**Title:**

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**Abstract**

**Introduction**

Globally populations of seabirds are declining, and pelagic species with expansive ranges are particularly vulnerable (Paleczny et al. 2015). There are numerous threats to seabirds that can affect the breeding period (such as predation, disturbance and habitat loss), or life stages in predominately marine habitats (such as bycatch, pollution and overfishing; Croxall et al. 2012). An important priority action highlighted by Croxall et al. (2012) is an increase and enhancement of protected areas. As bioindicators, seabirds can offer insight into marine ecosystem changes (Piatt et al. 2007), with seabird foraging ranges used to identify candidate locations for protection (Thaxter et al. 2012), and so protecting these areas could benefit the whole ecosystem (Hooker and Gerber 2004). However, some species are highly mobile covering expansive ranges that could require vast swathes of ocean to be protected, which would be intractable. These species would benefit through improved regulation of management practices covering large areas (Oppel et al. 2018) or more dynamic approaches to protected areas both spatially and temporally (Maxwell et al. 2020). Other seabird conservation research priorities include fishing, which forms a significant threat to seabirds either through competition or direct mortality (Grémillet et al. 2018), and climate change with respect to sea level rises impacting colonies and altering of prey distributions (Dias et al. 2019).

The impacts of fisheries on seabirds can be either direct (e.g. mortality via bycatch), or indirect (e.g. through competition for the same target species and depletion of the resources), although the impacts are not necessarily negative (e.g. increased food supply through discards; Tasker et al. 2000). Although overfishing is not impacting as many seabird species as other threats, the impacts can be very severe (Dias et al. 2019). Across the world many fisheries are depleted, and a third have collapsed (Neubauer et al. 2013). The declines of many seabird species have been linked to prey shortages (e.g. African penguins *Spheniscus demersus* and Cape cormorants *Phalacrocorax capensis* (Crawford et al. 2014), Atlantic puffin *Fratercula arctica* and common guillemot *Uria aalge* (Vader et al. 1989)). Cury et al. (2011) suggested that seabirds require one third of the available prey biomass in order to maintain populations. However, over the last four decades fisheries competing directly with seabirds have increased, and there is a need to improve management measures to mitigate these effects across the world (Grémillet et al. 2018). Fishing closures have been successful (e.g. Daunt et al. 2008; Sherley et al. 2015), and generally have greater ecological benefits than partially protected MPAs, but they can be more politically challenging to implement (Lester and Halpern 2008). Recovery of depleted stocks that were subjected to moderate overfishing is possible within a decade if the fishing pressures are greatly reduced (Neubauer et al. 2013). As seabirds are indicators of food shortages, tracking their movements is useful to understand the impact of fisheries in their foraging certain areas.

Climate change has been identified as one of the top three threats to seabirds globally, but it is more challenging to mitigate the effects compared with other threats (Dias et al. 2019). The speed and severity of climate change is more rapid in the Arctic than anywhere else on Earth, with range expansion not possible for many species and genotypic adaptations too slow, if possible at all (Gilg et al. 2012). Migrants, in particular long-distance migrants, are more likely to encounter mis-timed weather or food resources at one or more stages during their annual cycle (Carey 2009). During the breeding season, in addition to the direct impacts of adverse weather such as chick mortality (e.g. Descamps et al. 2015; Sherley et al. 2011), there is also a potential phenological mismatch with prey with changes in, for example, SST and wind impacting prey species recruitment or distributions (Bakun et al. 2015). It is vital to understand the foraging behaviour of seabirds to understand their resilience to climate change. For example, foraging strategies can play a role in a species’ ability to adjust the breeding window to avoid a mismatch with prey (Descamps et al. 2019).

In this study, we investigate the impact of local fisheries and a climatic variable on the foraging behaviour of breeding arctic terns *Sterna paradisaea,* a long distance migrant that use multiple stopover sites (McKnight et al. 2013), with little room for temporal adjustments to the breeding period and poor breeding success in years with low prey abundance (Monaghan et al. 1992; Vigfusdottir et al. 2013). Arctic terns are an indefatigable species that annually undertake the longest recorded migration of any organism (Egevang et al. 2010), travelling over 90,000 km (Fijn et al. 2013) from circumpolar breeding locations in the Temperate (southernmost at 41°N) and Polar zones to overwintering sites in the Southern Ocean (Hatch 2002). Populations are declining at many locations across the breeding range (e.g. in Canadian High Arctic (Mallory et al. 2018), Western Iceland (Petersen et al. 2020), Greenland (Burnham et al. 2017), and Norway (Barrett et al. 2006)). Generally there is high adult survival (Devlin et al. 2008; Mallory et al. 2018), with very high regional (Egevang and Frederiksen 2011) and colonial breeding site fidelity (Devlin et al. 2008). Declines are likely due to low juvenile survival or recruitment, although some dispersal is possible (Mallory et al. 2018). In Iceland, the collapse of sandeels (*Ammodytes* sp.), a key prey species, has coincided with lower adult survival since 2000 (Petersen 2020), and low fledgling rates caused by starvation (Vigfusdottir et al. 2013). It is therefore key to understand how and where arctic terns forage during the breeding season, and whether their behaviour alters in relation to fish stocks and the weather.

**Addressing the foraging strategies of breeding Arctic terns is therefore essential to develop an understanding of how changes to prey species will alter foraging strategies as this is likely to futher impact the declines in breeding success (such as those recorded in Western Iceland by Petersen 2020 and Vigfusdottir 2013.**

**Given arctic terns relative short foraging area (compared to other seabirds) (REF) they are an excellent species to investigate the impact of near shore activities- they will be impacted and have a lower ability to search for prey elsewhere**

Arctic terns feed on small schooling fish such as herring Clupeidae, sandeels, capelin *Mallotus villosus,* or crustaceans such as krill Euphausiacea (Hatch 2002). They have short foraging ranges generally remaining within 10 km of the colony and occasionally travelling further (Cabot and Nisbet 2013; Rock et al. 2007); Perrow et al. (2011) followed one foraging to a maximum of 29 km from the colony. Foraging trip duration and distance are further constrained by arctic terns being limited to carrying only one to a few prey items at a time, and by shallow plunge dives to a maximum depth of 50 cm (Pratte et al. 2018). Arctic terns are therefore particularly vulnerable to local food shortages (Robertson et al. 2014), with breeding attempts abandoned in years with low food availability (Monaghan et al. 1992). Understanding arctic tern foraging ecology is vital in order to investigate a key cause of the low breeding success (Vigfusdottir et al. 2013), and could also identify early signs of changing conditions that will affect other seabird species foraging further from the coast (Pratte et al. 2018).

Iceland supports *c.* 20-30%of the world’s population of breeding arctic terns (Asbirk et al. 1997). In the warmer waters in the south and west of Iceland, seabirds rely mainly on sandeels, and in the cooler waters in the north and east on capelin and krill (Lilliendahl 2009). Following the collapse of the sandeel population in 2000, annual arctic tern adult survival reduced by 10% in west Iceland (Petersen et al. 2020). 38% of the Icelandic coastal fleet operate in the west and southwest regions (Þórðarson and Viðarsson 2014), and in 2014 the most landings occurred at the harbour in Reykjavík (Edvardsson et al. 2018). We will focus on the foraging behaviours of arctic terns in this region (west of the Reykjanes peninsula and Faxaflói bay). Addressing factors that influence foraging success will shed light on the declines, which is key to preserve this population of arctic terns, and will also benefit the wide range of other species that breed in the rich waters around Iceland.

We aim to (1) describe for the first time where and how far away from the colony Icelandic arctic terns forage, (2) to understand whether these movements can be explained by the costs of travelling to different sites (i.e. travelling into headwinds would be more costly), and (3) to understand to what extent the movements and key foraging areas may overlap with local fisheries.

**Maybe useful notes**

Iceland identified as one of the countries with at least 10 seabird IBAS but with < 25% of the IBA extent within protected areas (Croxall et al. 2012).

Adaptability of arctic terns at the breeding grounds. Freydis’s paper about breeding failures. As the winds changing in Iceland- or broader are winds changing at any breeding locations and are they able to adapt?

In this study we investigate the impact of these two factors on arctic terns during the breeding season. This species does not generally follow fishing boats with no reported instances of bycatch (Check!), and there are no fisheries in the study area targettign the same species (CHECK!) so the focus will be whether there is an overlap in target areas by fishing vessels and birds. Arcitc terns also rely on winds during their migration (HRomankova?), and in years of extreme weatehr events are liable to abandon the breeding attempt (Freydis 2013) so are an excellent study species to investirage these two major threats to seabids.

Foraging – seven arctic terns tracked visually on a RHIB from the Skerries (Wales), with 2 complete foraging trips. Individual variation with one tracked for 57 km up to 29 km from colony, and others producing short range looping trips. (Perrow et al. 2011)

“Arctic terns have limited diving ability and forage more regularly by surface dipping than Common or Roseate terns, which mainly plunge-dive. Fish larvae and juvenile fish are more likely to congregate near the surface than adult fish, but are smaller than prey usually selected by terns. Arctic terns may have preferentially selected small juvenile fish as they were readily available an east to catch and transport, and delivered them regularly to compensate for their lower energy content.” Foraging range (95% contour) = 54.10 km2, core foraging area (25% contour) = 2.91 km2. (Robertson et al. 2014)

Arctic tern mean max foraging range: 24.2 +- 6.3 km (Thaxter et al. 2012)

‘considerable progress has been achieved in recent years in terms of the three highest priority actions: protecting key sites, eradicating/controlling invasive alien species and addressing sea bird bycatch. In contrast, less progress has been made in ensuring ecosystem approaches underpin implementation of fisheries management’ Croxall et al 2012

Paleczny et al 2015 Plos One: “Seabird population changes are good indicators of long-term and large-scale change in marine ecosystems because seabird populations are relatively well monitored, their ecology allows them to integrate long-term and large-scale signals (they are long-lived, wide-ranging and forage at high trophic levels), and their populations are strongly influenced by threats to marine and coastal ecosystems.” Importance as indicators of marine ecosystem status, and to marine ecosystem processes (“predators, scavengers, cross-ecosystem nutrient subsidisers, and ecosystem engineers”)

(Tratahn et al 2015 [**https://doi.org/10.1111/cobi.12349**](https://doi.org/10.1111/cobi.12349))

ARCTIC ANIMAL MOVEMENT ARCHIVE Climate change imapcts on Arctic vertebrates: “poleward range shifts, phenological trophic mismatches and changes in migration, foraging and predator-prey dynamics”. Arctic and adjacent regions are experiencing the most rpaid climate and environmental changes on Earth…notable treds include warming winter temperatures, ice loss and earlier spring snowmelt. These changes profoundly affect conditions experienced by animals, including food availability, interspecific competition, predation and increased human disturbances.” “key drivers of population responses, such as migration, parturition and foraging movement, are undergoing rapid changes, suggesting that climate change is affecting animals in ways that will shape the future of the Arctic.” (Davidson et al. 2020)

Croxall et al 2012 ‘climate change and severe weather largely reflects adverse weatehr and climatic events at breeding sires and potential impact of sed level rise but is clearly an important driver of change that is increasingly affecting seabirds in many ways, albeit mainly in the medium to long term.’

Bakun et al 2015: curr clim change reo 1: 85-93 ‘Marine mammals and seabirds that are tied to sparsely distributed nesting or resting grounds could experience difficulties in obtaining prey resources, or adaptively respond by moving to more favourable biogeographic provinces’

**Methods**

*Field site*

On the Southern Peninsula in Iceland is a breeding site with >10,000 pairs of arctic terns (near Sandgerᵭi, Iceland, 64.015 °N, -22.707 °W). The colony is located within a private eider (*Somateria mollissima*) down farm, and was accessed annually, with landowner permission, for 3–4 weeks during June 2018, 2019 and 2020 for tracking device deployment and retrieval.

*Animal capture*

Since June 2018, 347 breeding arctic terns have been caught and ringed at the study site using a tent spring trap (Moudry traps: TW45). The primed trap is placed on a nest with a trigger line over the eggs, which fires once the incubating bird lands back on the nest. This method does not cause damage to the adult or the eggs. The eggs in each nest were measured and the stage of development was determined with egg flotation (Liebezeit et al. 2007) adapted for arctic terns (Supp. Fig 1). Any arctic tern captured with eggs less than a third of the way through development was not considered for tracking device deployment as birds captured on early stage eggs were more likely to abandon their nests (Vigfúsdóttir, F. *Pers. Comm.*). All birds were ringed on their right tarsus with a unique metal ring from the Icelandic Institute of Natural History, and 216 were fitted with leg flags (blue with a white two character alpha code, sealed with waterproof plastic glue) on the right tarsus. All captured terns were measured (head and bill length: from the centre of the back of skull to the tip of the bill, bill length: from the start of feathering to the tip, and bill depth: on a closed bill at the nostrils) with Vernier callipers (to 0.1 mm). Wing length was measured (1.0 mm accuracy) from the carpal joint to the tip of the longest primary and mass was measured using a cotton bag with a Pesola spring balance (to 1.0 g accuracy). Six breast feathers were plucked with the calamus attached and stored dry at room temperature in an envelope to determine sex using molecular techniques adapted from Fridolfsson and Ellegren (1999; Supplementary Material). The tip of the longest claw was also cut and placed in an Eppendorf tube for stable isotope analysis.

*Tag deployment*

Tracking devices (Pathtrack GPS nanoFix GEO + RF) were deployed on 22 arctic terns in June 2019 (n = 11) and June 2020 (n = 11). They were scheduled to record GPS locations every 15 minutes and would transmit these data to a base station that was placed in the centre of the colony at a height of *c.* 5 m. Tags were attached using a leg loop harness (using 2.54 mm Spectra tape, Bally Ribbons, PA, USA), and weighed 2.9 g (± 0.3 g), which is approximately 2.6% of the mean mass of all arctic terns caught and ringed to date. The device was positioned on the lower back of the tern, with the antennae pointing towards the tail. Only arctic terns with a mass > 110g, and those that returned to incubate their eggs within 5 minutes after the trap was set, had tracking devices attached. Any individuals that were captured between 5–10 minutes were considered control birds and only measurements and rings were deployed on these birds, not tracking devices. If no incubating adult returned to the nest after 10 minutes the trap was removed. Total handling time was < 12 minutes. The nests of the tracked birds were monitored regularly during the deployment period between 05:00 to 00:00. Recapture of arctic terns carrying tracking devices was attempted prior to egg hatching within the same season.

*Wind modelling*

Wind data were modelled using the Met Office (UK) Deterministic Global model, with hourly wind forecasts at sea surface level for the duration of each field season at *c.* 10 km resolution. Wind data were opened using the *ncdf4* package (Pierce 2019). Wind direction and speed were calculated using the *rWind* package (Fernández‐López and Schliep 2018). Bearing between two subsequent arctic tern locations calculated with the *geosphere* package (Hijmans et al. 2017).

FROM HERE TO BE COMPLETED

*AIS data*

*Stable Isotope Analysis*

800 µg sample, Carbon and Nitrogen

*Statistical analysis*

Comparison between trip duration and departure direction in relation to wind (?).

Do biometric measurements or sex affect trip duration?

Unless otherwise stated all analyses were conducted in R (version 3.5.1).

**Results**

How many birds were recaptured?

During egg incubation, a total of XXX foraging trips were recorded for XX individuals (XX in 2019, XX in 2020). Devices were deployed in 2019 (GA-GL) for 8– 10 days and in 2020 (N?-N?) for XX – XX days, but did not all function for the whole period (suppl. table?). Trip duration varied from XX – XXX minutes (±XX minutes, median = XX minutes). The mean distance travelled per trip varied between individuals, where the range of minimum distance travelled = XX – XX km.

*Impact of wind conditions on foraging behaviour*

Difference in the 2019 and 2020 winds. Compare the direction, distance they travel in the two years.

Individual arctic terns departed the breeding colony consistently in xx direction (varies between years and wind conditiions?)

**Discussion**

**WIND**

Wind is a key abiotic factor that impacts seabird demography. It can affect adult survival (Frederiksen et al. 2008), or breeding success (e.g. Johnson and Colombelli-Négrel 2021; Mallory et al. 2009; Robinson et al. 2002). As a driver of coastal circulation wind conditions affect upwelling, and the speed, direction and duration of wind impacts prey species presence and recruitment (e.g. Bakun et al. 2015; Mills et al. 2008; Sætre et al. 2002; Wilson and Laman 2021). Changes to wind patterns can alter foraging seabird behaviour, with strong winds impacting trip duration, flight speeds, trip success (e.g. foraging mass gain, capturing smaller prey, difficulty locating prey) and target prey species (Dehnhard et al. 2013; Elliott et al. 2014; Finney et al. 1999; Saraux et al. 2016; Weimerskirch et al. 2012). Breeding seabirds have been shown to mitigate the impact of strong winds during foraging trips by altering foraging search strategies (e.g. Scopoli’s shearwaters, *Calonectris diomedea*; De Pascalis et al. 2020), flight altitudes (e.g. Antarctic petrels, *Thalassoica antarctica*; Tarroux et al. 2016), and altering flight airspeeds (Spear and Ainley 1997). These can come with energetic costs and

Wind is a driver of coastal ocean circulation (Wilson and Laman, 2020 Fisheries Oceanography)

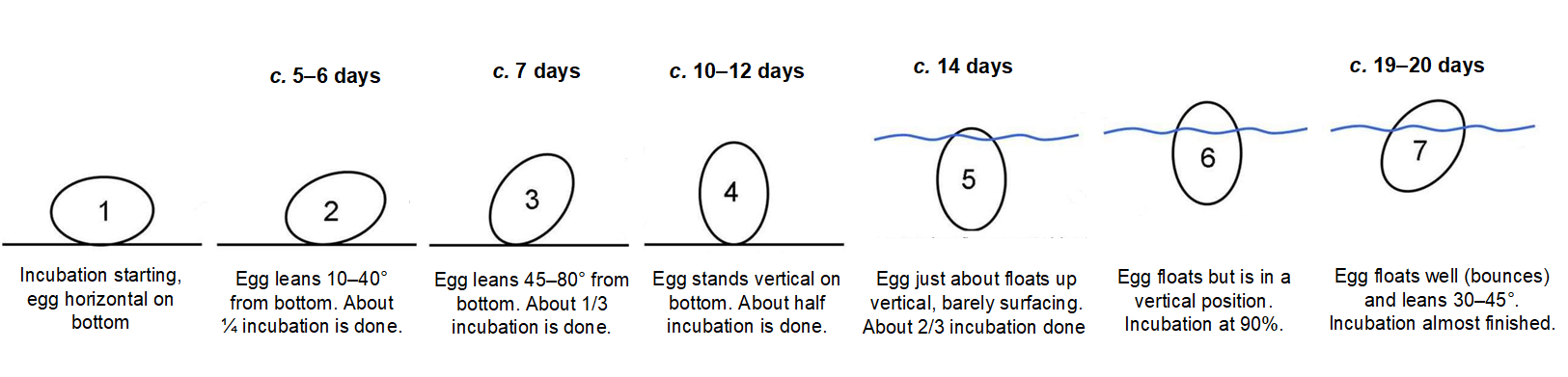
**Collins et al. 2020** [**https://doi.org/10.1111/jav.02057**](https://doi.org/10.1111/jav.02057) Monitored the effects of winds on foraging kittiwakes and that other ‘extrinsic factors, such as prey availability, have a more influential role in determining when and where kittiwakes fly during foraging trips than do wind conditions’

**Figures**

**Supplementary Material**

*Molecular sexing technique methods*

The down was removed from the lower part and the calamus and ~ 1mm of rachis dissected. Two dissected feather calamuses were submerged in 20 µl of Hot Sodium Hydroxide and tris (HotSHOT) lysing solution. Samples were heated at 95°C for 60 minutes and then neutralised with 20 µl of HotSHOT neutralising solution. 2 µl of the lysed cell solution was suspended in 8 µl of MasterMix (5.0 µl HSTaq [DNA Polymerase, PCR Buffer with 3mM MgCl2 and 400 µM of dNTPS], 1.60 µl RNAase free water, 1.0 µl Coral Red, 0.15 µl forward primer, 0.15 µl reverse primer), 0.1 µl Bovine serum albumin). The primers 2550F (5’-GTTACTGATTCGTCTACGAGA-3’) and 2718R (5’-ATTGAAATGATCCAGTGCTTG-3’) were used to amplify fragments of the *CHD* gene. For amplification an initial denaturing step of 95°C for 5 minutes was followed by a touchdown scheme with the annealing temperature lowered by 1°C per cycle, starting at 60°C until 50°C was reached. This was followed by an additional 30 cycles with an annealing temperature of 50°C. Denaturation occurred at 94°C for 30 seconds, annealing for 30 seconds and extension at 72°C for 30 seconds. This was followed with a final extension step of 72°C for 10 minutes. PCR products were run on a 1.5% agarose gel for 45 minutes at 120V in a standard TBE buffer and visualised by ethidium bromide staining.

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*Supplementary Figure 1.* Liebezeit et al. (2007) egg flotation categories adapted for arctic terns by T.G Gunnarsson

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