies at Bird Island, South Georgia in the southwest Atlantic Ocean (54°00'S, 38°03'W). Colonies of black-browed and grey-headed albatrosses, and all wandering albatrosses on the island are monitored intensively on a daily to weekly basis, providing information on survival, return and breeding probability and breeding success (Croxall et al. 1990). Demographic data were not available for white-chinned petrels, which are burrow-nesting and hence less tractable for this type of study.

Tracking data were collected from 1990 to 2015 using a range of devices: satellite transmitters, GPS loggers and geolocators (see Table 1 for sample sizes). Satellite transmitters (or platform terminal transmitters; PTTs) were deployed on breeding adults and juveniles, GPS loggers on breeding adults, and geolocators on non-breeding adults, immatures and juveniles. Details on deployment and retrieval of devices are, for the most part, already published (see e.g. Phillips et al. 2006, Clay et al. 2016, Jiménez et al. 2016, Tancell et al. 2016). We used all locations from PTTs (classes A, B, 0, 1 to 3), but, in order to filter unrealistic positions, we removed those that required an estimated flight speed above 90 km/h, based on an iterative forward/backward averaging filter (McConnell et al. 1992). Light data from geolocators were processed using MultiTrace Geolocation (Jensen Software Systems) or BASTrak software (British Antarctic Survey, Cambridge, UK), providing two positions per day with a mean error  $186 \pm 114$  km (Phillips et al. 2004). We excluded locations with interruptions around sunrise and sunset, and periods for 3-4 weeks around the equinoxes, when latitude cannot be estimated reliably. For each

individual, the non-breeding period was defined as the time from the start of outward migration to return to the breeding grounds, and was derived from locations and from saltwater immersion recorded by the geolocators. PTT and GPS data were interpolated at hourly intervals to obtain regular positions. GLS data were not interpolated as locations are already available at regular, approximately 12-hour, intervals.

In order to determine whether our tracking samples were sufficient to represent the home range of each population, a resampling procedure was used that involved assessment of the relationships between sample size and home range area. For each species and breeding stage, we calculated the home range area for an increasing number of individuals, selected at random 100 times, without replacement (Hindell et al. 2003, Soanes et al. 2013). We fitted a non-linear model to the resampled data and determined at which sample size the area occupied by the population reached an asymptote (Lascelles et al. 2016). This facilitated a gap analysis, which assessed whether sample sizes were sufficient to represent variability in movement strategies between individuals (see Table 2).

Tracking data were split into a unique combination of species-breeding stage-device type. Utilization distributions (UDs) were created for each combination using kernel analysis in the *adehabitatHR* package (Calenge 2006). To control for differences in the number of trips or years of tracking per individual, UD were generated for each bird and then merged so that each individual had equal representation in our larger sample (Clay et al. 2016). A fixed smoothing parameter ( $h$ ) of 50 km or 200 km was used for PTT and GPS data, and for GLS data, respectively, and a grid cell size of 10 km was used for all device types to enable averaging across grids. Interpolated hourly PTT and GPS data from the same species and breeding stage were pooled before kernel analysis. If PTT and geolocator data were available for the same breeding stage, distribution grids were weighted according to sample size before merging the two datasets.

## 2.2. Weightings of distributions by age class and status

Demographic estimates of survival, recruitment, return, breeding and success probabilities were obtained annually for juvenile, immature and adult birds using a multi-event capture-mark-recapture model (Fig. 1) (Lebreton et al. 2009, Pardo et al. In review). These values were fed into an age and stage-structured matrix population model using a pre-breeding census (Caswell 2001) based on a life cycle with six age-classes (based on a minimum age at recruitment of 6 years) and four adult stages (Fig. 1) (Pardo et al. In review). The expected proportion of the population in each stage or age-class was then calculated for each year (Fig. 1). For parsimony, age- or stage-classes with similar foraging distributions were pooled (detailed below), resulting in six life-history stages: juveniles in their first year at sea (post-fledging, J1), juveniles in their second or third year (J2+J3), immatures (IMM), successful breeders (SB), failed breeders (FB) and adult non-breeders (NB). White-chinned petrels are not routinely monitored and so the age and stage structure for this species was based on the values for black-browed albatrosses, given their similar life-histories (long-delayed maturity, single-egg clutch, annual breeding).

After fledging, juvenile albatrosses spend on average 5-6 years at sea before returning to the colony for the first time, after which they typically attend as immatures for increasing periods each year before eventually recruiting into the breeding population (Pickering 1989, Tickell 2000). During their first year at-sea, juvenile albatrosses have more dispersed distributions than in subsequent years (BAS unpublished data), which is why we considered the first year (J1) separate from the following two years at sea (J2+J3). For species where we had no distribution data for juveniles (in particular for J2+J3) or immatures, we substituted the winter distribution of adult non-breeders, when they are further north, away from the colony (Clay et al. 2016), which is likely to be similar to the distribution of juveniles (Weimerskirch et al. 2006). For immatures (IMM, pooling the immatures and pre-breeding classes used in the demographic modelling), the annual distribution of sabbatical (deferring) breeders was used for all species except wandering albatrosses, because individuals attend the colony during the breeding season but migrate to non-breeding areas a few months before breeding birds (Pickering 1989). Adults were split into 3 status classes: successful breeders (SB), failed breeders (FB) and non-breeders (NB, pooling the observable and non-observable non-breeder classes used in the demographic modelling). The breeding season of white-chinned petrels, black-browed albatrosses and grey-headed albatrosses lasts 6, 7 and 8 months, respectively, and so the annual distribution of all adult stages (SB, FB and NB) included breeding and non-breeding periods. In contrast, the breeding season of wandering albatrosses lasts the whole year and so the annual distribution of adult classes was based either on tracking data during the breeding season (SB) or non-breeding season (NB) or a combination thereof (FB).

Monthly distribution grids were created for each life-history stage, accounting for the breeding and migration schedules of each species, i.e., the grid for each class was weighted by the number of days that month which was represented. Distributions during incubation and brood were weighted by 0.5 as one member of each pair is at the

breeding colony at any one time. Separate distributions were used for each sex, for species and stages where sex differences have been found: adult wandering albatrosses (during both breeding and non-breeding; Prince et al. 1992, BAS unpublished data), and black-browed and grey-headed albatrosses (during breeding; Phillips et al. 2004). Sex differences in migration schedules and colony attendance were also taken into account (Tickell 1968, Tickell & Pinder 1975, Phillips et al. 2005, Clay et al. 2016). The monthly distribution grids for each life-history stage were multiplied by the proportion of the population in each of those stages from the outputs of the demographic modelling, averaged over 5-year periods (1990-1994, 1995-1999, 2000-2004, 2005-2009) and over the whole study duration (1990-2009), and summed to create monthly distributions grids for the whole population. Distribution grids were then resampled to a 5 x 5 degree resolution for overlaying onto fishing effort data. Given the patchy temporal extent of the tracking data, it was assumed that the bird distributions did not change over the study period.

### **2.3. Fishing effort data**

Fishing effort data were collated for all tuna RFMOs. Data on pelagic longline effort (numbers of hooks deployed) in 5 x 5° spatial grids were obtained in the Atlantic Ocean from the International Commission for the Conservation of Atlantic Tunas (ICCAT) Secretariat via a database of fishing effort and catches distributed by time-area strata (EFFDIS). ICCAT data are collected in two main groups: “Task 1” and “Task 2”. Task 1 data represent annual catch totals and are considered to be comprehensive, while Task 2 data have greater spatial (5 x 5°) and temporal (monthly) resolution but are only partially complete. Through the EFFDIS approach, ICCAT have improved their estimates of effort by raising observed effort by a scaling factor corresponding to the relationship between the Task 2 and Task 1 data (Beare 2015). Effort data were also obtained from the IATTC (some contributing countries raise the data, while others submit unraised effort data) and WCPFC via their website, and from the IOTC. We did not consider effort data from the CCSBT, as these data are also reported to the other four tuna RFMOs (CCSBT, pers. comm.). Fleet-specific information was available for all RFMOs except the WCPFC; as a result, this region was ignored in analyses of fleet-specific overlap (below). Fishing effort data were averaged over 5-year periods (1990-1994, 1995-1999, 2000-2004 and 2005-2009) and over the whole study duration (1990-2009), for each month and 5 x 5° cell.

### **2.4. Overlap analyses**

We calculated spatial overlap between birds and fisheries by multiplying the number of hooks by the proportion of the population of each species predicted in each grid square, for each month (Cuthbert et al. 2005, Jiménez et al. 2016). Overlap was calculated for each 5-year period and over the whole study period for the albatrosses, but only for the latter for white-chinned petrels, given the lack of reliable demographic information. For comparisons involving the whole population, life-history stages were multiplied by their respective proportions and summed, and for comparisons of overlap between life-history stages, unweighted values were used.

## **3. Results**

### **3.1. Seabird distributions**

A total of 1,144 trips were available for 530 breeding individuals of the four species, including 168, 303 and 690 trips from 164, 223 and 193 individuals during incubation, brood-guard and post-brood chick-rearing, respectively (Table 1). A total of 251 tracks were obtained from 187 non-breeding adults of all species. Tracking data were available from immatures only for the wandering albatrosses (239 tracks from 70 individuals). Additionally, 47 individuals of all four species were tracked as juveniles during their first year at sea (post-fledging). The gap analysis revealed that our tracking samples were sufficient to represent the home ranges of adult birds, except for breeding white-chinned petrels. In contrast, sample sizes for juveniles and immatures were sufficient only for wandering albatrosses (Table 2).

Distributions for the entire population were mapped for each species (Fig. 3a). Black-browed albatrosses predominantly used the South Atlantic Ocean throughout the year, particularly the region around South Georgia and the Benguela Upwelling. During the early breeding season (October – January), the population was largely centred around South Georgia (Fig A1). During the second half of the breeding season (February – May), many individuals were in the Benguela Upwelling (Fig. A1); these include failed and deferring breeders, which leave the colony earlier than successful breeders (Phillips et al. 2005). During the non-breeding winter, birds were

concentrated west of South Africa and Namibia, and to a lesser extent off the coasts of Tasmania and southern Brazil. Sabbatical non-breeders and failed breeders represent a large proportion of the total population (Table 3, Fig. 2), and hence have a major influence on the distribution of the population as a whole (Fig. 3a).

Grey-headed albatrosses were distributed predominantly in the southwest Atlantic, to some degree also in the southwest Indian Ocean, and to a lesser extent in the southeast Atlantic, Indian and Pacific oceans (Fig. 3b). There was substantial monthly variation in total population distribution, with greater use of the Atlantic during summer (October – May), and a more dispersed and northerly distribution, with greater use of the Pacific and Indian Oceans, in winter (June – September) (Fig. A2, also see Clay et al. 2016).

Throughout the year, wandering albatrosses were distributed predominantly around South Georgia and to a lesser extent on the Patagonian Shelf and in the Humboldt Upwelling region, while in winter months, non-breeding birds visited the Chatham Rise east of New Zealand, and the southwest Indian Ocean (Fig. 3c; Fig. A3). Finally, white-chinned petrels used the Patagonian Shelf region up to the Brazil-Falklands Confluence and the Humboldt Upwelling (Fig. 3d, Fig. A4).

### **3.2. Distribution of fishing effort**

Maps of pelagic longline effort across the entire southern hemisphere highlight that fishing effort has been greatest in equatorial waters, particularly in the Pacific and Indian oceans (Fig. 5). However, within subtropical waters, there is a band of high effort around 30-40°S associated with the fishery for southern bluefin tuna *Thunnus maccoyii*, and other tunas including albacore *T. alalunga* and bigeye *T. obesus* (Michael et al. 2015, Katsumata et al. 2016). Between 1990 and 2004, this effort was concentrated longitudinally off the coast of Uruguay and southern Brazil, off the coast of southern Africa, in the central South Indian Ocean and in the Tasman Sea. Pelagic longline effort appears to have decreased in the southwest Atlantic Ocean and the Tasman Sea in the latter part of the 2000s but increased off southern Africa (Fig. 5).

The magnitude of fishing effort within the distributions of all three albatross species was similar, peaking at around 300 million hooks set per year in the early 1990s and early 2000s (Fig. 4). Generally, longline fishing effort increased fairly linearly from the 1950s until a peak in the late 1990s, before declining to 1980s levels by the end of the study period (2009). The total fishing effort within the range of white-chinned petrels was much lower, likely due to their restricted spatial distribution, peaking at around 60 million hooks in the early 1990s. For all three species of albatrosses, a high proportion of fishing effort within their ranges was by the fleets of Chinese Taipei and Japan (Fig. 4, Fig. 10).

### **3.3. Overlap with pelagic longline fishing data**

#### **3.3.1. Spatial distribution**

Black-browed albatrosses had the highest overlap scores, followed by wandering albatrosses, white-chinned petrels, and lastly grey-headed albatrosses (Fig. 8). Hotspots of spatial overlap between black-browed albatrosses and pelagic longline fisheries were in the southeast Atlantic Ocean off the coast of Namibia and South Africa, off the coast of Uruguay and to a lesser extent, in the southeast Indian Ocean (Fig. 6). Grey-headed and wandering albatrosses overlapped with longline effort throughout the northern parts of their distributions and in similar regions to one another. Areas of highest overlap were in the southwest Atlantic Ocean in the Argentine Basin (particularly for wandering albatrosses), in the southwest Indian Ocean north and northwest of the Prince Edward Islands, and in the southeast Atlantic (particularly for grey-headed albatrosses). Wandering albatrosses also had moderate to high overlap in the Tasman Sea and off the northern tip of New Zealand. White-chinned petrels overlapped greatly with longline vessels off the coast of southern Brazil and Uruguay, and to a lesser extent off the coast of Chile.

#### **3.3.2. Temporal distribution**

For all species, overlap was highest in mid-winter (May – August) and lowest in mid-summer (October – January) (Fig 7). For all species, overlap was highest during the 1990s and declined in the 2000s due to a reduction in total effort, such that the lowest overlap was for the 2005-2009 period.

### 3.3.3 Within-population differences

We investigated differences in spatial overlap between life history stages (Fig. 8, 9). For all species, first-year juveniles had highest overlap scores, followed by second- and third-year juveniles with successful adults exhibiting lowest overlap with pelagic longline effort. Overlap for juvenile black-browed and grey-headed albatrosses was highest in the months just after fledging, when birds dispersed north- and north-eastwards to areas with high fishing effort. As PTT failure precluded more than a few months of tracking, it is likely that overlap would be higher in July – September than when using substituted data, as juveniles are likely to have a more northerly distribution with greater overlap with fishing fleets than non-breeding adults. In contrast, wandering albatrosses fledge in the summer when effort is low, and overlap was highest during their first winter. For all life history stages, overlap was highest in May – August and lowest in October – February.

### 3.3.4. Contribution of regional fisheries management organizations (RFMOs) and major fleets to overlap scores

The fleets of Japan and Chinese Taipei overlapped most with all species (Fig. 10). For black-browed albatrosses, the Japan fleet had the highest overlap, although this has reduced linearly over time since the early 1990s. In contrast, the Spanish, Namibian and South African longline fleets expanded in the 2000s, which led to higher overlap with black-browed albatrosses (Fig. 11). For grey-headed and wandering albatrosses, the greatest overlap was with the Chinese Taipei fleet, followed by Japan and South Korea, with the latter overlapping greatly with grey-headed albatrosses in the late 1990s (Fig. 11). For wandering albatrosses, the contribution of major fleets remained fairly consistent over the study period (Fig. 11). For white-chinned petrels, the greatest overlap was with fleets from Chinese Taipei, Other (likely Uruguay) and Brazil (Fig. 11). Brazilian and Uruguayan fleets also overlapped to a lesser extent with wandering albatrosses (Jiménez et al. 2016).

Overlap was highest in the IOTC region for wandering and grey-headed albatrosses, and to a lesser extent black-browed albatrosses (Fig. 12). Overlap was greatest for black-browed albatrosses and white-chinned petrels within the ICCAT region, where overlap was also high for grey-headed and wandering albatrosses (Fig. 12). For black-browed albatrosses, there has been a reduction in the contribution of Chinese Taipei within ICCAT, but overlap within the IOTC region has remained constant (Fig. 13). For grey-headed and wandering albatrosses overlap was higher within the ICCAT region in the 1990s, but overlap in the IOTC region has increased for these species since the late 1990s (Fig. 13). Overlap in the other two RFMO regions was much smaller than ICCAT and the IOTC, but white-chinned petrels overlapped with the Chilean longline fleet (Other) within the IATTC region and wandering albatrosses with unspecified fleets in the WCPFC region (Fig. 12). Although for all regions and species, overlap was greatest during winter months, there was noticeable seasonal variation between regions, likely due to changes in effort and the movements of birds between ocean basins. For example, overlap within the ICCAT region was generally high all winter (Mar – September), but overlap within the IOTC region appeared to be greatest in late-winter (June – September) (Fig. 14).

## 4. Discussion

The major findings of this paper are that overlap between pelagic longline fishing effort and the distributions of declining albatross and petrel species from South Georgia is dominated by the fishing effort of Japan and Chinese Taipei, and to a lesser extent of South Korea, Namibia and South Africa. Highest overlap between seabirds from South Georgia and pelagic longline fisheries occurs during winter months (May-September; when fishing effort below 30°S is highest) and in the southwest and southeast Atlantic and southwest Indian oceans, and also in some areas of the south Pacific Ocean.

### 4.1. Links between overlap with longline fisheries and bycatch

The areas of high spatial overlap of seabirds with longline effort generally accord with regions of reported bycatch of these species, both in the IOTC region and within the jurisdiction of other RFMOs. We found high overlap of wandering albatrosses, grey-headed albatrosses, and to a lesser extent black-browed albatrosses, with fishing effort in the southeast Indian Ocean (IOTC). These areas correspond to regions where seabird bycatch of these species has been recorded, particularly by the fleet of Japan (Inoue et al. 2011), but also wandering albatrosses have been caught by the fleet of Chinese Taipei (Huang and Liu 2010). A large proportion of the global population of wandering albatrosses, and to a lesser extent, grey-headed albatrosses breed in the Indian Ocean at the Prince Edward, Crozet and Kerguelen archipelagos. Bycatch in these regions is probably likely to be of birds from these populations (Delord et al. 2008, Rolland et al. 2010, Tuck et al. 2015) given that breeding and non-breeding birds

use the area extensively, year-round (e.g. Nel et al. 2001, Wakefield et al. 2011, Weimerskirch et al. 2013, 2015, Clay et al. 2016).

In contrast, outside the jurisdiction of the IOTC, the Atlantic Ocean (ICCAT region) is important for all SG populations in this study, and is used much less frequently by other major populations of these four species (e.g. Weimerskirch et al. 2015, Clay et al. 2016), except black-browed albatrosses from the Falkland Islands (Grémillet et al. 2000). We found particularly high overlap of wandering albatrosses and white-chinned petrels with fisheries in the Brazil-Falklands conference off Brazil and Uruguay region. High bycatch of several species, including wandering albatrosses, black-browed albatrosses and white-chinned petrels, has been reported by observers on board pelagic longline vessels from Uruguay (Jiménez et al. 2009, 2010), and from Japanese vessels that were operating for several years under license in Uruguayan waters (Jiménez et al. 2014), and also from Brazilian longline vessels (Bugoni et al. 2008). Uruguayan effort is very small in comparison to that of Chinese Taipei and Japan in adjacent waters, and it seems likely that bycatch would also be high for those other fleets, particularly given the high seabird bycatch rates reported from the Japanese distant-water fleet in several areas of the Southern Ocean (Inoue et al. 2011). Similarly, while no wandering albatrosses were reported by Chinese Taipei vessels in the southwest sector (Yeh et al. 2012), this is likely to reflect the small percentage (c. 1%) of fishing effort that was observed (Phillips 2013, Jiménez et al. 2016).

We identified another hotspot of overlap between birds and pelagic longline fishing effort in the southeast Atlantic Ocean, particularly in a region of high bycatch (particularly of grey-headed albatrosses but also black-browed albatrosses) by vessels of Japan and Chinese Taipei in the southeast Atlantic (Inoue et al. 2012, Yeh et al. 2012). Indeed, a recent report has highlighted high bycatch rates of grey-headed albatrosses, particularly over the last decade, from the Japanese fleet (Katsumata et al. 2016). Further north, we document high overlap between black-browed albatrosses and longline effort off the coast of South Africa and Namibia (Petersen et al. 2008). Previous studies recorded high bycatch of seabirds in that region, including black-browed albatrosses, shy albatrosses *Thalassarche cauta* and white-capped albatrosses *T. steadi* and white-chinned petrels (Ryan et al. 2002, Petersen et al. 2009). However, bycatch rates have been reduced in some of the fleets, particularly the South African demersal trawl fishery, and the South African foreign charter fleet (Ryan et al. 2002, Maree et al. 2014, Rollinson et al. 2016). Also wandering albatrosses overlap with pelagic longline fisheries in the Tasman Sea and in a region of southwest Pacific northeast of New Zealand (WCPFC), where bycatch of this species is reported by the fleets of Japan and Chinese Taipei (Huang & Yeh 2011, Inoue et al. 2012). In this analysis, we only considered fishing effort legally reported to the major tuna commissions, and estimates of illegal, unreported and unregulated (IUU) fishing effort within the areas of jurisdiction of each RFMO are unavailable. Although a study concluded that the scale of IUU effort was much lower in pelagic than demersal longline fisheries (Agnew et al. 2009), it could still represent a major problem for seabirds, as IUU vessels are very unlikely to use any bycatch mitigation.

#### ***4.2. Within-population differences in overlap with longline fisheries***

For all species, there were differences in overlap with pelagic longline fisheries between life-history stages. Juveniles in their first year at sea (post-fledging) showed the greatest overlap with fishing effort, due to their more northerly distribution. However, juveniles represent a small proportion of the total population. For all species assessed, the total population distribution was dominated by adult non-breeders and immature birds; for which our understanding of their distributions is much poorer than for breeding adults (Phillips et al. 2008). Failed and successful breeding adults overlapped least of any life-history stage with pelagic longline fishing effort, due to their more southerly distribution in the vicinity of South Georgia (Phillips et al. 2004, 2006, 2008).

#### ***4.3. Recommendations***

It appears that pelagic longline effort within the distribution of these threatened bird populations has declined over the last decade or so; however, there is still high overlap with fisheries in many areas, and continued population declines suggests that mitigation measures are not being fully implemented, presumably reflecting the small proportion of vessels in most fleets on which compliance is being monitored. Additionally, our gap analysis revealed that more tracking data is required for juvenile and immature stages, particularly for black-browed and grey-headed albatrosses, as initial results have revealed high overlap with fisheries in their first few months at sea.

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**Tables****Table 1.** Sample sizes for tracking data by species, stage and sex.

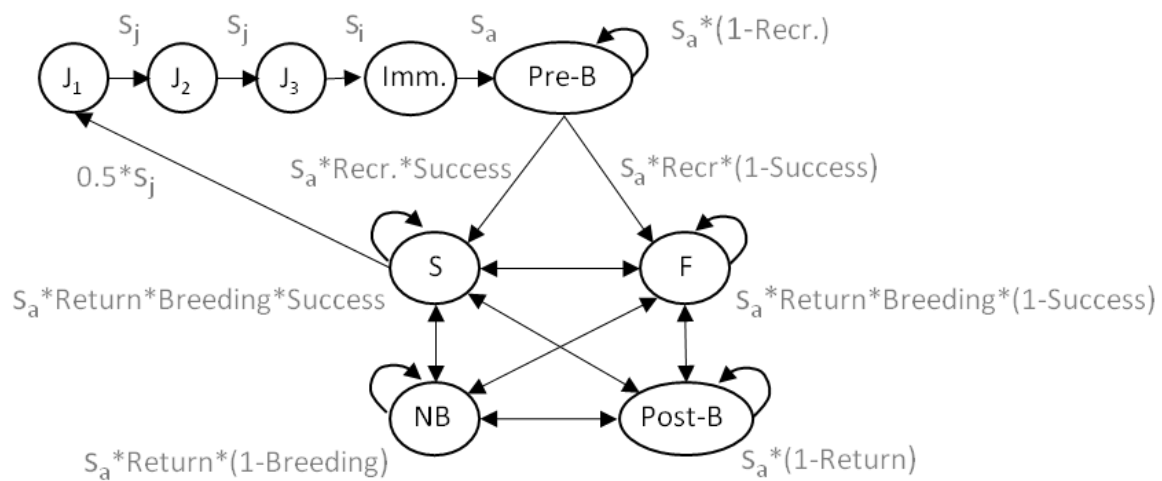
Species	Sex	Incubation	Brood	Post-brood	Non-breeding	Immatures	Juveniles
		N individuals (N tracks)	N individuals (N tracks)	N individuals (N tracks)	N individuals (N tracks)	N individuals (N tracks)	N individuals (N tracks)
WA	Both	63 (67)	80 (95)	137 (227)	111 (151)	70 (239)	27 (27)
	M	34 (36)	45 (48)	74 (121)	62 (89)	-	-
	F	29 (31)	35 (47)	63 (106)	49 (62)	-	-
BBA	Both	61 (61)	78 (120)	20 (269)	25 (49)	-	7 (7)
	M	28 (28)	47 (74)	13 (151)	-	-	-
	F	33 (33)	31 (46)	7 (118)	-	-	-
GHA	Both	25 (25)	63 (86)	20 (158)	41 (41)	-	5 (5)
	M	15 (15)	31 (45)	9 (85)	-	-	-
	F	10 (10)	32 (41)	11 (73)	-	-	-
WCP	Both	15 (15)	2 (2)	6 (19)	10 (10)	-	8 (8)

**Table 2.** Gap analysis for each demographic class showing where there are sufficient, insufficient and no data. Where there were no tracking data, appropriate data substitutions were used (see Methods).

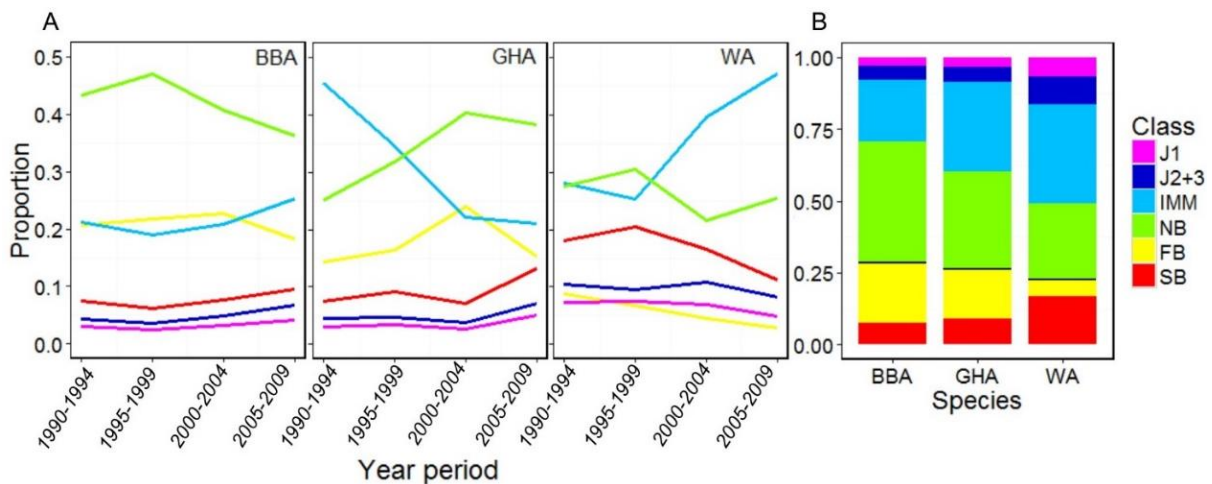
Species	SB	FB	NB	JUV1	JUV 2+3	IMM
WA	✓	✓	✓	✓	✗	✓
BBA	✓	✓	✓	✗	No data	No data
GHA	✓	✓	✓	✗	No data	No data
WCP	✗	✗	✓	✗	No data	No data

**Table 3.** Population sizes of the four species at South Georgia averaged over the period 2000-2009, split by life-history stage. Values were extrapolated from Bird Island to the wider population using archipelago-wide surveys of the number of breeding pairs (Martin et al. 2009, Poncet et al. 2006, 2017) and estimates of the population structure from demographic models (Pardo et al. Submitted). SB = successful breeder, FB = failed breeder, NB = adult non-breeder, IMM = immature, J1= juvenile in its first year at sea, J2+3 = juvenile in its second or third year at sea. Prop. = proportion; N ind. = number of individuals. WA = wandering albatross, BBA = black-browed albatross, GHA = grey-headed albatross, WCP = white-chinned petrel. Values for WCP are given in italics to indicate that they have been taken from BBA.

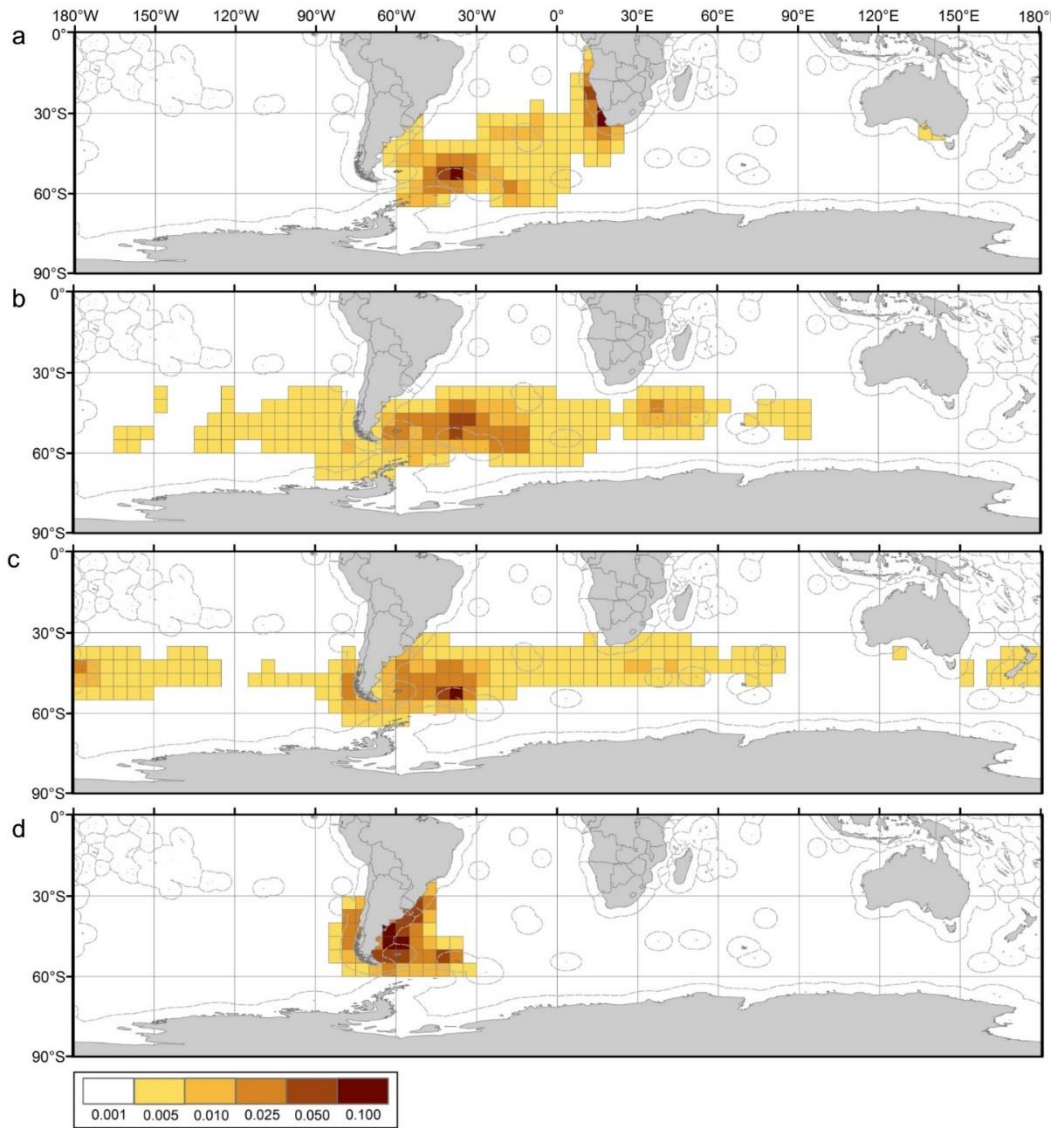
Species	Monitored pop. size (breeding pairs)	Estimated total pop. size (individuals)	SB		FB		NB		IMM		J1		J2+3	
			Prop.	N ind.	Prop.	N ind.	Prop.	N ind.	Prop.	N ind.	Prop.	N ind.	Prop.	N ind.
WA	1,559	19,065	0.14	2,472	0.04	646	0.23	4,849	0.44	8,288	0.06	1,069	0.10	1,741
BBA	75,299	543,509	0.09	49,257	0.19	101,341	0.37	199,980	0.25	137,951	0.04	21,155	0.06	33,824
GHA	40,367	245,988	0.11	27,349	0.22	53,384	0.39	95,681	0.17	44,246	0.04	10,631	0.06	14,696
WCP	773,150	5,552,399	<i>0.09</i>	<i>504,656</i>	<i>0.19</i>	<i>1,041,644</i>	<i>0.37</i>	<i>2,068,974</i>	<i>0.25</i>	<i>1,374,941</i>	<i>0.04</i>	<i>216,524</i>	<i>0.06</i>	<i>345,661</i>



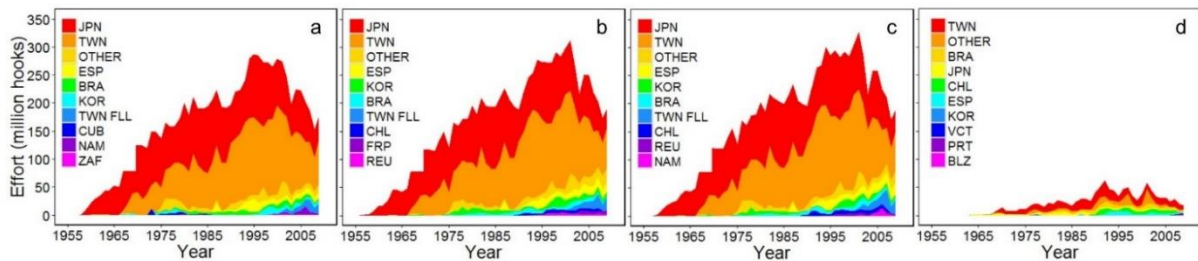
**Figure 1.** Age- and stage-structured population model. Each arrow corresponds to transitions from one stage to the next, Ages shown are juveniles (J, over three years), immatures and adults. Immatures in the year before recruitment are known as pre-breeders (Pre-B), and in this study are incorporated into the immature category (alongside Imm.) Adults are either successful (S), fail during breeding (F), or are seen as non-breeders (NB = observed non-breeders, Post-B = non-observed sabbatical birds). Only successful breeders raise chicks. The chick sex ratio at fledging is assumed to be even.



**Figure 2.** Population structure of black-browed (BBA), grey-headed (GHA) and wandering albatrosses (WA) from South Georgia, estimated from matrix population models over A) five-year periods and B) the whole study period (1990-2009). The proportion of the population represented by each demographic class is represented on the y-axis. Demographic classes are: J1 = juveniles in their first year at sea, J2+3 = juveniles in their second and third year at sea, IMM = juvenile birds in their fourth year onwards, up to recruitment into the breeding population (immatures), NB = adult non-breeders, FB = failed and SB = successful breeders. The black lines separate the breeding and non-breeding contingent.

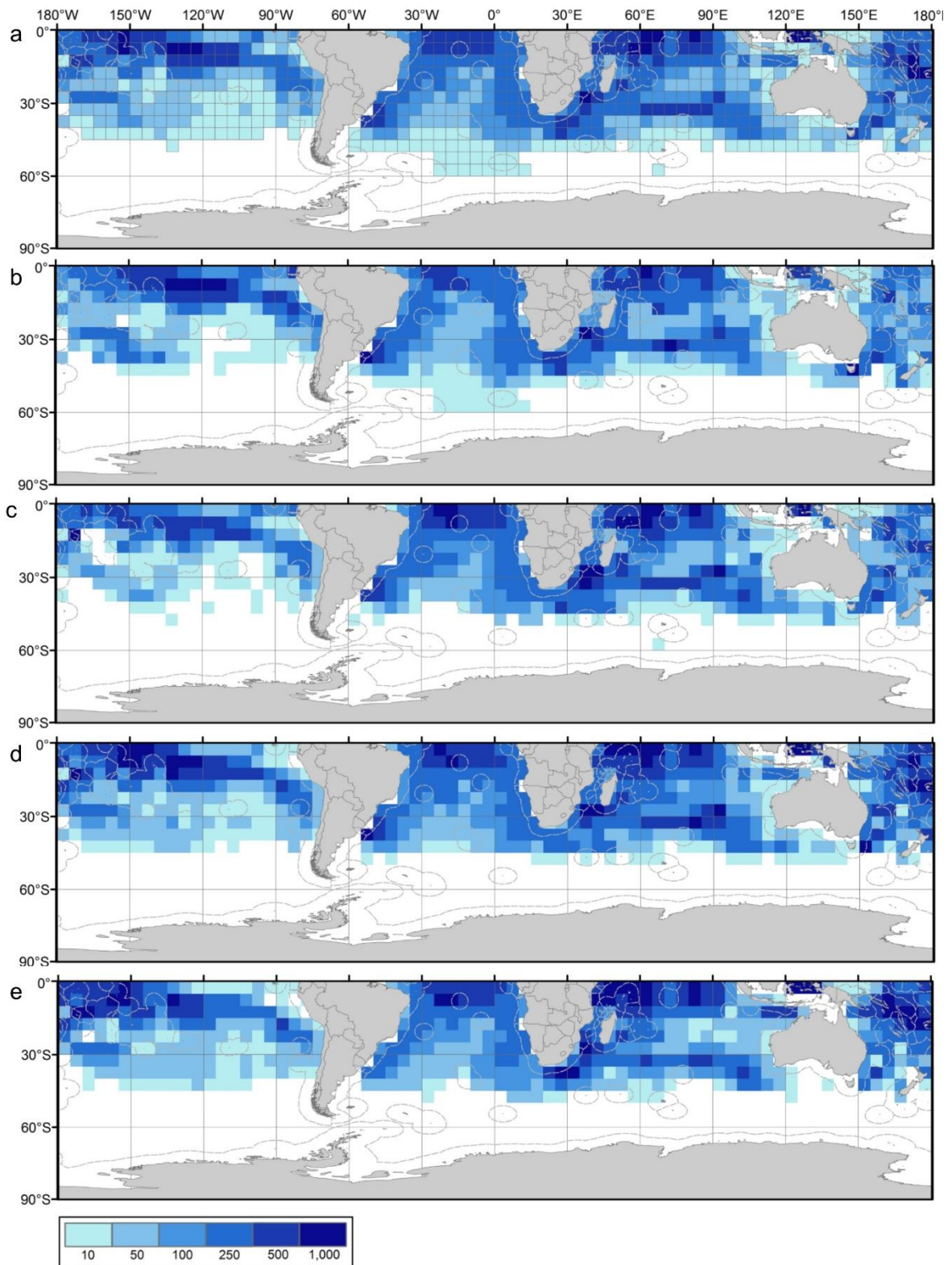


**Figure 3.** The annual population distribution of a) black-browed albatrosses, b) grey-headed albatrosses, c) wandering albatrosses, and d) white-chinned petrels from South Georgia calculated from the average of monthly distributions. The colour gradient refers to the proportion of the population represented within each 5 x 5° square.

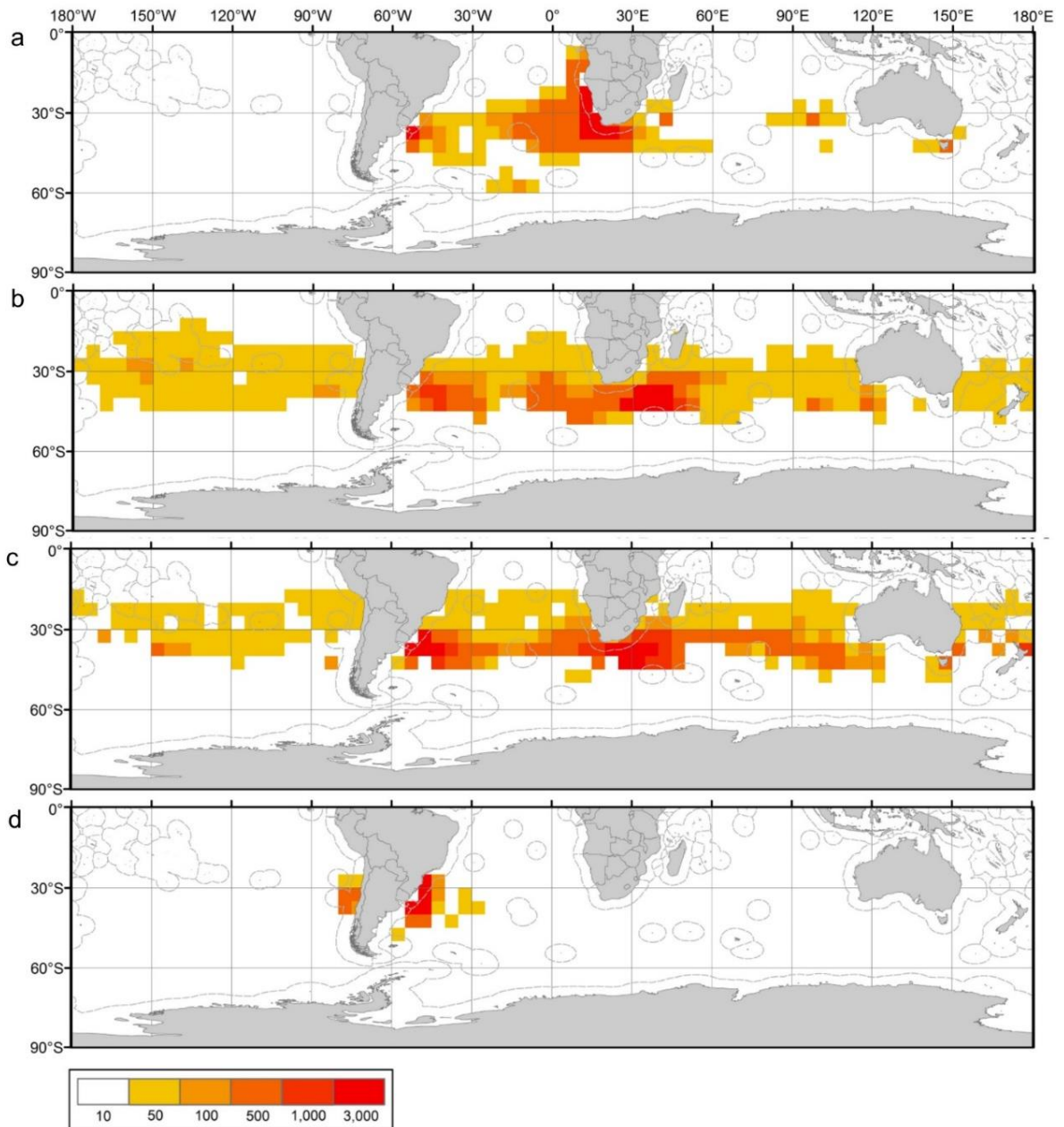


**Figure 4.** Pelagic longline effort within the annual distribution (in 5 x 5° cells where birds were present) of a) black-browed albatrosses, b) grey-headed albatrosses, c) wandering albatrosses, and d) white-chinned petrels. For each species, only the effort of the nine highest fleets are shown, while the other fleets are pooled in the category OTHER. Note that colours in each plot do not always refer to the same fleet. Fleet-specific information was not available for the WCPFC and so fleets within this region are not shown. JPN = Japan, TWN = Chinese Taipei, ESP = Spain, BRA = Brazil, KOR = South Korea, TWN FLL = Chinese Taipei fresh tuna fleet, CUB = Cuba, NAM = Namibia, ZAF = South Africa, CHL = Chile, FRP = French Polynesia, REU = Réunion, VCT = Vanuatu, PRT = Portugal, BLZ = Belize.



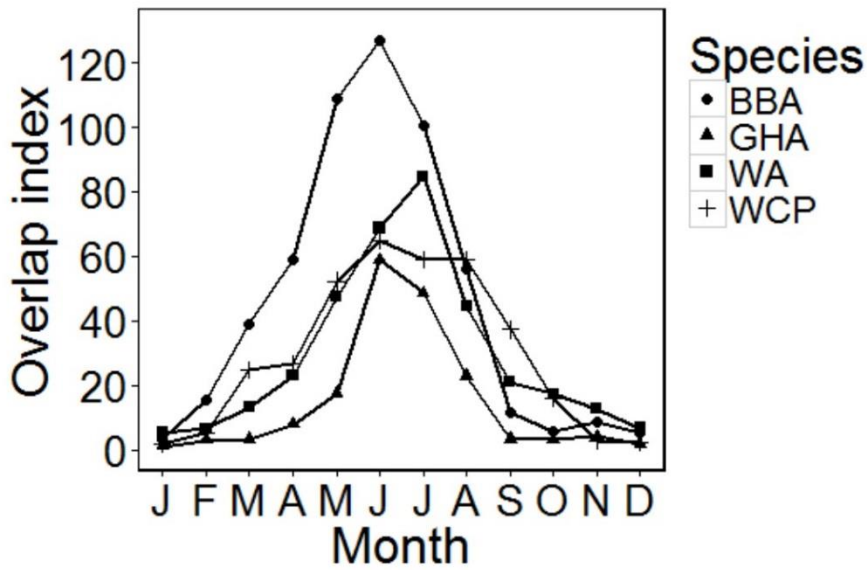


**Figure 5.** Annual pelagic longline effort averaged across months and years for a) the whole study period (1990-2009), b) 1990-1994, c) 1995-1999, d) 2000-2004 and e) 2005-2009. Effort values are shown per 1,000 hooks.

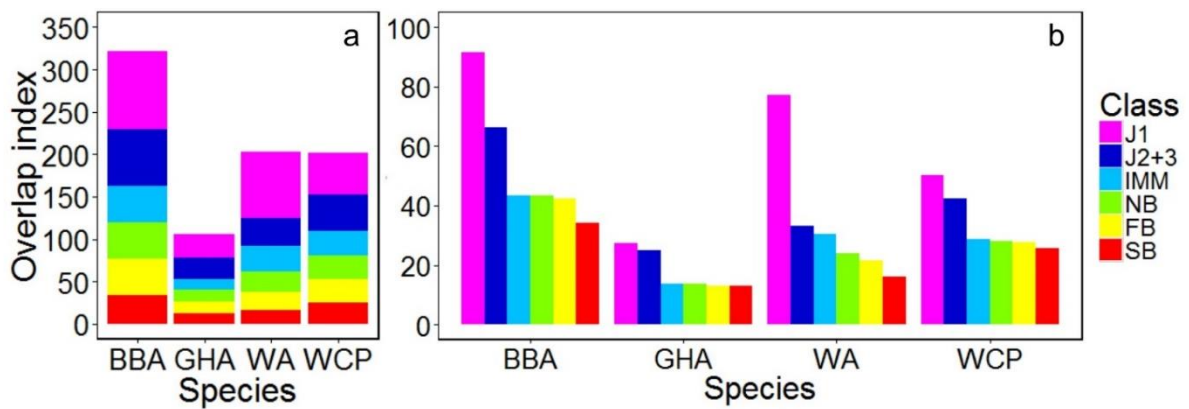


**Figure 6.** Annual overlap scores (percentage species distribution multiplied by number of hooks, per 5x5 grid) averaged across months and years (1990-2009) for a) black-browed albatrosses, b) grey-headed albatrosses, c) wandering albatrosses, and d) white-chinned petrels. Overlap values are shown divided by 1,000.

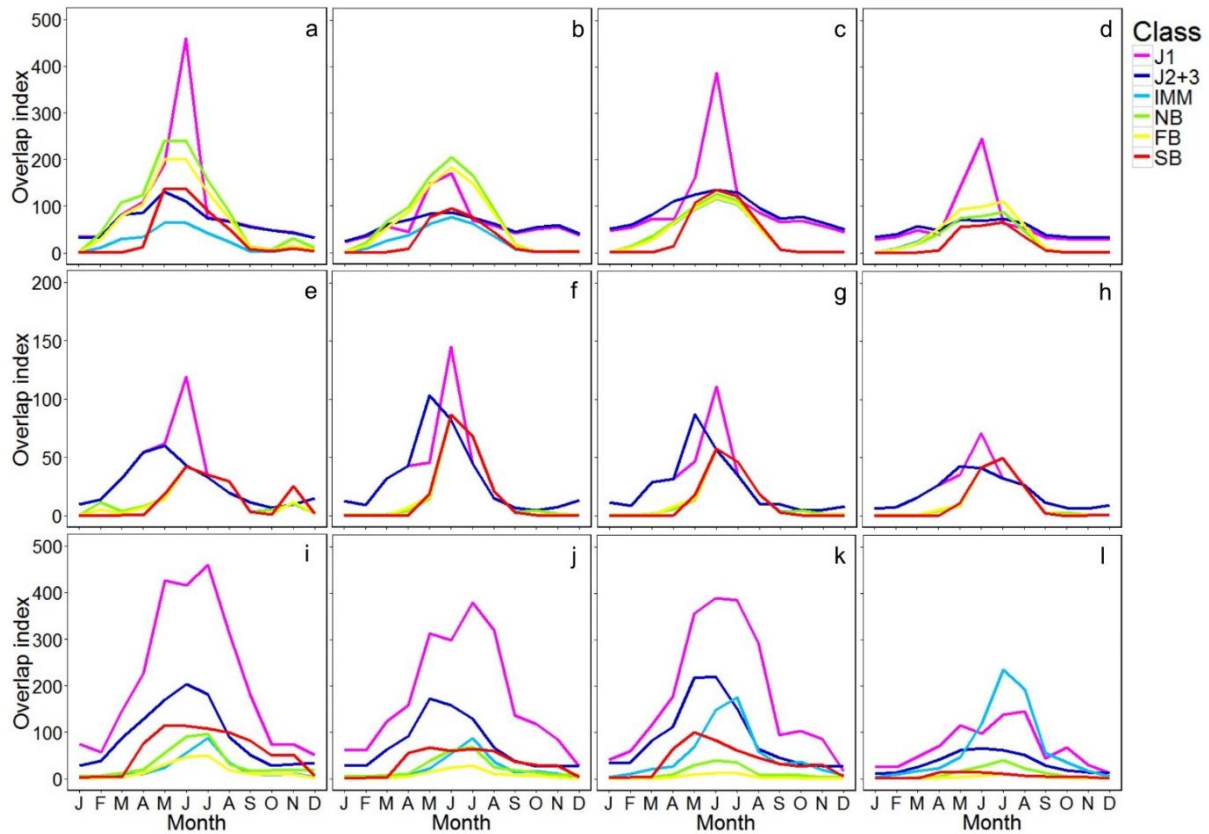




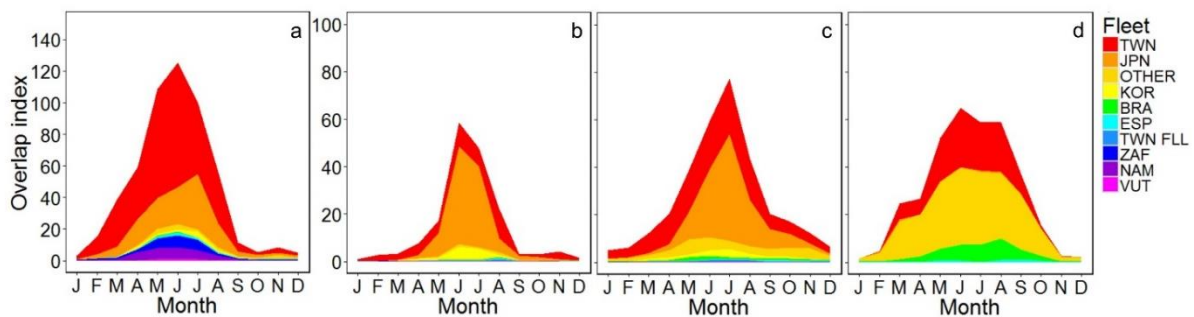
**Figure 7.** Monthly population overlap for each species. Demographic classes were multiplied by the population proportions and summed. Overlap values are shown divided by 1,000. BBA = black-browed albatross, GHA = grey-headed albatross, WA = wandering albatross, WCP = white-chinned petrel.



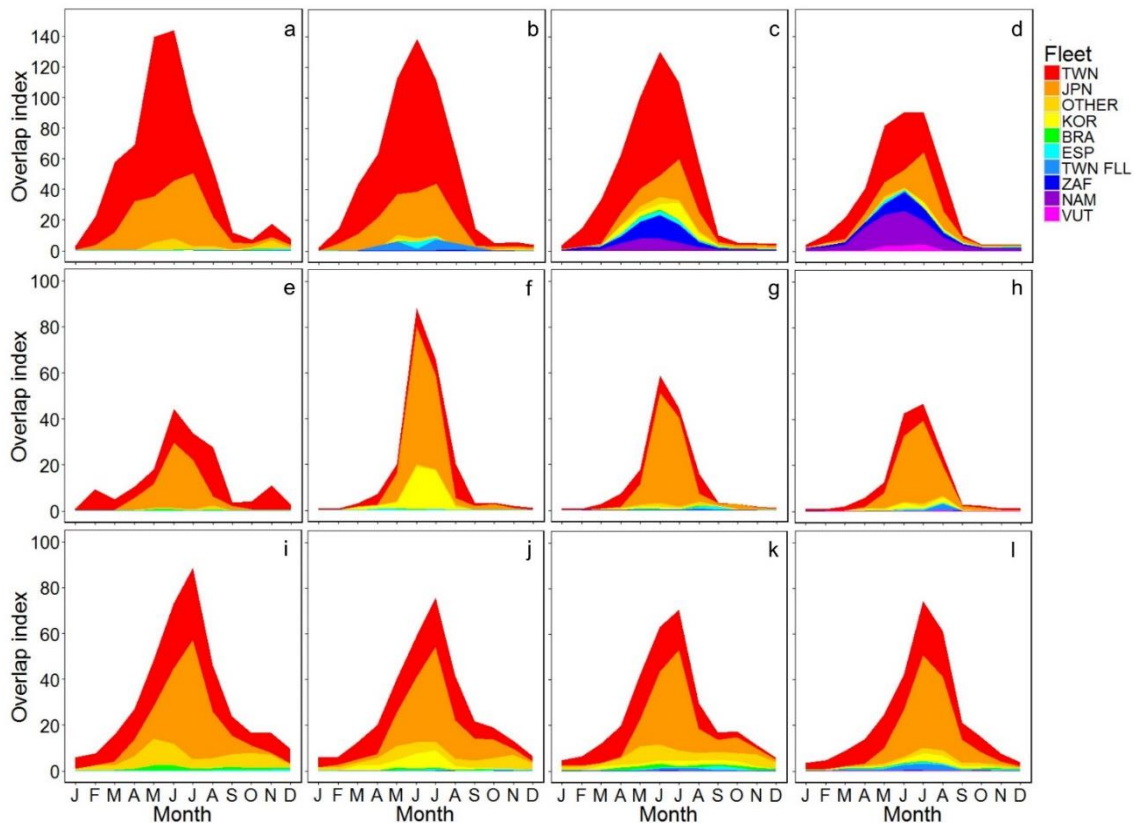
**Figure 8.** Average annual overlap for each species and life history stage (Class) shown as a) stacked bar plots, and b) side by side to enable comparison between groups. Values shown for life history stages have not been weighted by the population proportions. Overlap values are shown divided by 1,000. J1 = juveniles in their first year (post-fledging), J2+3 = juveniles in their second and third years, IMM = immatures, NB = non-breeding adults, FB = failed breeders, SB = successful breeders. BBA = black-browed albatross, GHA = grey-headed albatross, WA = wandering albatross, WCP = white-chinned petrel.



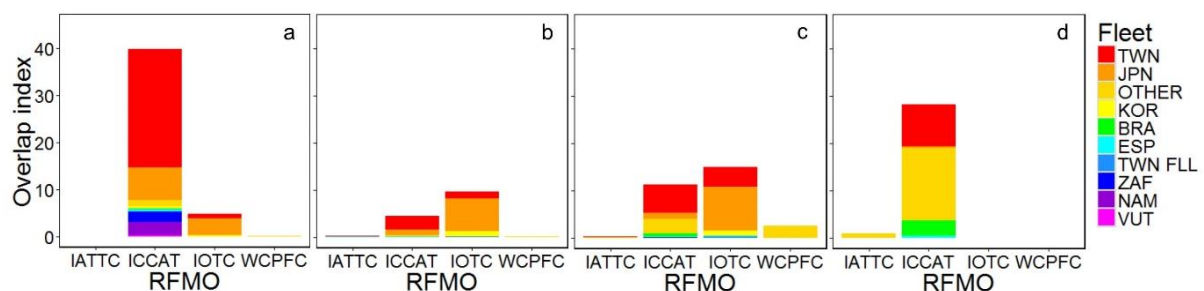
**Figure 9.** Monthly overlap for each species and life history stage (Class), showing how this has varied over time as a result of shifting patterns of fishing effort: 1990-1994 (first column), 1995-1999 (second column), 2000-2004 (third column) and 2005-2009 (fourth column); a-d) black-browed albatrosses, e-h) grey-headed albatrosses and i-l) wandering albatrosses. White-chinned petrels are not shown as year-specific population proportions were not available. Life history stages have not been weighted by the population proportions. Overlap values are shown divided by 1,000. J1 = juveniles in their first year (post-fledging), J2+3 = juveniles in their second and third years, IMM = immatures, NB = non-breeding adults, FB = failed breeders, SB = successful breeders.



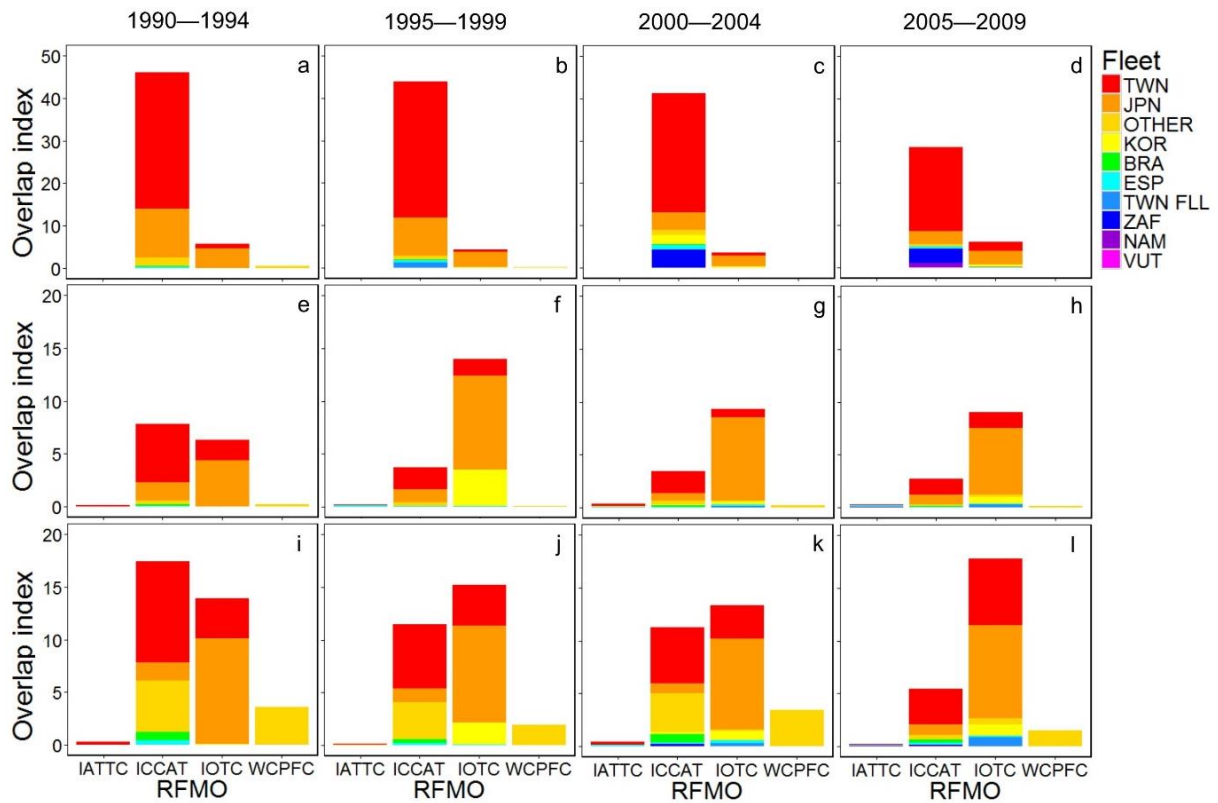
**Figure 10.** The contribution of each major fleet to the monthly population overlap for each species, averaged over the study period (1990-2009): for a) black-browed albatrosses, b) grey-headed albatrosses, c) wandering albatrosses and d) white-chinned petrels. Life history stages have been weighted by the population proportions and summed to create a population index of overlap. Overlap values are shown divided by 1,000. Only fleets with the nine highest overlap scores across all species are shown while the other fleets are pooled in the category OTHER. Fleet-specific information was not available for the WCPFC and so fleets within this region are not shown. TWN = Chinese Taipei, JPN = Japan, KOR = South Korea, BRA = Brazil, ESP = Spain, TWN FLL = Chinese Taipei fresh tuna fleet, SYC = Seychelles, ZAF = South Africa, CHL = Chile, NAM = Namibia.



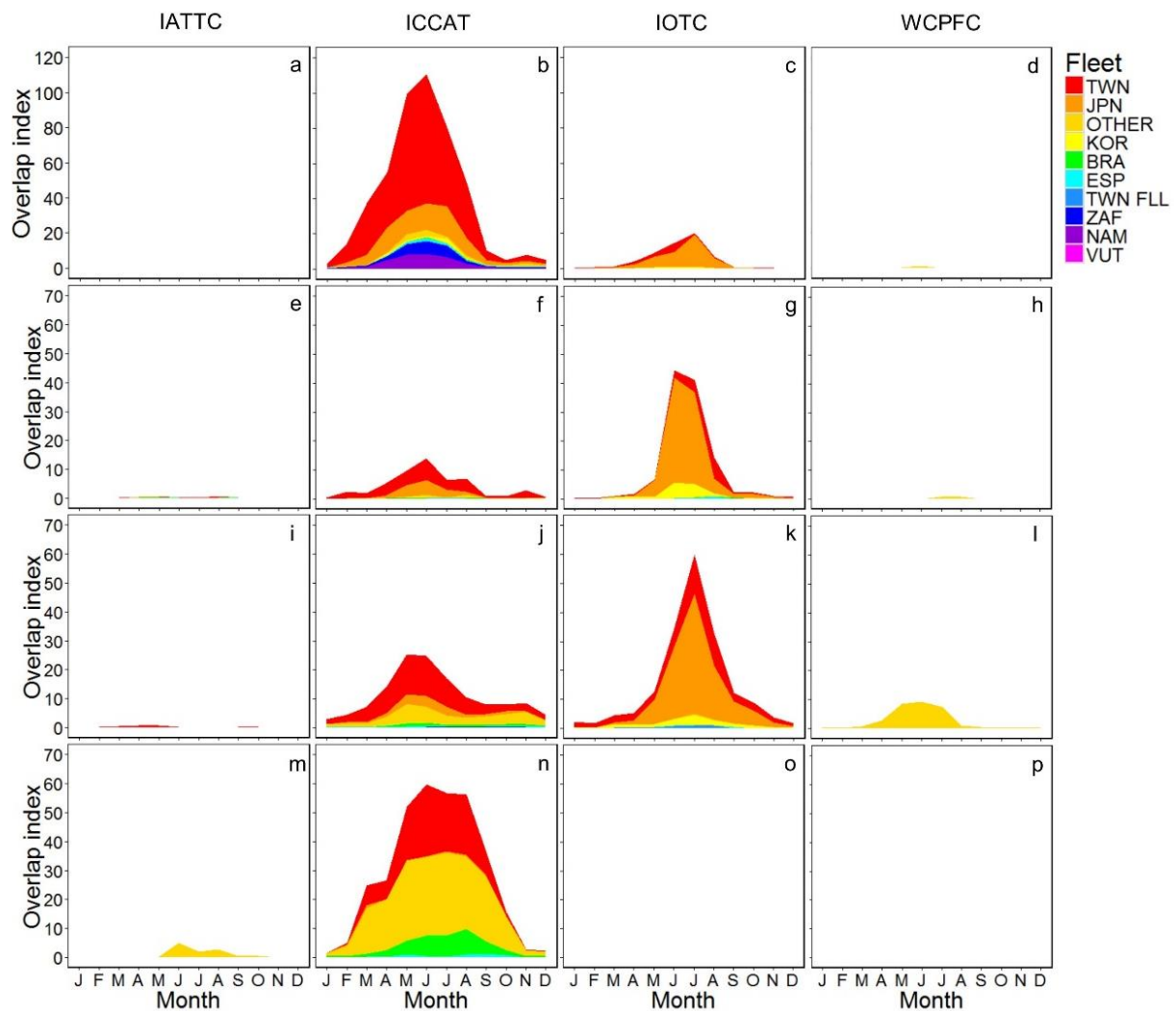
**Figure 11.** The contribution of each major fleet to the monthly population overlap for each species, and the changes over time as a result of shifting patterns in fishing effort: 1990-1994 (first column), 1995-1999 (second column), 2000-2004 (third column) and 2005-2009 (fourth column); a-d) black-browed albatrosses, e-h) grey-headed albatrosses and i-l) wandering albatrosses. White-chinned petrels are not shown as year-specific population proportions were not available. Life history stages have been weighted by the population proportions and summed to create a population index of overlap. Overlap values are shown divided by 1,000. Only fleets with the nine highest overlap scores across all species are shown while the other fleets are pooled in the category OTHER. Fleet-specific information was not available for the WCPFC and so fleets within this region are not shown. TWN = Chinese Taipei, JPN = Japan, KOR = South Korea, BRA = Brazil, ESP = Spain, TWN FLL = Chinese Taipei fresh tuna fleet, SYC = Seychelles, ZAF = South Africa, CHL = Chile, NAM = Namibia



**Figure 12.** The contribution of each regional fisheries management organization (RFMO) and major fleet to the average yearly population overlap for each species, averaged over the study period (1990-2009): for a) black-browed albatrosses, b) grey-headed albatrosses, c) wandering albatrosses and d) white-chinned petrels. White-chinned petrels are not shown as year-specific population proportions were not available. Life history stages have been weighted by the population proportions and summed to create a population index of overlap. Overlap values are shown divided by 1,000. Only fleets with the eight highest overlap scores across all species are shown while the other fleets are pooled in the category OTHER. Fleet-specific information was not available for the WCPFC and so fleets within this region are coloured as OTHER. TWN = Chinese Taipei, JPN = Japan, KOR = South Korea, BRA = Brazil, ESP = Spain, TWN FLL = Chinese Taipei fresh tuna fleet, ZAF = South Africa, NAM = Namibia. IATTC = Inter-American Tropical Tuna Commission, ICCAT = International Commission for the Conservation of Atlantic Tunas, IOTC = Indian Ocean Tuna Commission, WCPFC = Western and Central Pacific Fisheries Commission.



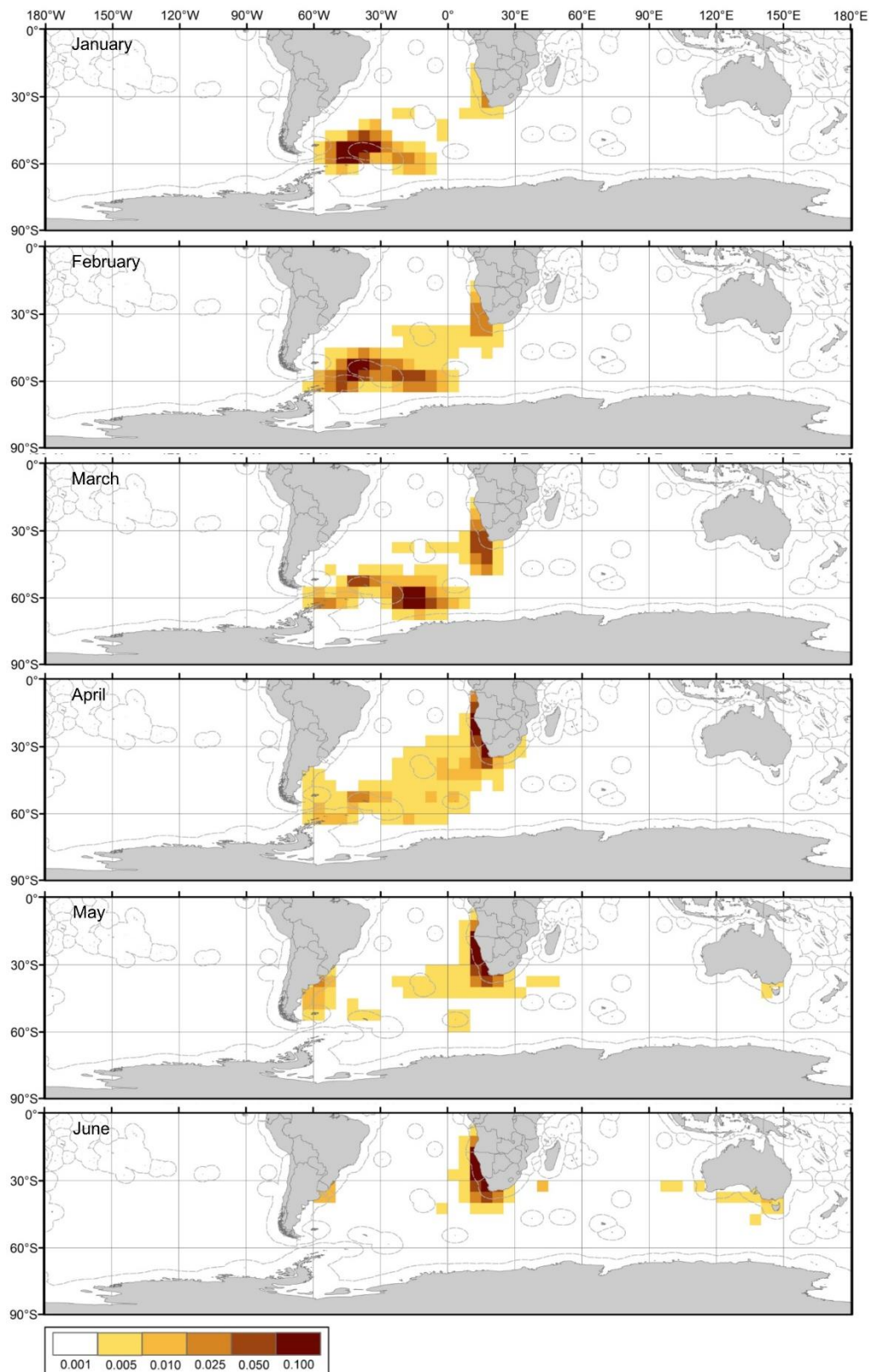
**Figure 13.** The contribution of each regional fisheries management organization (RFMO) and major fleet to the average yearly population overlap for each species, and the changes over time as a result of shifting patterns in fishing effort: 1990-1994 (first column), 1995-1999 (second column), 2000-2004 (third column) and 2005-2009 (fourth column); a-d) black-browed albatrosses, e-h) grey-headed albatrosses and i-l) wandering albatrosses. White-chinned petrels are not shown as year-specific population proportions were not available. Life history stages have been weighted by the population proportions and summed to create a population index of overlap. Overlap values are shown divided by 1,000. Only fleets with the eight highest overlap scores across all species are shown while the other fleets are pooled in the category OTHER. Fleet-specific information was not available for the WCPFC and so fleets within this region are coloured as OTHER. TWN = Chinese Taipei, JPN = Japan, KOR = South Korea, BRA = Brazil, ESP = Spain, TWN FLL = Chinese Taipei fresh tuna fleet, ZAF = South Africa, NAM = Namibia. IATTC = Inter-American Tropical Tuna Commission, ICCAT = International Commission for the Conservation of Atlantic Tunas, IOTC = Indian Ocean Tuna Commission, WCPFC = Western and Central Pacific Fisheries Commission.



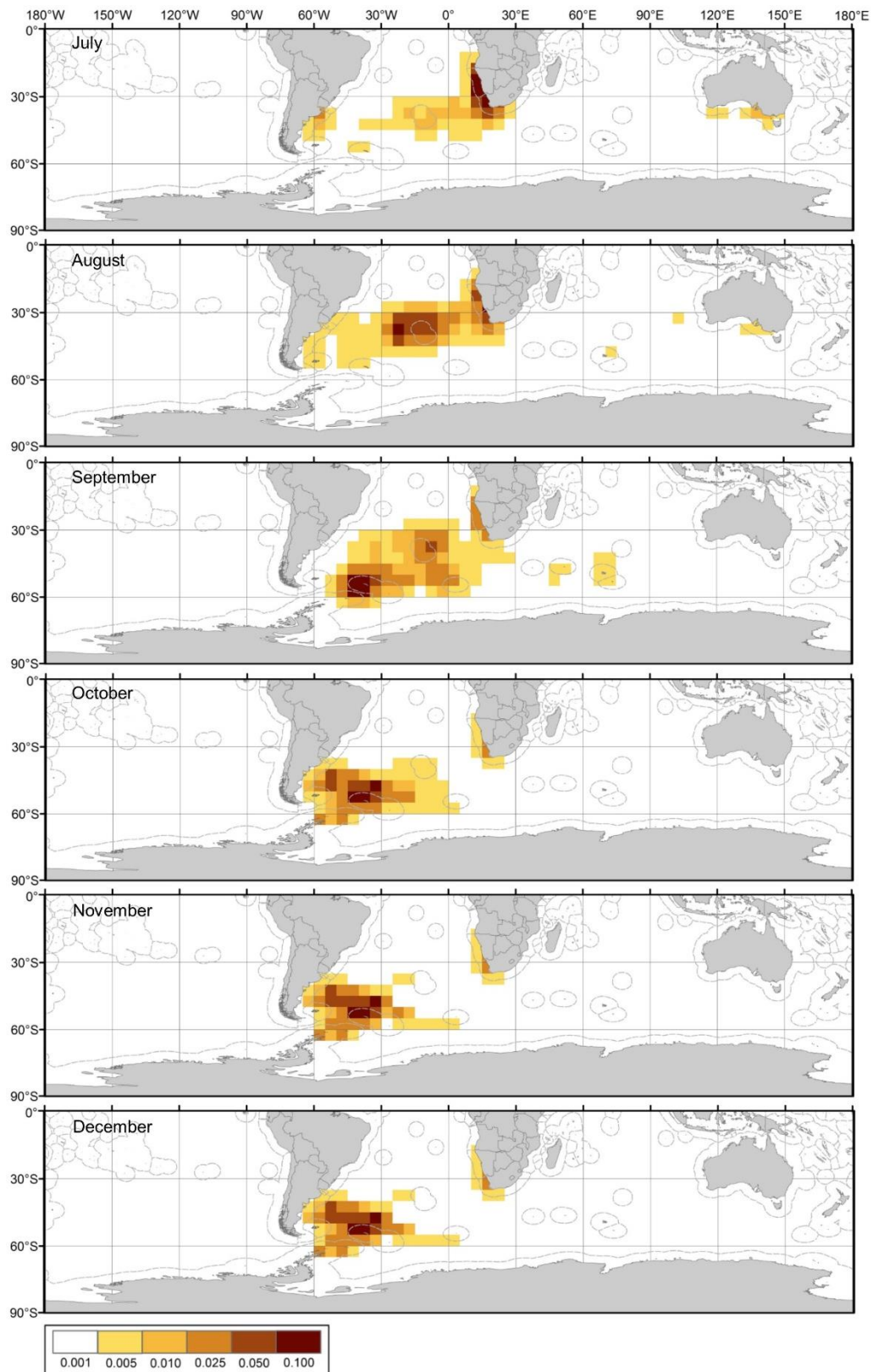
**Figure 14.** Monthly overlap for each regional fisheries management organization (RFMO) and major fleet: Inter-American Tropical Tuna Commission (IATTC, first column), International Commission for the Conservation of Atlantic Tunas (ICCAT, second column), Indian Ocean Tuna Commission (third column), Western and Central Pacific Fisheries Commission (fourth column). Overlap values are averaged over the study period (1990-2009): for a-d) black-browed albatrosses, e-h) grey-headed albatrosses, i-l) wandering albatrosses and m-p) white-chinned petrels. Life history stages have been weighted by the population proportions and summed to create a population index of overlap. Overlap values are shown divided by 1,000. Only fleets with the eight highest overlap scores across all species are shown while the other fleets are pooled in the category OTHER. Fleet-specific information was not available for the WCPFC and so fleets within this region are coloured as OTHER. TWN = Chinese Taipei, JPN = Japan, KOR = South Korea, BRA = Brazil, ESP = Spain, TWN FLL = Chinese Taipei fresh tuna fleet, ZAF = South Africa, NAM = Namibia.



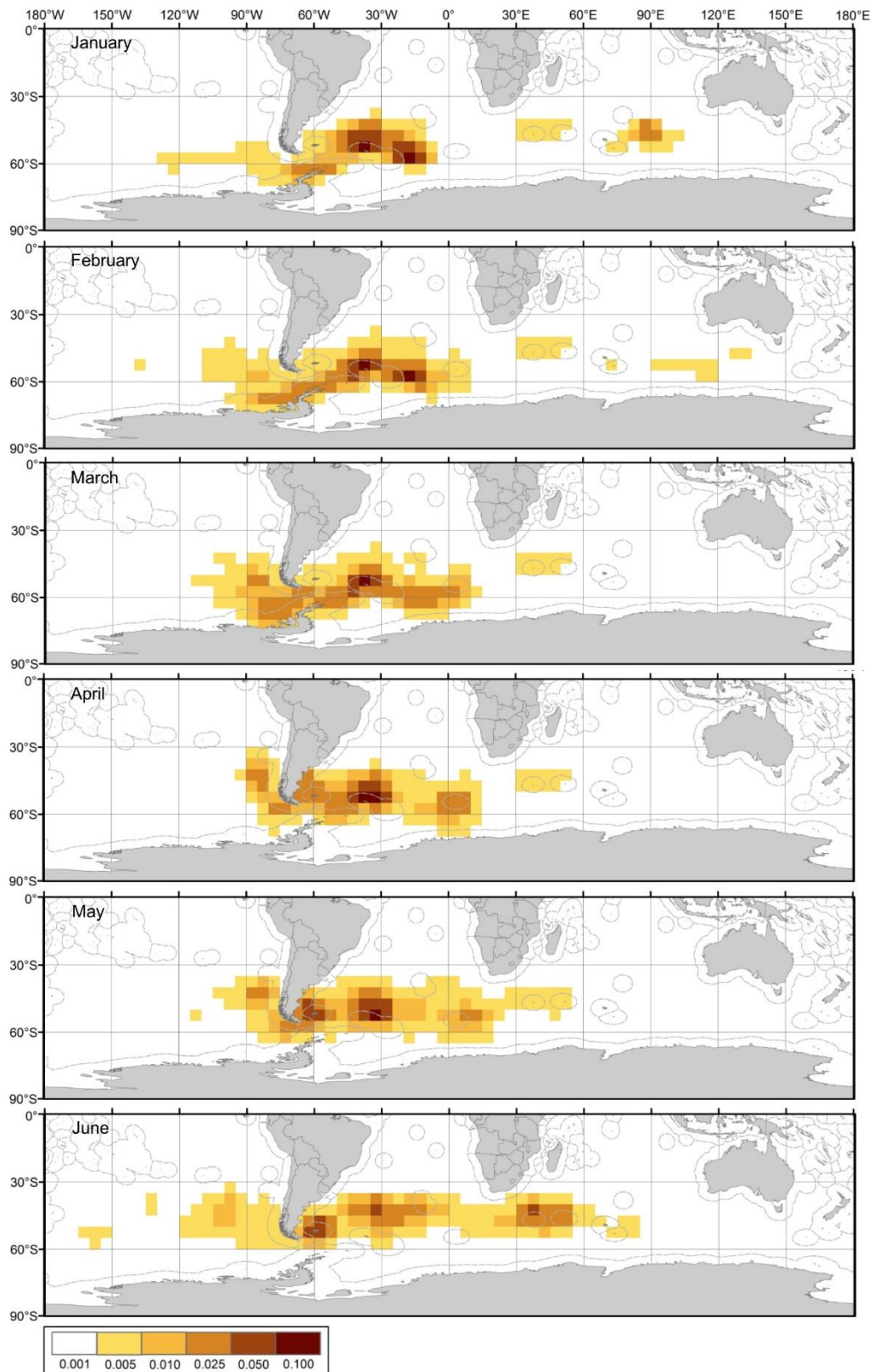
## Appendix



**Figure A1.** The monthly population distribution black-browed albatrosses from South Georgia. The colour gradient refers to the proportion of the population represented within each 5 x 5° square.



**Figure A1.** (Continued)



**Figure A2.** The monthly population distribution grey-headed albatrosses from South Georgia. The colour gradient refers to the proportion of the population represented within each 5 x 5° square.



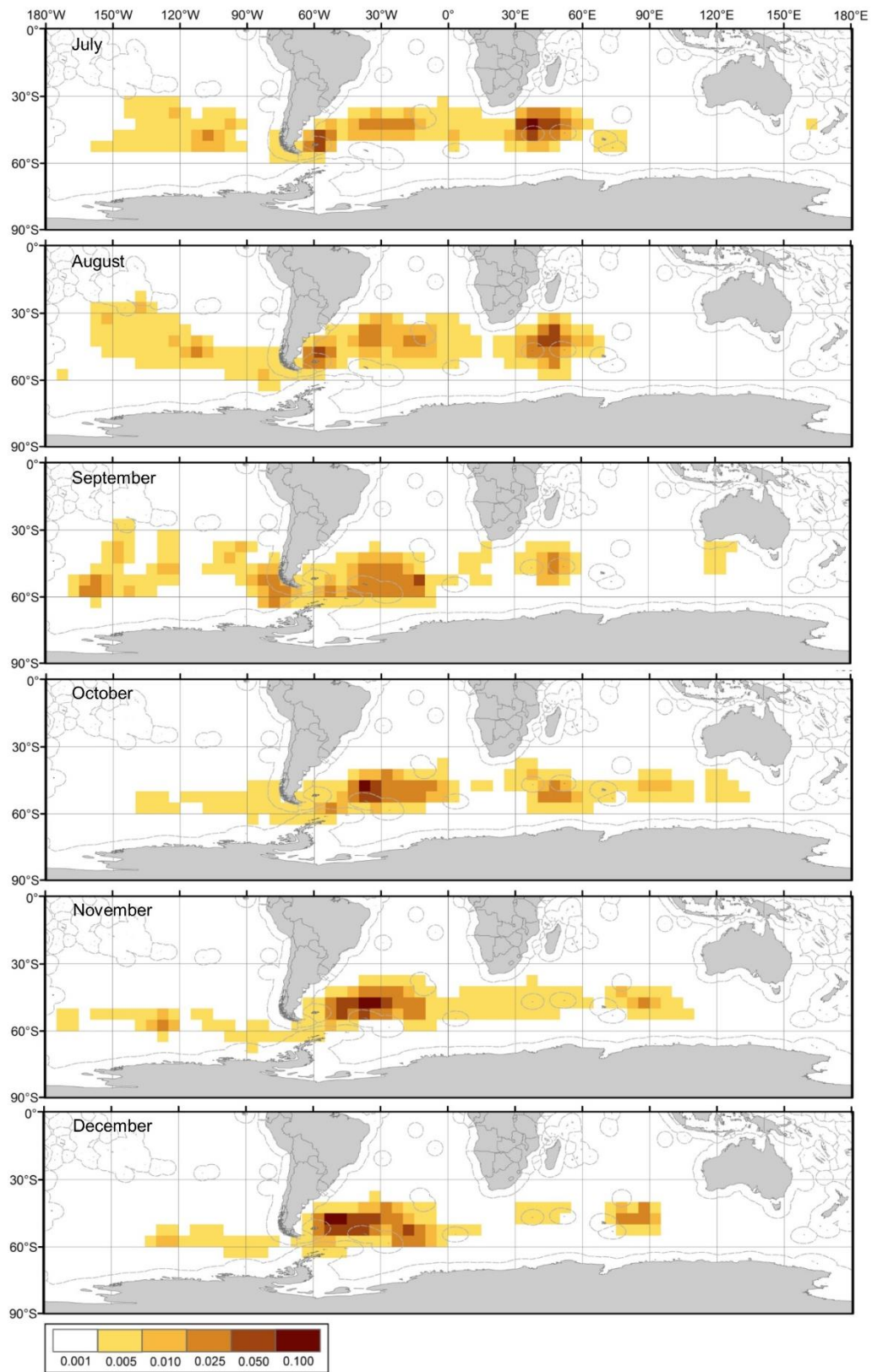
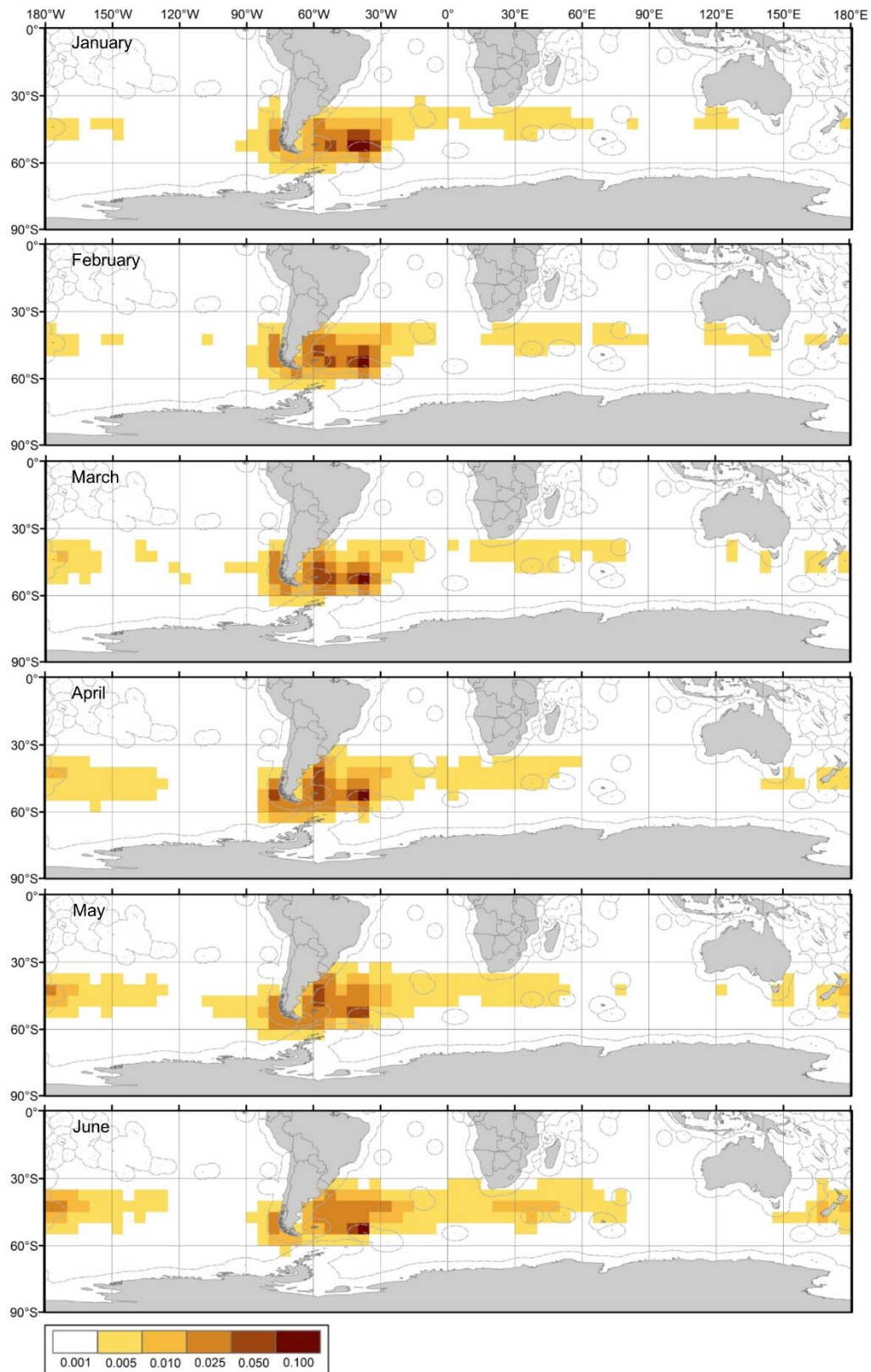


Figure A2. (Continued)



**Figure A3.** The monthly population distribution wandering albatrosses from South Georgia. The colour gradient refers to the proportion of the population represented within each 5 x 5° square.

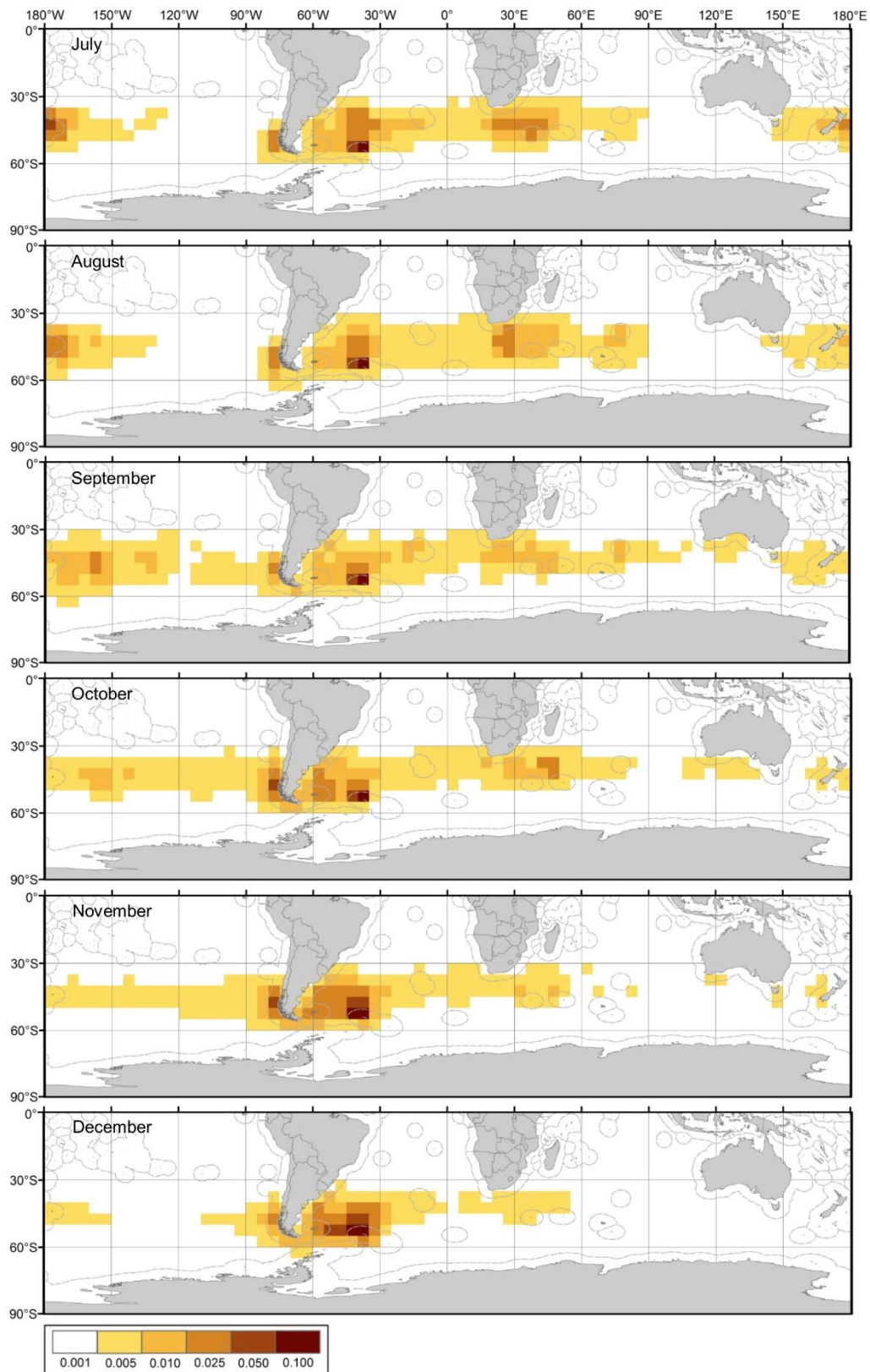
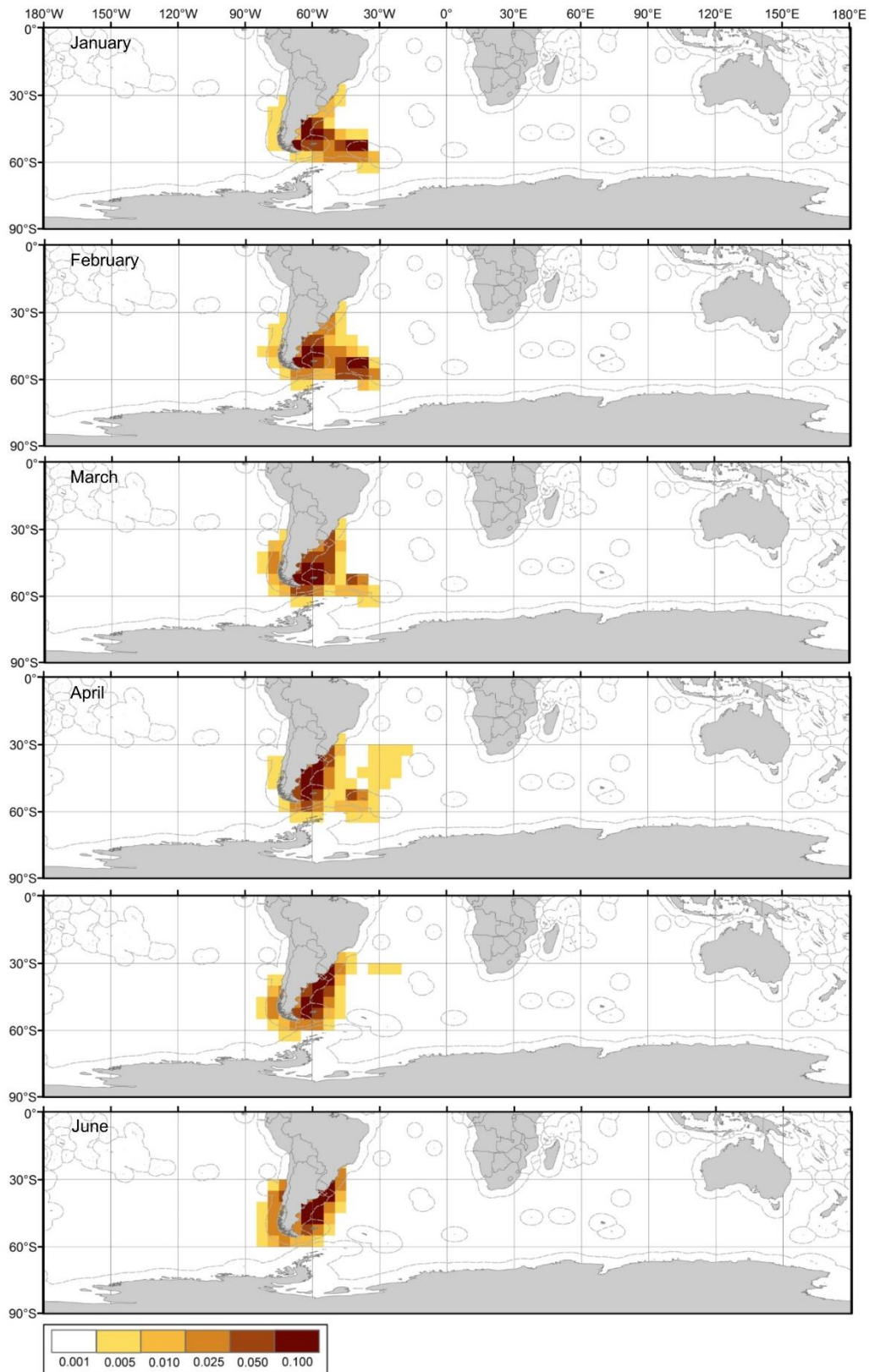


Figure A3. (Continued)





**Figure A4.** The monthly population distribution white-chinned petrels from South Georgia. The colour gradient refers to the proportion of the population represented within each 5 x 5° square.

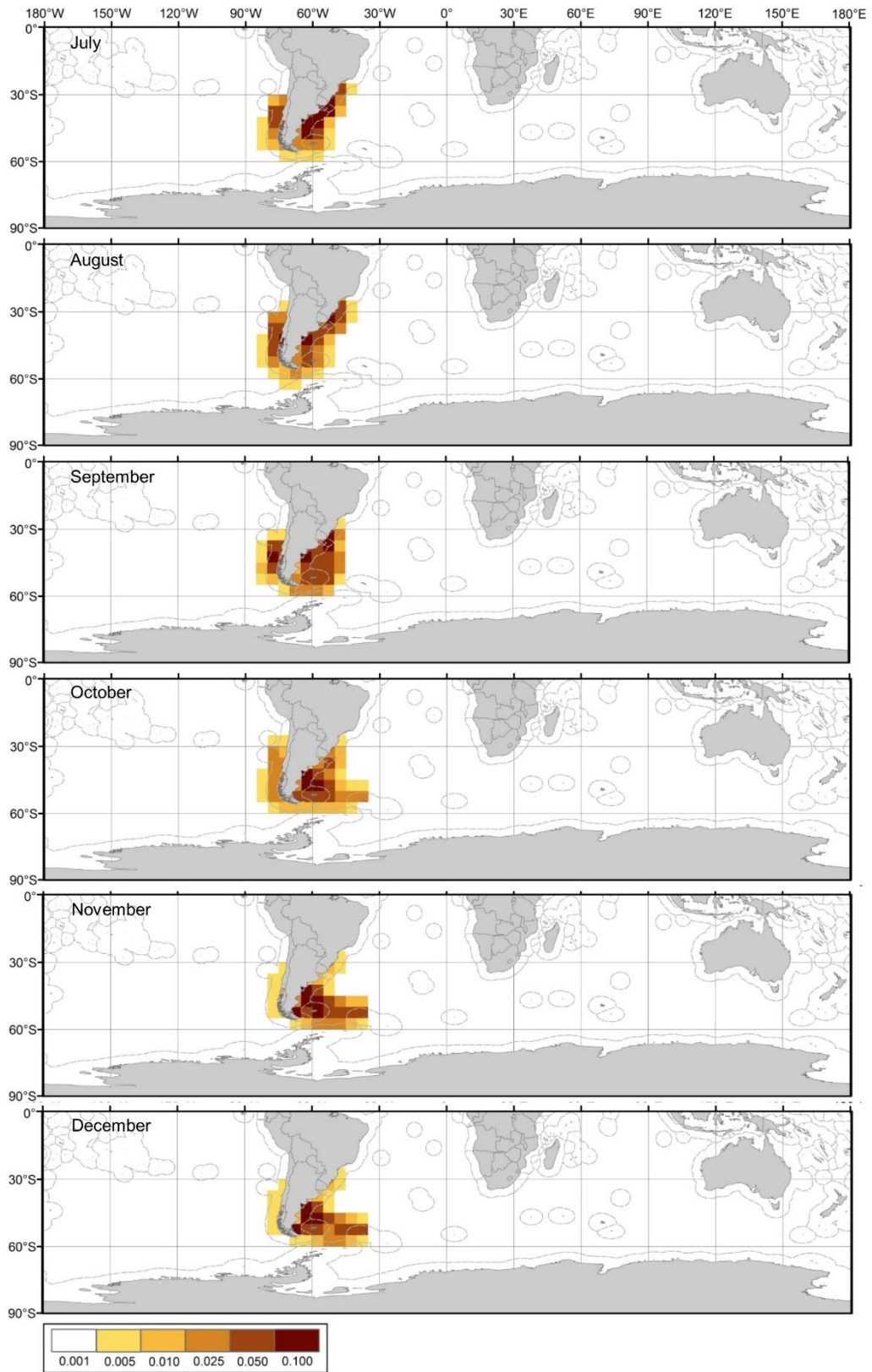


Figure A4. (Continued)