Future resilience scaled by surveillance: high sensitivity of albatross to regional illegal, unreported and unregulated fishing effort

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Abstract

For Kerguelen black-browed albatross (*Thalassarche melanophris*), warmer sea-surface temperatures (SST) near the colony during incubation have historically promoted chick survival, implying that future increased temperatures would support population viability. However, a historical population decline was driven by by-catch of albatross from the illegal, unreported and unregulated (IUU) demersal longline fleet. The virtual removal of this fleet from the region allowed this population to rebound, yet these albatross are susceptible to by-catch in many fleets and future fishing behaviour is uncertain. Albatross demographics were projected assuming forecast changes in SST and five future fishing effort scenarios. These scenarios indicate a high sensitivity to shelf/slope versus pelagic effort. Specifically, scenarios altering trawl and legal demersal effort estimated slight changes in bycatch while a scenario allowing the re-emergence of the IUU demersal longline effort produced high by-catch estimates and a decline in the number of breeding pairs. Negligible by-catch occurred in pelagic fleets across scenarios. The sensitivity of this population relates to intense use of these habitats during the breeding period, where IUU effort was historically greatest, and diffuse overlap with pelagic effort in non-breeding periods. These findings underscore the importance of continued surveillance and management of by-catch on the plateau region.

Résilience future à l'échelle de la surveillance : forte sensibilité des albatros à l'effort régional de pêche illicite, non déclarée et non réglementée

Résumé

Pour les albatros à sourcils noirs de Kerguelen (*Thalassarche melanophris*), des températures de surface de la mer (SST) plus élevées près de la colonie pendant l'incubation ont toujours favorisé la survie des poussins, ce qui implique qu'une hausse des températures à l'avenir serait favorable à la viabilité de la population. Cependant, par le passé, la capture accidentelle d'albatros par la flottille de pêche illicite, non déclarée et non réglementée (INN) à la palangre démersale a entraîné un déclin de la population. La disparition quasi-totale de cette flottille dans la région a permis à cette population de rebondir, pourtant de nombreuses autres flottilles posent des risques de capture accidentelle pour les albatros et les futures pratiques de pêche sont imprévisibles. Une

projection démographique de l'albatros a été effectuée en tenant compte des prévisions de changements de SST et de cinq scénarios d'évolution de l'effort de pêche. Ces scénarios indiquent une forte sensibilité à l'effort de pêche sur le plateau/la pente par rapport à l'effort de pêche pélagique. En effet, les scénarios modifiant l'effort de pêche au chalut et de pêche démersale licite ont estimé de légers changements des captures accidentelles alors qu'un scénario permettant la résurgence de l'effort de pêche INN à palangre démersale a produit des estimations élevées des captures accidentelles et un déclin du nombre de couples reproducteurs. Selon tous les scénarios, les captures accidentelles des flottilles pélagiques étaient insignifiantes. La sensibilité de cette population est liée à l'utilisation intense de ces habitats pendant la reproduction, une période pendant laquelle la pêche INN a toujours été plus importante, et à un chevauchement diffus avec les activités pélagiques pendant les périodes de non-reproduction. Ces résultats soulignent l'importance d'une surveillance et d'une gestion continues de la capture accidentelle dans la région du plateau.

Keywords: demographics, climate change impacts, fleet dynamics, black-browed albatross, IUU, long-term monitoring

Introduction

Climate change presents a unique challenge to management, as it can impact factors interacting with population dynamics, potentially creating new management paradigms (Veloz et al., 2012). The Southern Ocean is rapidly changing, with large regions currently and expected to remain affected by multiple stressors, including increasing ocean temperatures (Constable et al., 2014; Gutt et al., 2015; Turner et al., 2015). Therefore, considering how climate change may alter the factors that influence population dynamics can increase foresight and the ability to identify effective management strategies.

The demographics of albatross and other Southern Ocean seabirds can be impacted by environmental variation, including regional sea-surface temperature (SST) and broad-scale climate indices, such as the Southern Ocean Index (Barbraud et al., 2012). These relationships are often species or population-specific (Nevoux et al., 2010b; Rolland et al., 2010; Barbraud et al., 2011). Albatrosses are also susceptible to incidental capture during fishing activities (by-catch), which is thought responsible for many population declines and remains a threat for many populations (Phillips et al., 2016). Additionally, demographic feedbacks, such as population density, and environmental conditions during early life-stages can have long-term impacts on recruitment, breeding success and survival (Nevoux et al., 2010a; Fay et al., 2017a, 2017b). While reducing by-catch has resulted in some populations rebounding (Robertson et al., 2014), the combined impacts of future environmental change

and fisheries by-catch are likely to shape the viability of albatross populations (Rivalan et al., 2010; Thomson et al., 2015; Pardo et al., 2017b). Therefore, investigating the population-specific impacts of climate change on albatrosses should consider environmental, fisheries and demographic interactions.

The black-browed albatross (*Thalassarche melanophris*) population at Cañon des Sourcils Noirs, Kerguelen Islands, provides an excellent case-study for such an investigation. Recent work on over 30 years of demographic data from this colony has identified environmental, fisheries by-catch, and density-dependant factors that have shaped the historical demographics of this population (Michael et al., 2017b). For example, multiple studies have identified that relatively warm SST near the colony during incubation has historically promoted chick survival (Pinaud and Weimerskirch, 2002; Rolland et al., 2008; Michael et al., 2017b). Although the mechanism for this relationship is uncertain and krill is not known to be a significant component of the diet in this population, population size is generally associated with net primary productivity during the breeding period, suggesting some bottom-up regulation (Cherel et al., 2000; Cherel et al., 2002; Wakefield et al., 2014). Increasing information on regional ecosystem dynamics and albatross diet composition may soon inform this understanding (Koubbi et al., 2016; McInnes et al., 2017).

In addition to environmental associations, the majority of models estimated that by-catch during a historical population decline between the mid-1990s through the mid-2000s was allocated to the

illegal, unreported, and unregulated (IUU) demersal longline fleet targeting toothfish near the colony during the albatross breeding season (Michael et al., 2017b). Fortunately, increased surveillance and deterrence of IUU effort in this region since 2005, due to the Treaty on Cooperation in the Maritime Areas Adjacent to the French Southern and Antarctic Territories, Heard Island and McDonald Islands entering into force, has virtually removed this fleet from the region, allowing the albatross population to rebound (Duhamel and Williams, 2011; Delegation of France, 2015). However, this population remains susceptible to by-catch, particularly if shifts in the distribution or mitigation compliance of fishing effort was to occur. Furthermore, as climate change is likely to result in continued SST warming (Constable et al., 2014), increased chick survival could produce density-dependant feedbacks that alter chick and juvenile survival. Thus, density dependence or changes in fishing effort could outweigh the benefits of increasing SST. Alongside changes in SST and density dependence, considering potential changes in fishing effort could inform the development of management strategies for this population.

Shifts in fish distributions have been observed (Dulvy et al., 2008; Mueter and Litzow, 2008) and are anticipated for many species (Hobday, 2010; Dueri et al., 2014; Lehodey et al., 2015). However, projecting the response of fishers in terms of the distribution and magnitude of fishing effort is notoriously difficult, occasionally resulting in unintended consequences (Abbott and Haynie, 2012; Dowling et al., 2013; Chan et al., 2014; Mangel et al., 2015). The distribution of fishing effort is ultimately determined by the fishers and their response to multiple factors. These factors could include previous areas fished, perceived risk, target market, and other considerations (Pinsky and Fogarty, 2012; Dowling et al., 2015; Watson and Haynie, 2018). Furthermore, the current suite of models for fishing fleets is not comprehensive, with pelagic fleets infrequently modelled and high-seas fleets modelled even less frequently (Girardin et al., 2016); therefore, they fail to capture the range of fleets that overlap with far-ranging marine predators such as albatrosses. Nevertheless, knowledge of current fleet behaviour, region-specific insights, and how effort could vary due to climate change can provide novel and useful insights into future interactions with albatrosses.

The aim of this study is to explore the future demographics of the black-browed albatross on the Kerguelen Islands given climate change across a range of future fishing effort scenarios. To achieve this, we apply recently estimated demographic parameters in an integrated modelling framework incorporating forecast changes in SST and density dependence on young albatrosses (Michael et al., 2017b). We then develop five individual future fishing effort scenarios (hereafter 'effort scenarios'), based on a current understanding of possible fleet response to climate change, fleet-specific models when available, and broad-scale generalisations across gear-types. Each effort scenario is individually associated with the model framework, producing five distinct model scenarios. We then compare the projected demographics and fleet-specific by-catch across model scenarios. This assessment broadens the understanding of climate change impacts on albatrosses by explicitly considering fleet behaviour when making demographic projections.

Material and methods

Demographic data

Annual demographic data were collected from 200 monitored nests in a colony of approximately 1 000 breeding pairs at Cañon des Sourcils Noirs, Kerguelen Islands (48°14'S 68°13'E) (Rolland et al., 2008; Barbraud et al., 2011). From 1967, adults and chicks were ringed with stainless steel rings, and since 1979 a capture–mark–recapture program has been undertaken annually between October and March. The breeding success of each pair was determined through additional visits to monitored nests in late December and late March. All chicks and un-ringed breeding individuals encountered in the study area were ringed just before fledging. Sex was determined from blood samples and by using standard protocols (Angelier et al., 2007).

Demographic model and parameter estimation

To assess the potential impacts of climate change on the black-browed albatross population breeding on the Kerguelen Islands we applied the demographic, environmental and by-catch parameters estimated within a maximum likelihood framework identified by Michael et al. (2017b). Briefly, these estimates were derived from a spatially explicit integrated population model to quantify the impact

of environmental conditions, by-catch and density dependence on this population for the period 1950 to 2011. The integrated model framework incorporates all data sources into the estimation framework, enabling separation of observed mortality rates and the theoretical mortality rates for a population unimpacted by other covariates (e.g. by-catch), super-fleet specific by-catch rates and the impacts of density dependence on young albatross mortality. Super-fleets are groups of fleets that use a similar gear-type and are assumed to have similar by-catch characteristics. The presence and extent of density dependence was assessed and linked to the number of breeding pairs for chicks and the total population size for juveniles and immatures. The model operated at a $5° \times 5°$ spatial scale and monthly temporal scale, and was structured by age-class, breeding stage and sex.

We assume the previously identified association of warm average SST near the colony during the breeding period, October–December, with increased breeding success (Michael et al., 2017b). Though others have identified non-linear relationships with demographic rates in this population (Barbraud et al., 2011), we assume a linear relationship as non-linear relationships are difficult to differentiate in this model framework (Thomson et al., 2015). Mortality was based on age-class (e.g. 'juvenile', 'adult') and not age-specific as in Pardo et al. (2013). The model framework does not currently assess the impacts of environmental conditions on the survival of adults, inexperienced birds, or the relationship between natal conditions and recruitment (Nevoux et al., 2007, 2010a; Rolland et al., 2010) nor offspring quality (Dupont et al., 2018). In addition to environmental impacts on chick mortality, a by-catch parameter was estimated for each of five super-fleets, based on gear type and reported by-catch rates of fishing fleets: Japanese pelagic longline, other pelagic longline, legal demersal longline, trawl, and IUU demersal longline. See Michael et al. (2017b) for model framework and super-fleet details.

Forecast environmental variables

To incorporate the impacts of climate change on SST as well as Japanese and Taiwanese pelagic longline fleet dynamics which relate to modelled tuna catch per unit effort (Michael et al., 2017a), we used data SST, sea-surface height anomaly, and phytoplankton data generated by the Ocean Eddy-resolving Model within BLUElink (Oke et al., 2008; Sun et al., 2012; Matear et al., 2013). This is based on corrected output from the CSIRO Mk.3.5 output which is forced by the A1B scenario for the 2060s (Hartog et al., 2011). Data were obtained for 2063–2067, setting the boundaries for our projections. To convert phytoplankton data to chlorophyll (Chl) values, we multiplied phytoplankton values by 1.59. This conversion factor assumes 50 mg Carbon to 1 mg Chl (Sharp et al., 1980; Eppley et al., 1998). The SST for the years between the last observed data within black-browed albatross model and the BLUElink data were linearly interpolated based on the average BLUElink SST, as there was no clear temporal trend in the BLUElink data. As data were produced on an irregular grid, they were aggregated to a $5° \times 5°$ scale for the fleet-dynamics models or calculated across the area and months of interest regarding the average SST near Kerguelen during the incubation period. We assume the same historical incubation period, October–December, for the future.

Effort scenarios

Given uncertainty in the response of fleets to climate change, we developed a range of scenarios for future fishing effort and assess their impact on the albatross population, described below (Table 1). These effort scenarios, unless otherwise noted (e.g. assumptions based on Michael et al., 2017a), generalise the potential response of fleets to climate change by gear type, which is an important factor relating to broad-scale fleet behaviour and by-catch patterns (Løkkeborg, 2011; Melvin et al., 2014; Girardin et al., 2016). Historical fishing effort data are described in Michael et al. (2017b). The scenarios evaluated are summarised in Table 1 and below.

Scenario-specific assumptions include:

(i)   The last historical observed or assumed distribution and magnitude of effort, which is 2011, will be maintained for all active fleets through 2067. Unless otherwise stated, all other effort scenarios also assume 2011 levels and locations for effort.

(ii) The application of fleet-dynamics models incorporating historical species-specific catch per unit effort distribution, their association with the environment, and the targeting

Table 1:   Description of effort scenarios including abbreviated scenario name.

Effort scenario		Other effort scenarios assumed	Fleets or super-fleets impacted	Assumed 2063–2067 effort
Number	Name			
i	2011	None	All active fleets	2011
ii	J&T	2011	Japanese pelagic longline, Taiwanese pelagic longline within other pelagic longline	Michael et al. (2017a)
iii	2× shelf	J&T, 2011	Trawl and demersal longline, J&T	2×2011 effort
iv	1/2 shelf	J&T, 2011	Trawl and demersal longline, J&T	$1/2 \times 2011$ effort
v	IUU	J&T, 2011	IUU demersal longline	1/2 average effort

preferences of the Japanese and Taiwanese pelagic longline fleets operating within the Indian Ocean Tuna Commission region (20°S to 50°S, 20°E to 145°E) of the southern Indian Ocean (Michael et al., 2017a). This assumes the distribution and magnitude of effort projected for 2063 through 2067 and a linear interpolation in the change in effort in space and time from the last observed effort in 2011. All remaining effort scenarios (iii–v) also assumes these dynamics.

(iii) A linear increase in trawl and demersal longline super-fleet effort from 2011 through 2063, which stabilises at twice the 2011 levels, which is maintained through 2067. Though trawl effort is generally associated with static geographic features and is sensitive to weather conditions, an increase in effort could compensate for reduced access to or numbers of target species, or the addition of a new target species.

(iv) A linear decrease in trawl and demersal longline super-fleet effort from 2011 through 2063, which stabilises at half of the 2011 effort levels, which is maintained through 2067. Such a decrease in effort could occur due to reduced access to target species shifting due to climate change (Perry et al., 2005; Dulvy et al., 2008).

(v) The re-emergence of the IUU demersal longline super-fleet targeting toothfish. The IUU super-fleet is assumed to reappear in 2025, which is an arbitrarily selected date, and linearly increase to a maximum of half the historical average magnitude of effort. Given the restricted distribution of the toothfish targeted by this fleet and seasonal conditions,

we assumed the same relative distribution of effort in space and time. This could occur if surveillance and deterrence cease or become ineffective.

We did not investigate altering the magnitude of effort for fleets within either pelagic longline super-fleet, with the exception of our modelling of Japanese and Taiwanese fleet dynamics in scenarios (ii–v), as recent work indicates that by-catch of black-browed albatross from the focal colony is very rare in these fleets (Michael et al., 2017b). With the exception of the final effort scenario, we do not explore the possibility that fleets assumed to be inactive in 2011 will return, nor explore the explicit emergence of new fleets. Due to a lack of fleet-specific inference in the spatial response of fleets, we do not consider an effort scenario implementing a uniform shift in the spatial distribution of fishing effort across super-fleets. Lastly, we did not assess a potential shift in the at-sea distribution of albatross (Krüger et al., 2017). Although shifts have been observed in wandering albatross (Louzao et al., 2013), a habitat model for this population of black-browed albatross is not yet available. Furthermore, the highly neritic habitat preference of black-browed albatross (Wakefield et al., 2011; Wakefield et al., 2014) makes a uniform shift at the relatively coarse scale of this model, particularly during the breeding period, unlikely.

To assess the cumulative impacts of forecast SST and each effort scenario on the demographics of the black-browed albatross population breeding on Kerguelen through 2067, we run five versions of the model. All versions assume the historically estimated parameters in Michael et al. (2017b) and forecast SST while each effort scenario is only used
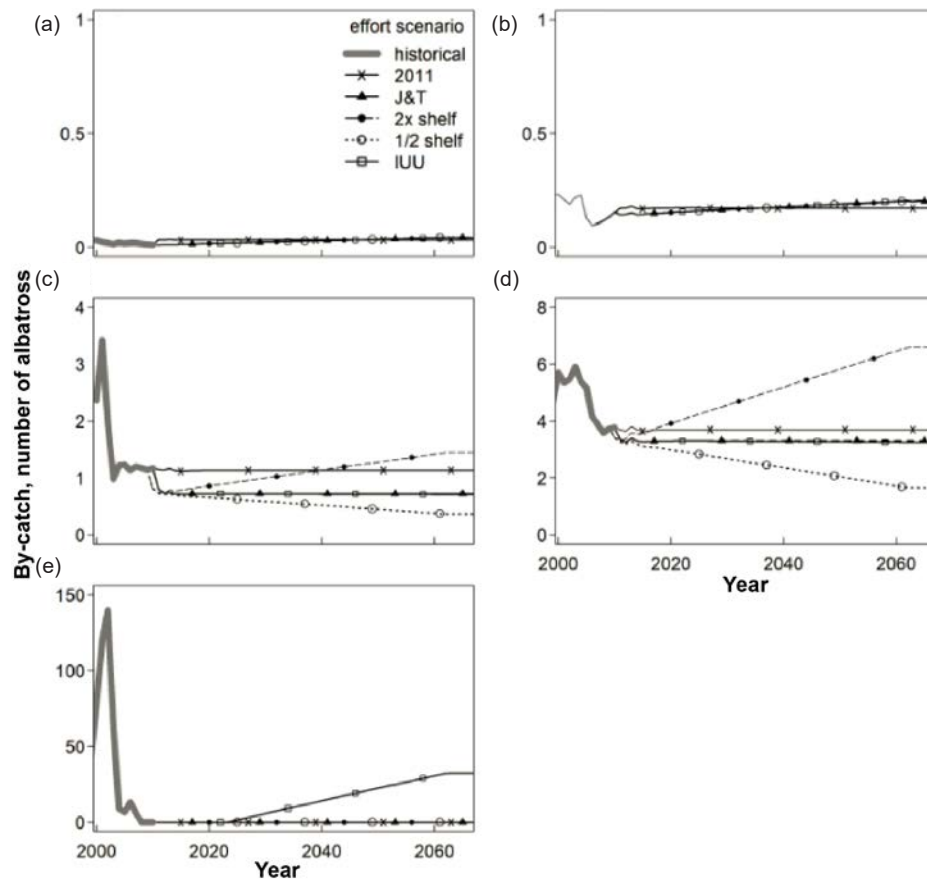
Figure 1: Annual projected by-catch by super-fleet: (a) Japanese pelagic longline, (b) other pelagic longline, (c) demersal longline, (d) trawl, and (e) IUU demersal longline, for each model scenario. All models assume the parameters estimated in Michael et al. (2017b) and forecast SST. The 'historical' modelled period (prior to 2011) is shown to provide a historical context. Values before 2000 are not shown. Effort scenarios are described in Table 1.

in a single version of the model, hereafter 'model scenario'. We then compare the estimated number of breeding pairs over time as well as the estimated fleet-specific by-catch across model scenarios.

Results

Across model scenarios, projected by-catch was greatest for the IUU demersal longline super-fleet, low for the trawl, followed by the demersal longline super-fleet, and virtually zero in both pelagic longline super-fleets (Figure 1). The projected by-catch by super-fleet differed across model scenarios. The exceptions to this were by-catch projections for both pelagic longline super-fleets, which was essentially zero across all model scenarios (Figures 1a, 1b). Legal demersal by-catch was projected to be quite small across models, with up to two birds per year estimated in the doubling of the shelf/slope effort model scenario and slightly less than one per year in the halving of the

shelf effort model scenario (Figure 1c). By-catch projections for the trawl super-fleet ranged from around two to seven, in the halving and doubling of shelf/slope effort model scenarios, respectively (Figure 1d). The other model scenarios showed negligible variation in projected by-catch. The greatest projected by-catch occurred in the IUU model scenario, with up to 32 birds caught per year (Figure 1e). As the IUU fleet was assumed to be absent in all other models, projected IUU by-catch after the mid-2000s in all other model scenarios is zero. Differences in projected by-catch of less than a single bird are considered negligible.

The projected demographic impacts of climate change on the Kerguelen black-browed albatross population were similar across four of the five model scenarios assessed (Figure 2), with impacts differing in the IUU model scenario. The estimated number of breeding pairs in 2067 was between 7.1% and 8.2% lower for the IUU model scenario
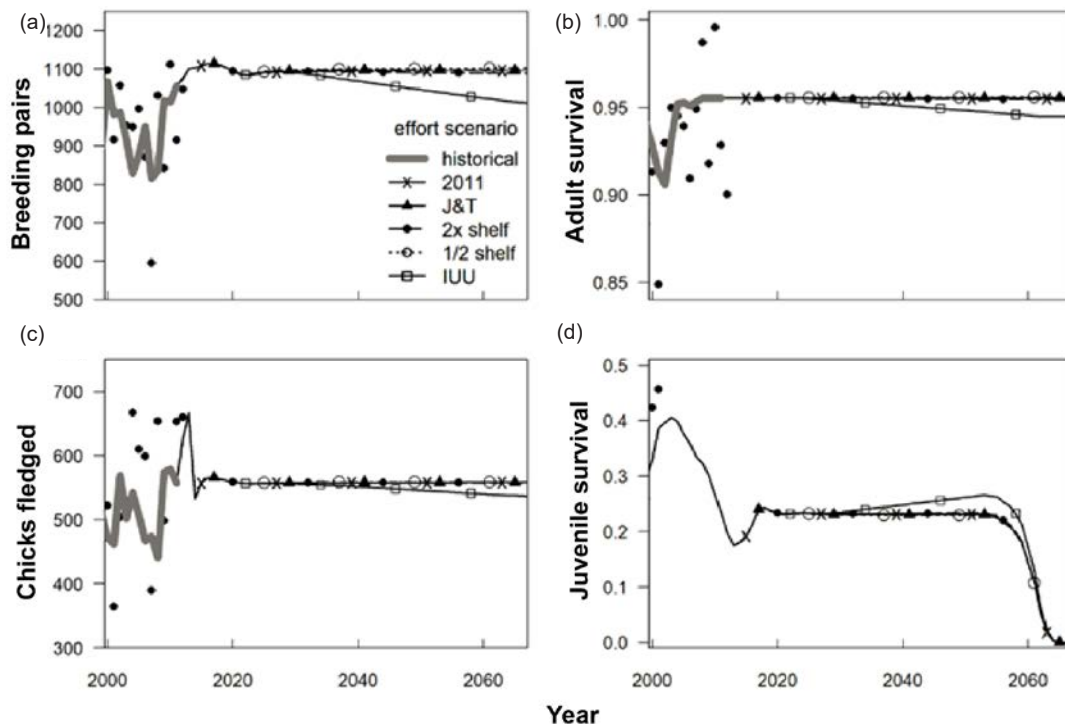
Figure 2: Time series of observed (circles) and modelled (lines and dashes and symbols): (a) number of breeding pairs, (b) adult survival expressed as a percent, (c) number of chicks fledged, and (d) survival to age 5 expressed as a percent across model scenarios. All models assume the parameters estimated in Michael et al. (2017b) and forecast SST. The sharp decline in (d) juvenile survival beginning 2057 relates to the temporal lag required to estimate survival of each cohort, and does not reflect a predicted decline in survival. The 'historical' modelled period (prior to 2011) is shown to provide a historical context. Note that the historical estimated juvenile survival is not shown due to the temporal lag of 10 years required to estimate survival for each cohort. Values before 2000 are not shown. Effort scenarios are described in Table 1.

than the other model scenarios (Figure 2a). Similarly, adult survival was also projected to decline in the IUU model scenario, along with the number of chicks fledged relative to the other scenarios (Figures 2b, 2c). In contrast to the relative decrease in other demographic rates, the IUU model scenario projected an increase in juvenile survival to age 5 while virtually no change was projected in the other model effort scenarios (Figure 2d).

Discussion

Across the effort scenarios assessed, the re-emergence of IUU demersal longline fleet targeting toothfish on the Kerguelen Plateau would have the greatest impact on Kerguelen black-browed albatross demographics. This impact could outweigh the benefits afforded to albatross by an increase in SST due to climate change. Therefore, sustaining this population of albatross requires continued vigilance on multiple fronts. Specifically, continued surveillance of fishing effort near the colony, particularly during the breeding period when albatross

density is high (Delord et al., 2013) is essential to the viability of this colony. Partnered with IUU deterrence is the fundamental need to maintain the at-colony long-term monitoring program. As by-catch was also estimated to occur in other fleets, surveillance of fishing effort across the habitat of this population is also advisable. The above will support continued growth in the understanding of demographic feedback loops and environmental associations in this population, informing managers, regional fisheries management organisations, the fishing industry, modellers, and ecologists (Patrick and Weimerskirch, 2014a, 2014b; Pardo et al., 2017a).

The demographic impacts of the IUU by-catch during the breeding period are clearly seen when compared to the other models. For example, by-catch of breeding adults begins to reduce the number of breeding pairs from the year of the assumed re-emergence of IUU effort (2025) onwards, concurrently reducing adult survival (Figures 2a, 2b). The slight lag between the initiation of the decrease

in the number of breeding pairs and the decrease in the number of chicks fledged likely relates to short-term compensation for the loss of chicks fledged through reduced numbers of breeding pairs via (i) SST-related increase in breeding success and (ii) a slight reduction in density-dependant related pressure on chick survival (Figure 2c).

For juveniles, the loss of individuals from the population via by-catch, and eventually reduced numbers of chicks fledged, promotes greater survival due to reduced density-dependant pressures relative to other model scenarios (Figure 2d). This sensitivity of young birds to the number of individuals in a population has been observed in other populations (Fay et al., 2015). However, as IUU effort in the model scenario increased and the other values declined, the continued increase in juvenile survival was insufficient to prevent an overall decline in the number of breeding pairs with increased by-catch (Figures 1d and 2a). Thus, the combination of IUU by-catch, increasing SST, and density-dependant feedbacks could shift the age-distribution of this population towards younger individuals. A similar finding was identified by Pardo et al. (2017a) in their evaluation of projected increases in mean or standard-deviation, implicating extreme events, in SST in an age-structured model of this population. Assessing the impacts of the projected by-catch in the IUU model scenario on multiple age-classes provides a detailed view of how these impacts flow through the population.

Effort scenarios assessing the demographic impacts of non-IUU super-fleets also contribute to our understanding of this population. In scenarios with little or no by-catch estimated, the absence of a long-term increase in the number of breeding pairs indicates the population could be near the theoretical carrying capacity given the assumed parameter values estimated from historical data (Michael et al., 2017b). Given the high use of neritic habitats by black-browed albatross (Wakefield et al., 2011; Wakefield et al., 2014), the by-catch estimated for the trawl and demersal longline super-fleets makes as these fleets operate in shelf/slope areas. Given the dynamic nature of fishing fleets, continued vigilance of fishing activities in breeding and non-breeding habitats used by this population would enhance the ability to manage and sustain this albatross population.

To broaden the understanding of climate change impacts on albatrosses by incorporating fleet behaviour into population dynamics models, we made a range of simplifying assumptions. Alternative assumptions could have produced slightly different results. For example, applying Krüger et al.'s (2017) approach modelling the presence of fisheries grouped into high and low by-catch for pelagic and demersal fleets would have produced by-catch probability estimates. This would have been difficult to integrate into a demographic framework, but is an efficient approach to identifying areas at sea with a high probability of by-catch across species and regions. By assuming the historical spatial and temporal distribution of albatross and fishing effort, excepting the Japanese and Taiwanese pelagic longline fleets, we also constrained the spatial footprint of by-catch. Our model scenarios do not consider the impacts of a potentially active illegal gillnet fishery in the region, which may impact albatross as high-seas driftnets had in the North Pacific (Johnson et al., 1993; Purves et al., 2007). Lastly, assuming shared by-catch characteristics across a super-fleet and no change in by-catch rate in the future does not allow for improved mitigation nor fleet-specific mitigation efficacy or compliance (Wanless and Small, 2016; Gladics et al., 2017). As our understanding, proficiency in modelling and projecting behaviour increase, additional detail can be incorporated into this and other model frameworks.

There are many opportunities to build upon this research by adding mechanistic understanding and greater demographic detail. As noted above, identifying a mechanism for the association of SST with increased breeding success would provide a valuable context for this frequently identified association (Pinaud and Weimerskirch, 2002; Rolland et al., 2008; Michael et al., 2017b). Incorporating non-linear impacts, variation, and extreme SST events would explicitly acknowledge uncertainty in the shape of this relationship and add realism to the presently linear increase in SST assumed between 2011 through 2063 (Barbraud et al., 2011; Thomson et al., 2015; Pardo et al., 2017a). Shifts in breeding phenology of albatross could also be considered. Investigating the potential for shifts in habitat use at sea could provide novel insight into future interactions (Krüger et al., 2017). Finally, including age-dependant (Pardo et al., 2013), experience (Nevoux et al., 2007), as well as personality (Patrick and Weimerskirch, 2014a) and sex (Patrick

and Weimerskirch, 2014b) related interactions with climate, habitat use and demographic parameters would provide a more detailed and comprehensive picture of potential climate change impacts. Continued integration of these and other factors into climate change projections will provide a more complete representation this population's demographics and enable more informed demographic projections.

Conclusions

This study is one of few to consider alternative effort scenarios on seabird population viability given climate change (Barbraud et al., 2008; Rivalan et al., 2010; Thomson et al., 2015) and the first, to our knowledge, to include fleet-dynamics models. This integrated view of environmental and by-catch impacts on black-browed albatross demographics indicate that by-catch management near the plateau and continued deterrence of IUU effort may be the most efficient way to preserve this colony. Fortunately, these aims are well supported by management, through collaborations with France, Australia, and the CCAMLR Secretariat (Delegtion of France, 2015). However, as stated above, this work does not incorporate the full range of demographic nor environmental subtleties shaping the viability of this population; much remains to be tested regarding future fleet dynamics. Continued exploration, comparison and harmonisation of modelling approaches is essential to efficiently inform management of key drivers and sensitivities, as well as progress the field of predictive population modelling.

Acknowledgments

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