

Universidade de Évora - Escola de Ciências e Tecnologia

Mestrado em Biologia da Conservação

Dissertação

The use of the Portuguese coast by migratory seabirds

Ana Isabel Correia Fagundes

Orientador(es) | Carlos Godinho

Vitor Hugo Rodrigues Paiva

Évora 2021



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A dissertação foi objeto de apreciação e discussão pública pelo seguinte júri nomeado pelo Diretor da Escola de Ciências e Tecnologia:

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Évora 2021

"A true conservationist is a man who knows that the world was not given by his parents but burrowed from his children"

> John James Audubon Ornithologist, naturalist and painter, 1785-1851

Acknowledgements

This work is not just mine and it would not be possible without a group of people who share the love for birds, and in particular for seabirds, who provided their time, knowledge and have contributed to a greater knowledge of seabirds in Portugal. I would like to thank:

My official advisers Carlos Godinho and Vitor Hugo Paiva and the non-official adviser Jaime Albino Ramos for accepting to help me with this work and for sharing all their precious knowledge and experience.

All the observers who have ensured the counts at the different points of the coast during these 10 years. Special thanks to those responsible for the observation points that voluntarily guarantees the RAM counts: Leonel Rocha (Praia da Vagueira); Helder Cardoso, Pedro Ramalho, Ana Santos and Elisabete Silva (Cabo Carvoeiro); Nuno Oliveira (Cabo Raso); João Paulo Carvalho, Ricardo Guerreiro, Ana Meirinho and André Ferreira (Cabo Espichel); Carlos Santos (Cabo de Sines); Nuno Barros and Tiago Caldeira (Cabo de São Vicente); Miguel Mendes (Ilha do Farol).

SPEA who coordinate the RAM Network in Portugal - Iberian Seabird and Marine Mammal Monitoring and allowed me to have the opportunity to explore this topic.

My colleagues in the marine department of SPEA for all the support, but a special thanks to those who share many hours of fieldwork with me (Nuno, Edward, Tânia and Rita) for putting up with my stresses and mood swings.

Nuno Oliveira, Tânia Nascimento and Hany Alonso for reading the work and giving important inputs and Edward Cormac for helping me practice my English and for the final proofreading.

My family and friends who, even with a sea full of seabirds separating us, always transmitted their positive energies and gave me all possible support.

Last but not least, thank you, Filipe, for being my life partner and for all the support throughout these two years, but especially throughout life.

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Abstract

Portuguese waters are an important migratory corridor for European seabirds and coast-based counts can be used to monitor local and global populations and to study the long-term trends in seabird populations. After 10 years of counts in seven different sites along the Portuguese coast, we aimed to identify the period of occurrence and distribution areas of the seven most common seabird species, evaluate abundance trends and associations with potential oceanographic drivers. The trim model was able to estimate the trend for most of the species with the Balearic Shearwater, the Great Skua, and the post-breeding populations of Sandwich Tern and Common Scoter presenting strong negative trends. The Mediterranean Gull and the Northern Gannet during the pre-breeding migration show a moderate increase. The GAMs found that the abiotic parameters that most often had a significant influence in the models were sea surface temperature, ocean mixed layer thickness and eastward wind speed.

Keywords: seabirds; migration; coastal counts; environmental variables; population trend; Portugal coast

O uso da costa Portuguesa pelas aves marinhas migratórias

Resumo

As águas portuguesas são um importante corredor migratório para as aves marinhas europeias e, contagens a partir da costa podem ser utilizadas para monitorizar e mostrar as tendências a longo prazo das populações de aves marinhas. Após 10 anos de contagens, pretendeu-se identificar o período de ocorrência e áreas de distribuição das sete espécies mais comuns, avaliar as tendências de abundância e potenciais associações com variáveis ambientais. O *trim* estimou a tendência para quase todas as espécies, com a pardela-balear, o alcaide e, as populações pósreprodutoras de garajau-de-bico-preto e da negrola a apresentarem acentuadas tendências negativas. A gaivota-de-cabeça-preta e a população pré-reprodutora do alcatraz apresentam um aumento moderado. Os *GAMs* indicam que os parâmetros abióticos que mais frequentemente tiveram uma influência significativa nos modelos foram a temperatura da superfície do mar, a espessura da camada mista do oceano e a velocidade do vento vindo de Este.

Palavras-chave: aves marinhas; migração; censos costeiros; variáveis ambientais; tendência populacional; costa de Portugal

Introduction

Seabirds have evolved and adapted to live and depend on the marine environment. They breed on land and yet spend most of their lifetime at-sea. The unique characteristics of the marine environment forced birds to develop remarkable adaptations, such as salt glands, webbed feet, specialized feathers and wing shape. The constraints imposed individually by those habitats and the interactions of those constraints are the evolutionary drivers for a host of traits that are unique to seabirds, influencing their ecology, behaviour, physiology and life history (Ballance, 2007).

The truly pelagic seabird species are those spending most of their lives out in the sea and just coming ashore to breed. These species usually breed in places with reduced accessibility, such as small islets or inaccessible cliffs (Burger & Schreiber, 2002). During reproduction, they can be absent from the nests for long periods, up to a week or two, which allows them to access remote areas from their colonies while foraging for food (Burger & Schreiber, 2002; Meirinho et al., 2014). In a summarized form, pelagic seabirds are those that forage on the sea but not in the intertidal, benthic or demersal zones. It's a group that comprises wide-ranging, surface-feeding and relatively shallow-diving predators.

Coastal birds (e.g. gulls, terns) are more dependent on land habitats, where they rest every day. Their nests can be built at ground level or on cliffs and they lay two or more eggs (potentially reaching six), and some of the species can make replacement clutches (Burger & Schreiber, 2002; Meirinho et al., 2014). In general, they do not make long trips during the breeding season, rarely leaving more than a few tens of kilometres from the nesting site, where they return often, either to incubate or feed their chicks.

Besides other important morphological adaptations, the shape of the wing seems to be adjusted, to a large extent, with the ecological niches that the different species explore. Longer wings with a small area are typical of pelagic species, such as shearwaters, while species with diving habits, such as Razorbills, have generally shorter wings and larger body size (Warham, 1977; Burger & Schreiber, 2002). These wing morphologies have evolved not only as adaptations adjusted to the habits of their prey but have also been shaped to efficiently fly larger distances over the oceans. Overall, all these morphological and behavioural adaptations allow seabirds to save maximum energy while searching for and capturing their prey (Burger & Schreiber, 2002).

Seabirds have a key role in marine ecosystems, acting as good environmental indicators (e.g. Ballance, 2007; Piatt & Sydeman, 2007; Parsons et al., 2008). They occur across all oceans, from coastal areas to the high seas, and are easier to study when compared to other marine animals because they are readily visible at sea and depend on land to breed, allowing for a better understanding of their population trends and of their threats (Croxall et al., 2012; Dias et al., 2019). Nevertheless, their study is challenging when compared to terrestrial birds. Most species nest on islands, often in remote regions of the world that are difficult to access. Studying seabirds at sea is also more difficult because it requires expensive resources (Ballance, 2007). Despite these challenges, knowledge of the at-sea component of a seabird's life is essential for a comprehensive understanding of seabird biology (Ballance, 2007).

Seabirds at-sea

The vast majority of our understanding of seabird populations comes from monitoring seabird colonies. However, this is only one stage of their lifecycle and without data from their time at sea (either during breeding, migration or non-breeding stages) an understanding of the full-annual cycle will remain incomplete. While the focus on successful breeding populations is critical, so is understanding the factors affecting seabird distribution and movements at sea. This information has potential to evaluate and minimize threats and inform prioritized marine conservation areas (e.g. Ramírez et al., 2008; Lascelles et al., 2016; Arroyo et al., 2020). Studying migration and non-breeding seabirds' distribution is challenging, as these large-scale movements take place at sea and often involve huge distances (Kubetzki et al., 2009). Additionally, distribution often varies seasonally because of migratory movements, and inter-annually due to oceanographic and climatic factors (Ballance, 2007).

The first method to study seabird migration routes, and their main wintering grounds, was assigning recaptures of ringed birds to their original tagging location. This technique was followed by systematic studies of coastal seabird migration (e.g. Valeiras et al., 2006; Sengo et al., 2012; Arroyo et al., 2014; Jones et al., 2014) which has been an essential tool for the monitoring of local and global populations. Although land-based counts are an efficient technique, these surveys must consider the possible effects of weather conditions on data collected (Jones et al., 2014; Egunez et al., 2018). Another way to collect at-sea data for seabirds is through ship-based surveys. This method provides a platform for researchers to collect data that represent a real-

time picture of seabird populations at the community level as the ship moves (Ballance, 2007). More recently, researchers started using data recorders or remotelytransmitting devices to study at-sea species distribution, which gives us an unprecedented view of the individual foraging choices, and in some cases, that individual's environment, as it moves through the marine ecosystem (Ballance, 2007; Meirinho et al., 2014). Improvements in tracking technologies have dramatically increased our ability to collect data on the movement and behaviour of individual birds, with high resolution and at different spatiotemporal scales (e.g. Ropert-Coudert & Wilson, 2005; Fort et al., 2012; Guilford et al., 2012).

Studies of seabirds at sea can also provide significant information about the marine environment because seabirds have attributes that make them important as indicator species. They spend most of their time at or above the sea surface and they are highly mobile, thereby integrating an ecosystem on a large spatial scale. Results of at-sea research on seabirds can also provide a unique perspective on ecologic processes, health and change in the ocean (Ballance, 2007).

Environmental variables

Marine ecosystems are characterised by strong heterogeneity and variability, both spatially and temporally. In particular, seasonal variations may lead to severe constraints for predators which have to cope with these variations, for instance through migration to avoid unfavourable seasons, or adaptation to local modification of the ecosystem (Lambert et al., 2016). The distribution of most marine pelagic predators is generally connected to a range of dynamic oceanographic processes which determine oceanic productivity and, correspondingly, prey availability, with these processes interacting at different temporal and spatial scales (Hyrenbach et al., 2000; Garthe et al., 2017).

Understanding patterns in distributions, activities, and seabirds foraging behaviours require interdisciplinary approaches. The physical properties of the sea establish the basic habitat parameters with which both the seabirds and their prey have to cope, while biological conditions influence the birds' food supply and foraging behaviours (Garthe et al., 2017).

The use of bio-logging revealed that the at-sea distribution of seabirds is frequently associated with particular oceanographic features, such as frontal systems, gyres, shelf edges or upwelling, which all correspond to highly productive marine areas (Yésou, 2003; Bost et al., 2009; Wakefield et al., 2009). Besides, these studies also showed that seabirds adjust their foraging effort to the persistence and predictability of potential prey patches (Louzao et al., 2012). Many environmental variables (both abiotic and biotic) have been implicated in explaining seabird distribution. For instance, Bathymetry and Sea Surface Temperature are assumed as proxies for physical processes or features driving prey distribution; Chlorophyll concentration as an index of marine productivity; Slope is assumed as a proxy for regions of upwelling and known to influence seabird distributions (Louzao et al., 2012; Nishizawa et al., 2017; Araújo et al., 2017), since food resources are likely more available at shallow (Louzao et al., 2012; Afán et al., 2014).

Decades of ecological research on marine ecosystems has also shown that climatic variables are primary drivers of distribution and dynamic of pelagic organisms (Roessig et al., 2004). In this sense, global climatic indices have received much attention due to their ability to capture a large part of the inter-annual climatic variations over large areas and temporal scales (Stenseth et al., 2002; Gordo, 2007). In particular, the North Atlantic Oscillation (NAO) index, is linked to large-scale patterns in winter conditions in north-western Europe and is correlated with many aspects of the biology of a wide range of marine organisms (Frederiksen et al., 2004). For instance, higher NAO index values are related to stronger western winds across the middle latitudes of the North Atlantic toward Europe (Hurrell & Deser, 2010), which facilitates the seabird migration towards north (Louzao et al., 2015). The extended winter NAO index (December-March) can leave persistent surface anomalies in the seascape that might significantly influence the marine ecosystems throughout the year (Hurrell & Deser, 2010), and thus the distribution and abundance of seabirds at-sea (Paiva et al., 2013) and along coastal areas (Martin et al., 2019).

Temperate ecosystems typically show two blooms of phytoplankton production, the most important one in spring and a smaller one in autumn. Despite this highly predictable cycle, the location and intensity of the main seasonal processes can vary among years according to decadal fluctuations or longer-term trends, as well as year-to-year variations in nutrient input of continental origin by river plumes (Pingree & Garcia-Soto, 2014). Seabirds living at temperate latitudes have evolved in this highly seasonal environment that has shaped their life traits and migration patterns according to the main recurrent large-scale features in physical and biological characteristics of the ocean (Lambert et al., 2016).

Changes in bird assemblages may be a consequence of sometimes rapid variations in hydrographic and/or meteorological parameters. Also, species may differ in their response to these changes, as well as in their choice of habitat, especially pelagic versus coastal seabirds (Garthe et al., 2009). Thus, long-term trends of seabirds depend in part on their shifts in distribution and abundance in response to changes in environmental factors (Ainley et al., 2005; Cox et al., 2018; Gorta et al., 2019).

Seabird threats

Seabirds are one of the most threatened groups of birds (Croxall et al., 2012; Dias et al., 2019). According to the International Union for Conservation of Nature (IUCN) Red List criteria, 31% of all seabird species are globally threatened. Additionally, almost half of all species (47%) have declining population trends (Dias et al., 2019), frequently linked to climate change and human impacts on habitat and prey (Gorta et al., 2019). Some of the drivers of these declines are threats faced at the colonies, whereas others operate at sea. At the breeding grounds, the main threats are the hunting/trapping and the presence of invasive alien species such as rats, cats and goat. Threats at sea can be direct (fisheries bycatch, pollutants and entanglement in marine debris) and indirect, such as the competition with fisheries (Ballance, 2007; Croxall et al., 2012; Dias et al., 2019). Another important threat, which on average is causing the highest impacts on seabirds' life cycle, is climate change/severe weather. This threat impacts seabirds mostly due to habitat shifting and alteration, and extreme temperatures (Dias et al., 2019).

According to Gordo (2007) many organisms, especially migrating birds, are experiencing phenological changes in their life cycles as a result of climate change that has promoted shifts in the timing of migration. With particular consequences for pelagic seabirds, recent studies have evidenced a global increasing trend in wind speed, associated with long-term climatic oscillations (e.g. Committee on Ecological Impacts of Climate Change, 2008; Goldstein, 2009). Some species require wind for efficient long-distance flight, however, not all seabirds are adapted to forage under windy conditions. Small species, such as terns, probably experience considerable difficulty to maintain stability under stronger wind speed (Burger & Schreiber, 2002). During their breeding and non-breeding season, highly migratory seabirds follow prevailing oceanic wind patterns to reduce flight costs on their long-distance migrations (e.g.

Weimerskirch et al., 2000; Adams & Flora, 2009; Ventura et al., 2020; Felicísimo et al., 2008). Changes in wind patterns can cause shifts in foraging ranges and travel rates and may ultimately affect breeding performance (e.g. Weimerskirch et al., 2000, 2012; Ramírez et al., 2013). Besides changes in the wind patterns, the global warming trend observed is expected to increase the amplitude of inter-annual variations in sea surface temperatures, which can induce a shift in the foraging areas of several key apex predators.

Despite all these threats, a global effort is being developed to minimize some of these problems affecting seabirds. According to several studies (e.g. Croxall et al., 2012; Maree et al., 2014; Jones et al., 2016), there is a decrease in the pollution by hydrocarbons, in the impact by invasive alien species and several measures are being implemented to avoid bycatch. Now, the great challenge is the effective management of threats in key areas on land and at sea (Dias et al., 2019). However, seabirds are trans-boundary, crossing arbitrary political boundaries, utilizing the high seas and waters belonging to different countries. Their trans-boundary nature poses a huge management challenge to effectively protect the priority areas for conservation at sea.

Marine Important Bird Areas

Important Bird Areas (IBAs), are areas designated according to objective criteria defined by BirdLife International and are key sites for conservation (Ramírez et al., 2008). The criteria used for the identification of IBAs are clear, objective and have been a global reference value and methodology for decades to protect and improve the conservation status of birds and their habitats.

Marine predators, such as seabirds and cetaceans, are suitable biological indicators to identify and prioritize areas for marine conservation. However, the application of IBA criteria to the marine environment requires some modifications, both in terms of the definition of types of marine IBA, and in the numerical criteria establishing the importance of the birds' populations that uses it (Ramírez et al., 2008). The designation and identification of marine IBAs started in Europe, as it happened in the case of terrestrial IBA, following the recognition of the application of the Birds and Habitats Directives to the territorial waters of each Member State (Ramírez et al., 2008).

The pioneering works of Spain and Portugal in the identification of marine IBAs in their national waters (Ramírez et al., 2008; Arcos et al., 2009), provided the first

complete and comprehensive inventories worldwide, and settled the methodological framework to guide the definition of IBAs for seabirds in open sea waters. Since then, more than 1200 marine Special Protection Areas (SPAs) have been declared in 23 countries of the EU, representing 3.9% of the total EU marine area (Ramírez et al., 2017). In Portugal, 17 marine IBAs were identified in the Portuguese Exclusive Economic Zone (EEZ): four in the Portuguese mainland, 11 in the archipelago of the Azores and two in the archipelago of Madeira (Ramírez et al., 2008). Of the four marine IBAs identified in Portugal mainland EEZ, two of them have important breeding populations of seabirds (the Berlengas archipelago and Ria Formosa), while the other two (Figueira da Foz and Cabo Raso) have relevant gatherings of diverse species that do not breed in Portugal such as the Balearic Shearwater *Puffinus mauretanicus* and Mediterranean Gull *Larus melanocephalus* (Ramírez et al., 2008).

The importance of the Portuguese waters for seabird species

Portugal has one of the largest EEZ in the world (Meirinho et al., 2014) and holds marine areas of the greatest importance for seabirds, being included in the top 20 countries whose EEZs support 50 or more seabird species (Croxall et al., 2012). For many seabirds, Portuguese waters are an important migratory corridor for populations crossing southern European waters, either breeding in northern Europe to overwinter in the African coast or Mediterranean, or breeding in the Mediterranean or South Atlantic to overwinter in northern Europe (Meirinho et al., 2014). For some seabird species and populations, the Portuguese EEZ is also a wintering spot and the importance of our waters for this group of birds is evident in the diversity and abundance of species found outside their breeding season (Ramirez et al., 2008; Meirinho et al., 2014). Both in terms of abundance and diversity, the community of passage migrants and wintering birds is considerably richer than that of birds breeding in Portugal. Some of the non-breeding species even use the continental EEZ in significant numbers, considering their global or European populations, as is the case of the Balearic Shearwater, the Northern Gannet Morus bassanus, the Great Skua Catharacta skua, the Sandwich Tern Thalasseus sandvicensis and the Mediterranean Gull (e.g. Poot, 2003, 2005; Fort et al., 2012; Elmberg et al., 2013, 2016; Araújo et al., 2017). Hence, Portugal has considerable responsibility in the biodiversity conservation of the marine environment and in the maintenance of the ecological balance of this ecosystem.

Since the Portuguese coast is an obligatory migratory corridor for several seabird populations, coast-based counts from strategically located points can be used to monitor local and global populations but also to show their long-term trends (e.g. Yésou, 2003; Arroyo et al., 2014; Martín et al., 2019). Long-term time series data are crucial for understanding the effects of changing ecosystems on wide-ranging predators since the first response of animals might be related to changes in foraging traits (e.g. distribution), while demographic effects might be evidenced in the long-term (e.g. Weimerskirch et al., 2012; Egunez et al., 2018; Gorta et al., 2019).

In Portugal, systematic seabird coastal counts have been performed since 2009 within the RAM Network - Iberian Seabird and Marine Mammal Monitoring (Valeiras et al., 2006; Sengo et al., 2012). This project involved monthly land-based surveys during the whole annual cycle, to obtain a better understanding of the spatio-temporal distribution of seabirds along the coast of Portugal.

Target species

Most sighted species during the RAM counts are Balearic Shearwater, the Northern Gannet, the Great Skua, the Sandwich Tern, the Mediterranean Gull, The Common Scoter *Melanitta nigra* and the Razorbill *Alca torda* (e.g. Sengo et al., 2012; Guedes & Fagundes, 2019).

The Balearic Shearwater is a Spanish endemic breeding seabird which only reproduces in the Balearic Islands. Currently, it is considered one of the most threatened seabirds in the world (BirdLife International, 2020). This species is listed as Critically Endangered (CR) on the IUCN Red List (BirdLife International, 2020) due to the estimation of a mean extinction time of just over 40 years, based on previous population viability analysis (Oro et al., 2004). The main threats the species is facing are predation by invasive mammals and bycatch at fishing gear (BirdLife International, 2020). After breeding, birds migrate into the northeast Atlantic to coastal regions off Portugal and western France, where they spend about one quarter of the year (June to October; Perez-Roda et al., 2016). Spatially, birds on migration appear largely to restrict their activity to one of two core areas off western Portugal or southwestern Brittany (Guilford et al., 2012; Louzao et al., 2012). In Portugal, the species is more concentrated between Porto and Lisboa (e.g. Poot, 2005; Catry et al., 2010; Louzao et al., 2012; Meirinho et al., 2014). There are several observations of large numbers (up to thousands) of Balearic Shearwaters along the Portuguese coast (Catry et al.,

2010) and according to Araújo et al. (2017) during the 2012 post-breeding period, the Portuguese Continental Shelf Waters was used by up to 96.8% of the latest migratory population assessment.

The Northern Gannet breeds in the North Atlantic, mainly in northwest Europe and Canada, with the largest colonies located on the British Isles (del Hoyo et al., 1992). This species has a broad range, the population size is very large and although the population trend is increasing, the species is evaluated as Least Concern (LC; BirdLife International, 2020). Using geolocator tags, several studies revealed the postbreeding movements and non-breeding distribution of this species and confirmed that their breeding and wintering grounds are connected by a major flyway running along the coasts of Western Europe and Africa (e.g. Kubetzki et al., 2009; Fort et al., 2012; Garthe et al., 2016; Grecian et al., 2019). Several tracked individuals used our coast mainly during the pre-breeding migration (Garthe et al., 2016) and others wintered along the coast of Portugal (Fort et al., 2012; Grecian et al., 2019). In Portugal, it is one of the most abundant seabirds and is distributed throughout the continental coast. In some places, such as in the areas in front of Cabo Carvoeiro and Cabo São Vicente, hundreds of individuals can pass per hour during migration (e.g. Walker, 1996; Elmberg et al., 2013, 2016). It is observed throughout the year, especially in winter and during pre-breeding (January and February) and autumnal (September to November) migrations (Catry et al., 2010; Garthe et al., 2016).

Great Skuas are endemic to the northeast Atlantic, breeding in colonies from western Scotland (56° N), to Svalbard, Norway (80° N) and winters off the west coast of Ireland, France, Iberia, West Africa and in the Great Banks of Newfoundland (Magnusdottir et al., 2012). Although this species may have a small range, the population trend appears to be stable and the population size may be moderately small to large, the species is evaluated as Least Concern (LC; BirdLife International, 2020). According to Magnusdottir et al. (2012), the birds are present in their wintering areas between November and the end of January. In Portugal, it can be observed throughout the year, being more common in autumn and winter when gathers in estuarine areas such as Ria de Aveiro, Ria Formosa and the Tagus estuary (Meirinho et al., 2014).

The Sandwich Tern has an extremely large range, occurring in Europe, Africa, western Asia, and the Americas. It breeds seasonally from the coast of east Europe to the Caspian Sea, and winters from the Caspian, Black and Mediterranean Seas to the coasts of western and southern Africa, and from the south Red Sea to north-west India

and Sri Lanka (BirdLife International, 2020). The species is evaluated as Least Concern (LC) due to its extremely large range, large population size and fluctuating population trend (BirdLife International, 2020). It is the most common member of the Sternidae family observed in mainland Portugal, and is abundant as a passage migrant throughout the coast, although its non-breeding population is relatively small. Prebreeding migration takes place between March and June, while post-breeding migration takes place mainly between August and October (Meirinho et al., 2014).

The Mediterranean Gull has a distribution that is essentially circumscribed to Europe (from Russia to the south of France and Spain), with breeding populations located all over central Europe and Mediterranean (BirdLife International, 2020). Although the population trend is decreasing, this species has a wide range and the population size is very large. For these reasons, the species is evaluated as Least Concern (LC; BirdLife International, 2020). During the non-breeding period it is distributed along the coasts of the Black Sea, the Mediterranean, the European Atlantic and the northwest of Africa (del Hoyo et al., 1996). In mainland Portugal it is distributed throughout the coast, occurring mostly in the southern half of the country (Poot & Flamant, 2006; Meirinho et al., 2014). Post-breeding migration runs from mid-June to November and pre-breeding migration from February to early April (Moore, 1992).

The Common Scoter breeds in Iceland, eastern Greenland, northern United Kingdom, across Scandinavia and northern parts of western and central Russia and winters in the Baltic Sea, off the Atlantic coast of Europe and North Africa, south to Mauritania, and in the western Mediterranean (BirdLife International, 2020). This species has an extremely large range and the population size is extremely large and although there are conflicting data on the species' population trend, the species is regarded as not declining sufficiently rapidly to approach the thresholds for Vulnerable. For these reasons, the species is evaluated as Least Concern (LC; BirdLife International, 2020). Along the Portuguese coast it occurs mainly during the winter and migratory periods (Meirinho et al., 2014). The pre-breeding migration is between March and April and the post-breeding migration is longer, lasting from August until October (Catry et al., 2010). During the winter is more frequent in the north of Portugal (Catry et al., 2010).

The Razorbill breeds exclusively in the North Atlantic, both in eastern North American coast and in Western Europe from north-west Russia to north-west France (BirdLife International, 2020). Regarding their winter range, Razorbills from Britain and Ireland mainly overwinter from the Irish Sea south to the Bay of Biscay and Portugal, although some migrate as far as Morocco and into the western Mediterranean Sea (Lavers et al., 2009). This species has undergone moderate declines in Europe, including very rapid declines in Iceland since 2005, therefore, it is listed as Near Threatened (NT). Crashes in sand eel stocks around Iceland may be a contributing factor to the declines (BirdLife International, 2020). In Portugal, it occurs as a passage migrant and as a non-breeding population along the entire continental coast. Postbreeding migration starts in October, but only reaches its greatest expression in November and December. The pre-breeding migration is visible from January, extending until the end of March, or even April (Meirinho et al., 2014).

After 10 years of RAM monitoring in mainland Portugal, there is a need to assess the distribution along the coast of the most common migratory seabird species and their population trends, to inform potential applied conservation measures. We analysed a unique temporal and spatial dataset, regularly collected by skilled voluntary birdwatchers, recorded year-round from seven sites on the Portuguese coast. We evaluated temporal trends in seabird occurrence and abundance, as well as associations with potential oceanographic drivers.

The results of our investigation are presented in the scientific article that follows.

Scientific article

The use of the Portuguese coast by migratory seabirds

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Abstract

Portuguese waters are an important migratory corridor for European seabirds and coast-based counts can be used to monitor local and global populations and to study the long-term trends in seabird populations. After 10 years of counts in seven different sites along the Portuguese coast, we aimed to identify the period of occurrence and distribution areas of the seven most common seabird species, evaluate abundance trends and associations with potential oceanographic drivers. The trim model was able to estimate the trend for most of the species with the Balearic Shearwater, the Great Skua, and the post-breeding populations of Sandwich Tern and Common Scoter presenting strong negative trends. The Mediterranean Gull and the Northern Gannet during the pre-breeding migration show a moderate increase. The GAMs found that the abiotic parameters that most often had a significant influence in the models were sea surface temperature, ocean mixed layer thickness and eastward wind speed.

Keywords: seabirds; migration; coastal counts; environmental variables; population trend; Portugal coast

Introduction

Seabirds have evolved and adapted to live and depend on the marine environment. They breed on land and yet spend most of their lifetime at-sea. They occur across all oceans, from coastal areas to the high seas, and are easier to study when compared to other marine animals because they are readily visible at sea and depend on land to breed, allowing for a better understanding of their population trends and of their threats (Croxall et al., 2012; Dias et al., 2019). Thus, seabirds have a key role in marine ecosystems, acting as good environmental indicators (e.g. Ballance, 2007; Piatt & Sydeman, 2007; Parsons et al., 2008).

The vast majority of our understanding of seabird populations comes from monitoring seabird colonies. However, this is only one stage of their lifecycle and without data from their time at sea (either during breeding, migration or non-breeding stages) an understanding of the full-annual cycle will remain incomplete. While the focus on successful breeding populations is critical, so is understanding the factors affecting seabird distribution and movements at sea. This information has potential to evaluate and minimize threats and inform prioritized marine conservation areas (e.g. Ramírez et al., 2008; Lascelles et al., 2016; Arroyo et al., 2020).

Marine ecosystems are characterised by strong heterogeneity and variability, both spatially and temporally. In particular, seasonal variations may lead to severe constraints for predators which have to cope with these variations, for instance through migration to avoid unfavourable seasons, or adaptation to local modification of the ecosystem (Lambert et al., 2016). The distribution of most of the marine pelagic predators is generally connected to a range of dynamic oceanographic processes which determine oceanic productivity and, correspondingly, prey availability, with these processes interacting at different temporal and spatial scales (Hyrenbach et al., 2000; Garthe et al., 2017). Many environmental variables (both abiotic and biotic) have been implicated in explaining seabird distribution. For instance, Bathymetry and Sea Surface Temperature are assumed as proxies for physical processes or features driving prey distribution; Chlorophyll a concentration as an index of marine productivity; Slope is assumed as a proxy for regions of upwelling and known to influence seabird distributions (Louzao et al., 2012; Nishizawa et al., 2017; Araújo et al., 2017). Climatic variables are also primary drivers of distribution and dynamic of pelagic organisms (Roessig et al., 2004). In this sense, global climatic indices have received much attention due to their ability to capture a large part of the inter-annual climatic variations over large areas and temporal scales (Stenseth et al., 2002; Gordo, 2007). In particular, the North Atlantic Oscillation (NAO) index, is linked to large-scale patterns in winter conditions in north-western Europe and is correlated with many aspects of the biology of a wide range of marine organisms (Frederiksen et al., 2004).

For the management and conservation of threaten organisms under habitat degradation and climate change scenarios, the knowledge of their movement and distribution in space and time is crucial. Seabirds are one of the most threatened groups of birds (Croxall et al., 2012; Dias et al., 2019) and according to the International Union for Conservation of Nature (IUCN) Red List criteria, 31% of all seabird species are globally threatened (Dias et al., 2019). Some of the drivers of these declines are threats faced at the colonies, whereas others operate at sea. Threats at sea can be direct (fisheries bycatch, pollutants and entanglement in marine debris) and indirect, such as the competition with fisheries (Ballance, 2007; Croxall et al., 2012; Dias et al., 2019) and climate change/severe weather, mostly due to habitat shifting and alteration, and extreme temperatures (Dias et al., 2019).

Portugal has one of the largest Exclusive Economic Zones (EEZ) in the world (Meirinho et al., 2014) and holds marine areas of the greatest importance for seabirds, being included in the top 20 countries whose EEZs support 50 or more seabird species (Croxall et al., 2012). For many seabirds, Portuguese waters are an important migratory corridor for populations crossing southern European waters, either breeding in northern Europe to overwintering in the African coast or Mediterranean, or breeding in the Mediterranean or South Atlantic to overwinter in northern Europe (Meirinho et al., 2014). For some seabird species and populations, the Portuguese EEZ is also a wintering spot and the importance of our waters for this group of birds is evident in the diversity and abundance of species found outside their breeding season (Ramirez et al., 2008; Meirinho et al., 2014). Some of the non-breeding species even use the continental EEZ in significant numbers, considering their global or European populations, as is the case of the Balearic Shearwater Puffinus mauretanicus, the Northern Gannet Morus bassanus, the Great Skua Catharacta skua, the Sandwich Tern Thalasseus sandvicensis and the Mediterranean Gull Larus melanocephalus (e.g. Poot, 2003, 2005; Fort et al., 2012; Elmberg et al., 2013, 2016; Araújo et al., 2017). Hence, Portugal has considerable responsibility in the biodiversity conservation of the marine environment and in the maintenance of the ecological balance of this ecosystem.

Coast-based counts from strategically located vantage points can be used to monitor local and global populations but also to show their long-term trends (e.g. Yésou, 2003; Arroyo et al., 2014; Martín et al., 2019). In Spain, the Strait of Gibraltar, a bottleneck of only 14.4 km that separates the European and African coasts, has been

an important place to monitor the migration of seabirds between the Mediterranean and the Atlantic (Programa Migres, 2009). Data from these systematic counts has been widely used to estimate the population of the Balearic Shearwater (Arroyo et al., 2014; Martín et al., 2019) as well as to estimate numbers of Northern Gannets or Scopoli's Shearwaters *Calonectris diomedea* passing through this specific site (e.g. Mateos et al., 2010; Mateos-Rodríguez et al., 2012). The Bay of Biscay, in the north of Spain, as well as the northwest coast of France and the southwest coast of the United Kingdom (covering the western English Channel), are sites where coastal censuses have been providing important information to evaluate seabirds spatio-temporal distribution patterns (e.g. Yésou, 2003; Mouriňo et al., 2003; Jones et al., 2014; Egunez et al., 2018; Martín et al., 2020).

In Portugal, systematic seabird coastal counts have been performed since 2009 within the RAM Network - Iberian Seabird and Marine Mammal Monitoring (Valeiras et al., 2006; Sengo et al., 2012). This project involved monthly land-based surveys during the whole annual cycle, to obtain a better understanding of the spatio-temporal distribution of seabirds along the coast of Portugal. Most sighted species during the RAM counts are Balearic Shearwater, the Northern Gannet, the Great Skua, the Sandwich Tern, the Mediterranean Gull, The Common Scoter *Melanitta nigra* and the Razorbill *Alca torda* (e.g. Sengo et al., 2012; Guedes & Fagundes, 2019).

After 10 years of RAM monitoring in mainland Portugal, there is a need to assess the distribution along the coast of the most common migratory seabird species and their population trends, to inform potential applied conservation measures. We analysed a unique temporal and spatial dataset, regularly collected by skilled voluntary birdwatchers, recorded year-round from seven sites on the Portuguese coast. We evaluated temporal trends in seabird occurrence and abundance, as well as associations with potential oceanographic drivers. Specifically, we had three objectives: (1) to study the seasonality in occurrence and distribution areas of seven seabird species; (2) to detect overall trends of seabird abundances and; (3) to identify environmental drivers affecting the abundance of seabird species along the coast of mainland Portugal.

We hypothesize that 1) most of our target species should exhibit a negative population trend and 2) different seabird species will likely respond to diverse environmental predictors and the abundance of our target species should be mainly influenced by shifts in the NAO index and sea surface temperature, as documented in the literature for seabird species in other coastal ecosystems elsewhere in the world.

Materials and Methods

Study Area

The study area encompassed seven sites along the West and South Portuguese coast within the RAM survey (Fig. 1): Praia da Vagueira (40°33'37" N, 8°46'16" W), Cabo Carvoeiro (39°21'33" N, 9°24'31" W), Cabo Raso (38°42'33" N, 9°29'9" W), Cabo Espichel (38°24'48" N, 9°13'12" W), Cabo de Sines (37°57'26" N, 8°53'13" W), Cabo de São Vicente (37°01'23" N, 8°56'58" W), and Ilha do Farol (36°57'47" N, 7°52'7" W). The counts were undertaken from a vantage point, located on a flat platform at an altitude that varied from 4 m above sea level (Praia da Vagueira and Ilha do Farol) and 100 m in Cabo Espichel.

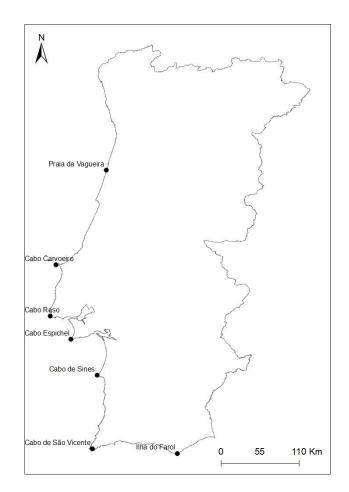


Figure 1 – Location of the counting sites along the Continental Portuguese coast

Seabird Observations

Monthly censuses were conducted on each cape from January 2009 to December 2018, usually on the first Saturday of each month. In general, the counts were performed over the first 3 hours of the day (07h00 to 10h00 between May and September; 08h00 to 11h00 between October and April) whenever the weather and visibility conditions permitted (RAM, 2005; Sengo et al., 2012).

Each count was carried out by two experienced seabird ornithologists, occasionally assisted by trained volunteers. Observers employed continuous telescope, binocular and naked eye scanning to ensure even surveillance of near and far-fields (RAM, 2005; Sengo et al., 2012). The main observer carried out continuous counts equipped with a fixed telescope (magnification x 20), so that the field of vision included about 30% to 50% of the sea under the horizon line, to record the movements of all seabird species. Simultaneously, a second observer with binoculars (10 x 42) surveyed seabird flocks flying out of the field of view of the telescope either because they were flying too close or too high to be recorded by the main observer (RAM, 2005; Sengo et al., 2012). For each seabird sighting, species name, number of birds and behaviour (e.g. flight direction, feeding, local movements, etc.) were recorded. The protocol did not consider any method to avoid double-counting. However, in most cases, birds were observed to show single-direction movements (e.g. north or southwards migration), so double-counting was assumed to be minimal.

The amount of survey effort collected at each site varied; for example, observations were performed over different recorded periods (range: 30–180 minutes). Besides this, each observation point has different total hours of monitoring over the years (see Table 1).

Site	Period of counts	Total observation
		effort (hours)
Praia da Vagueira	2016 - 2018	80
Cabo Carvoeiro	2009 - 2014	175
	2017 - 2018	
Cabo Raso	2009 - 2018	238
Cabo Espichel	2009 - 2015	165
	2017	
Cabo de Sines	2009 - 2016	231
Cabo de São Vicente	2011 - 2018	209
llha do Farol	2013 - 2018	201

Table 1 – Observation effort for each count site. Indication of the years when the counts were performed and total hours of observation.

Bird Data

To have enough information to test models, for analysis we selected the seven most common migratory seabird species out of 52 species observed. We also excluded eight species that breed in Portugal mainland: Cory's shearwater (*Calonectris borealis*), Audouin's Gull (*Larus audouinii*), Yellow-legged Gull (*Larus michahellis*), Lesser Black-backed Gull (*Larus fuscus*), Band-rumped Storm-petrel (*Hydrobates castro*), European Shag (*Gulosus aristotelis*), Cormorant (*Phalacrocorax carbo*), and Little Tern (*Sternula albifrons*).

Environmental variables

A leading pattern of weather and climate variability over the Northern Hemisphere is the NAO index. The NAO index refers to a redistribution of atmospheric mass between the Arctic and the subtropical Atlantic, and swings from one phase to another producing large changes in surface air temperature, winds, storminess and precipitation over the Atlantic as well as the adjacent continents. Ocean, through changes in heat content, gyre circulations, mixed layer depth, salinity, high latitude deep water formation and sea ice cover, is also depicted by the NAO index (Hurrell & Deser, 2010). NAO index also induces variations in upwelling patterns and changes across various marine trophic levels, including small pelagic fish and marine top predators such as seabirds (Stenseth et al., 2002). The NAO index is estimated from differences in sea level pressure between two distant meteorological stations at Lisbon, Portugal and Stykkisholmur, Iceland (Hurrell & Deser, 2010). Positive NAO values are related to strong western winds across the middle latitudes of the North Atlantic towards Europe (Hurrell & Deser, 2010). We used monthly and annual NAO values since it is highly variable, tending to change its phase from one month to another, and its longer-term time-average behaviour reflects the combined effect of residence time in any given phase and its amplitude therein (Hurrell & Deser, 2010). NAO data was extracted from https://crudata.uea.ac.uk/cru/data/nao/.

Other environmental proxies of productivity (e.g. chlorophyll-a concentration) and biophysical meteorological variables (e.g. wind speed) were obtained for the 2009-2018 period from Cupernicus marine environment maritime service (https://www.copernicus.eu/en/services/marine). In spite of having a large set of hydrographic and meteorological parameters, only those that were considered meaningful from a seabird biology and marine ecology point of view were selected (see Table 2). Monthly raster data (~4 km spatial grid) was extracted and manipulated within R (R Core Development Team, 2020), using functions from the raster package (Hijmans, 2020). We then extracted the mean value of all environmental predictors at 10 km radii from each cape (seven locations), to be used as independent variables on the regression models.

Table 2 - Environmental parameters and their time scales as used in this study. The measurement frequency for each parameter is the average value for each month.

Parameter	Units	Description
Chlorophyll-a (chla)	mg m ⁻³	Sea surface chlorophyll a concentration. Used as a proxy for phytoplankton biomass
Primary productivity (pp)	mg C m⁻³	Net primary production of biomass
Ocean Mixed Layer Thickness	cm	OML mediates the exchange of mass, momentum, energy, and heat between the
(so_sst)		atmosphere and the ocean. The injection of nutrients from the nutrient-rich waters below the
		seasonal thermocline are higher the finer this layer
Sea Surface Temperature (sst)	٥C	Average of sea surface temperature for the Northern hemisphere
Wind speed (wind_speed)	m s-1	Wind velocity, without a specific direction
Eastward wind speed	m s⁻¹	Wind velocity from East to West
(eastw_wind)		
Eastward wind speed root	m s⁻¹	Reflects the average energy of the wind from East to West. Strong winds count for more than
mean square (eastw_rms)		weak winds.
Northward wind speed	m s ⁻¹	Wind velocity from North to South
(northw_wind)		
Northward wind speed root	m s⁻¹	Reflects the average energy of the wind from North to South. Strong winds count for more
mean square (northw_rms)		than weak winds
Wind stress (wind_stress)	Ра	Pressure at the ocean surface, without a specific direction
Surface downward eastward	Pa	Downward eastward stress is a downward pressure of eastward momentum at the ocean
wind stress (surf_down_east)		surface. The surface downward stress is the wind stress on the surface

Surface downward northward	Ра	Downward northward stress is a downward pressure of northward momentum at the ocean
wind stress (surf_down_north)		surface. The surface downward stress is the wind stress on the surface
Sea surface height above	cm	The sea surface height fluctuates through the different seasons due to thermal expansion
geoid (uo_sst)		and contraction. In order to quantify the changes, there is a reference level from which to
		measure it. This reference level is called the 'geoid', and it represents the sea surface height
		when no external factors are taken into consideration
Sea surface height anomaly	cm	Sea surface height anomaly data is able to characterize the small and large-scale changes
(vo_sst)		over weeks and years. Is the difference between the long-term average (since 2002) for
		different regions of the ocean and what is actually observed by satellites

Data Analysis

All sightings were effort-corrected by conversion into an encounter rate given by the number of birds per hour (hereafter BPH). We estimated the encounter rates, dividing the number of birds observed by the duration (hours) of the counts per day. This encounter rate was used as an index of seabird abundance.

To evaluate seasonality, the data from the seven sites was gathered in three different regions: North (Praia da Vagueira and Cabo Carvoeiro), Centre-Southwestern (Cabo Raso, Cabo Espichel, Cabo Sines and Cabo São Vicente) and South (Ilha do Farol).

To estimate trends and evaluate the influence of environmental variables we only used the data regarding the periods each species was most abundant on the Portuguese coast: Northern Gannet post-breeding (October and November); Northern Gannet pre-breeding (January to March); Balearic Shearwater (June to October); Common Scoter post-breeding (August to December); Common Scoter pre-breeding (March and April); Sandwich Tern post-breeding (September and October); Sandwich Tern pre-breeding (April and May); Mediterranean Gull (October to March); Razorbill (November to April) and Great Skua (September to January). For these analyses we used the total number of BPH, without considering the flight direction.

The species population trend was calculated using the trim function (Trends and Indices for Monitoring Data) of the R package '*rtrim*' (Bogaart et al., 2020). The trim model is widely used for estimating growth and decline of animal populations based on frequent (annual) counts at a varying collection of sites. The model is able to take in to account missing data through the incorporation of an estimated value based on the overall time series (Bogaart et al., 2020). In this model, data from Praia da Vagueira was excluded because there were only three years of counts and it clearly influenced the trend of the species that concentrate more on the north region.

To test for the effect of meteorological variables and abiotic parameters on species abundance patterns, we used Generalized Additive Models (GAMs; Wood, 2017) which are known to describe biological count data appropriately (e.g. Zuur et al., 2007; 2012). For each species, the response variable was the number of BPH in each month and year. We entered the year as a factor and the explanatory variables included the abiotic parameters referred in the previous section. The location was inserted as a random factor. Multi-collinearity between explanatory variables was examined by the variation inflation factor (VIF; Zuur et al., 2007) using the vifstep and

vifcor R functions. Where collinearity was encountered, the predictors showing the value of vif >7 were removed from the model. Concurvity was also used to check collinearity between smoothed terms (Morlini, 2006). GAMs with Tweedie family on error distribution were performed using R package 'mgcv' (Wood, 2017). We limited thin plate regression splines to 3 or 5 knots to avoid overfitting (Wood, 2017). Before starting to select models to determine which variables affected which seabird, we determined which spatial scale was better at explaining seabird counts. With that goal, we ran all the possible models for each radius (10 and 20 km). Models were constructed for all possible combinations of explanatory variables (using between 3 and 5 knots). Model selection was performed using Akaike's An Information Criterion corrected for small sample sizes (AICc; Sakamoto et al., 1986). According to this approach, models with a lower AICc value show a better fit to the data, because they explain a greater amount of variance with a (reduced) number of parameters. Models were considered to fit the data equally well when they differed by less than 2 AICc units (Williams et al., 2002). Models were first ordered by their AICc value and among equivalent models, the best model was chosen as the most parsimonious one with highest explained deviance. All statistical models were run with R software (R Core Development Team, 2020).

Results

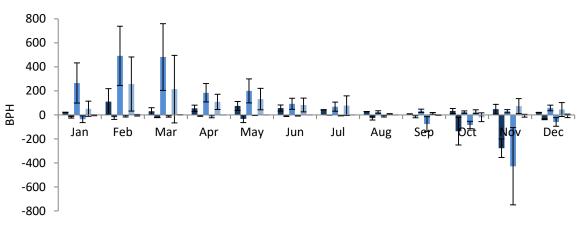
Fifty-two species were recorded over 1299 hours in 388 days of observations across the 10 years. The most frequently recorded species was the Northern Gannet with 260.081 individuals, while the least recorded species in the top seventh was the Great Skua, with 2.172 individuals (Table 3).

Table 3 – List of the seven most common migratory seabird species and total individuals recorded in the coastal census from 2009 to 2018, excluding seabird species breeding in Portugal. Maximum count, in Birds Per Hour (BPH), is also shown.

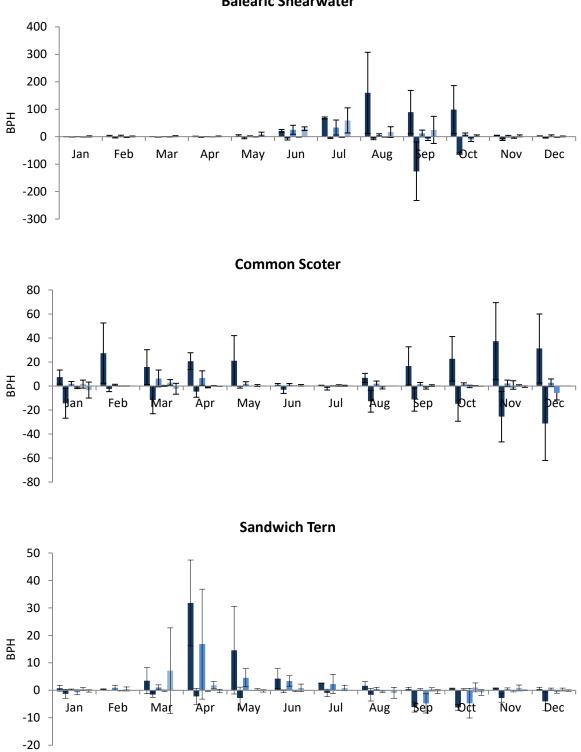
Common name	Scientific name	Total	Max. count
		individuals	(BPH)
		recorded	
Northern Gannet	Morus bassanus	260.081	2.782
Balearic Shearwater	Puffinus mauretanicus	24.242	650
Common Scoter	Melanitta nigra	10.673	659
Sandwich Tern	Thalasseus sandvicensis	6.051	164
Mediterranean Gull	Larus melanocephalus	4.516	85
Razorbill	Alca torda	4.004	174
Great Skua	Catharacta skua	2.172	30

Species seasonality

The species in the study area exhibited different seasonal patterns. While some species were present year-round, others occurred only at certain periods (Fig. 2).



Northern Gannet



Balearic Shearwater

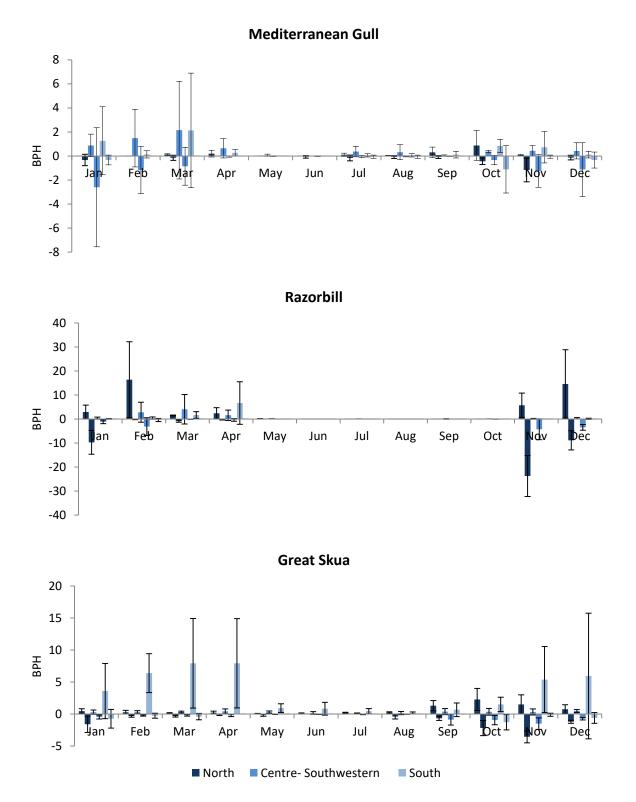


Figure 2 – Seasonality of each of the seven target species in the three different Portuguese regions – North, Centre-Southwestern and South. Number of Birds per hour (BPH) are presented on the Y-axis (mean value ± standard deviation). Months are represented on the X-axis. For visualization purposes only, numbers of birds flying North are positive and numbers of birds flying South are negative, except for the South region where positive numbers are birds flying West and negative numbers birds flying to East.

Although the Northern Gannet was present all year-round, the higher abundance of birds occurred during the winter months which coincides with its non-breeding season (October/November and January to March). In October and November, most of the birds observed were flying towards South while between January and March the flight direction was predominantly to North. The region with a higher number of individuals was the Centre-Southwestern.

Balearic Shearwater is a summer species present in Portuguese waters between June and October. From June to August most of the birds recorded were flying to North while in September and October the predominant direction of flight was south. The North region was an important site for the species during the non-breeding phase. Data shows that the species was recorded consistently (albeit in lower numbers) throughout the winter and spring.

The Common Scoter is a passage migrant that was present in two different seasons - March/April and later between August and December. During the first period, birds were predominantly flying to North while during the post-breeding migration most of the birds were flying south. In the North region, the staging period was higher (August to May), and during the post-breeding period, the number of birds flying to the north was similar to birds flying to the south which may indicate that most of the birds stayed in this area and didn't migrate further south.

Sandwich Tern is also a passage migrant that was present in April/May and September/October although higher numbers were registered during the spring months. As expected during the post-breeding period (September/October) birds were predominantly flying to South and during the pre-breeding period, most birds flew to North.

The Mediterranean Gull is a wintering species present along the Portuguese coast from October to March, mainly in the areas south of Lisboa. During the prebreeding period (January to March) the number of birds was higher although the numbers observed in the North region were very small.

The Razorbill exhibited a strong seasonality being present on the Portuguese coast from November to April. Between November and January, birds flew to the south (post-breeding migration) while between February and April birds flew North (prebreeding migration). It is also clear that the North region was an important site for the species during the non-breeding phase. The Great Skua is also a wintering species that was present in Portugal between September and January, although in the South region the staging period was extended until April. The birds observed in the South region were predominantly flying to West while the birds registered in the North region and Centre-Southwestern showed a proportional direction of flight both for North and South.

According to the country regions where the target species were more frequent, we estimated the average number (minimum and maximum) of individuals observed per hour in the last years (10 years for the Centre-Southwestern region, 6 years for the South and 3 years to the North).

In the last 10 years, on average, 172 - 741 Northern Gannets/hour flew along the Portuguese west coast (Cabo Raso to Cabo São Vicente) during the pre-breeding period and 140 - 595 individuals/hour in the post-breeding period.

Balearic Shearwaters, Common Scoters and Razorbills showed a clear preference for the North region (Cabo Carvoeiro and Praia da Vagueira), staging in this area for most of the non-breeding period. On average in this region were observed 142 - 266 Balearic Shearwater/hour, 26 - 104 Common Scoter/hour and 12 - 20 Razorbill/hour.

Although the data does not indicate a clear preference of the Sandwich Tern for one of the regions, the North seemed to concentrate a higher number of individuals, especially in the pre-breeding period. In the last three years, the average number of Sandwich Terns observed in the North during this period was 25 - 46 individuals/hour.

On the Portuguese coast, the main wintering area of the Mediterranean Gull was the South region (Ilha do Farol), where in the last 6 years, on average 13 birds/hour were recorded. It is also in this region where the largest number of Great Skua was observed where it remained between October and April, with an average number of 5 individuals/hour.

Trends of seabird species abundances

Most species showed a significant temporal trend in abundance (Table 4). Balearic shearwater, post-breeding Common Scoter, post-breeding Sandwich Tern and Great Skua presented a strong negative trend, while the Mediterranean Gull was the only species with a positive trend. The other species presented a moderate decrease or increase and only for the pre-breeding Common Scoter, the trend was uncertain. Table 4 – Estimated trend using trim for each species and seasonality for passage migrants, between 2009 and 2018. Estimate values, standard error and significance (p) are also presented. Significant values are in bold

Species	Estimate	SD	Significance	Trend
			(<i>p</i>)	
Northern Gannet post-	-0.02	0.003	<0.01	Moderate
breeding				decrease
Northern Gannet pre-	0.02	0.002	<0.01	Moderate
breeding				increase
Balearic Shearwater	-0.17	0.007	<0.01	Strong decrease
Common Scoter post-	-0.15	0.03	<0.05	Strong decrease
breeding				
Common Scoter pre-	0.03	0.02	0.07	Uncertain
breeding				
Sandwich Tern post-	-0.23	0.04	<0.05	Strong decrease
breeding				
Sandwich Tern pre-	-0.06	0.01	<0.05	Moderate
breeding				decrease
Mediterranean Gull	0.04	0.02	<0.05	Moderate
				increase
Razorbill	-0.05	0.01	<0.05	Moderate
				decrease
Great Skua	-0.10	0.02	<0.05	Strong decrease

The contrasting trend between Balearic Shearwater (decrease) and Mediterranean Gull (increase) is presented in Figure 3. See graphs for the other species in Appendix 1.

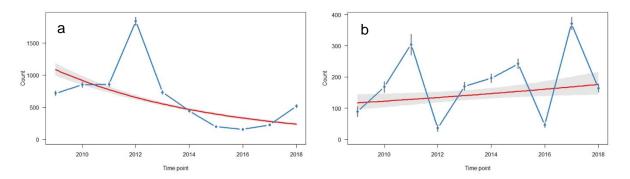


Figure 3 – rtrim model predictions of (a) Balearic Shearwater and (b) Mediterranean Gull annual trends in seabird abundance. Grey lines show 95% confidence intervals.

The influence of environmental variables on abundance of seabird species

The abundance of seabird species in the study area was significantly related to 14 meteorological parameters, though to a different degree (Table 5). Our results reveal that at least two abiotic parameters explains the variance in abundance for most of the study seabird species. The final models accounted for a substantial proportion of the deviance (from 41 to 72%), except for Sandwich Tern post-breeding and Great Skua, respectively 27 and 25% (see details in Appendix 2).

The single factors that most often had a significant influence in the single models were sst (sea surface temperature), so_sst (ocean mixed layer thickness) and eastw_wind (eastward wind speed; Table 5). The abundance of the Northern Gannet post-breeding, Balearic Shearwater, Common Scoter post-breeding, Sandwich Tern pre-breeding, Razorbill and Great Skua were significantly related to sst, with all of them showing a negative relationship.

2009 was the year that influenced the abundance of the most species (four). The year 2017 also had a significant influence on the abundance of four species but the Northern Gannet post-breeding showed a negative relationship while the others were positively related.

Parametric coefficients	Northern Gannet post- breeding	Northern Gannet pre- breeding	Balearic Shearwater	Common Scoter post- breeding	Common Scoter pre- breeding	Sandwich Tern post- breeding	Sandwich Tern pre- breeding	Mediterranean Gull	Razorbill	Great Skua											
											Intercept	3.27 ***	2.74 ***	1.62 ***	-	0.74 *	-	1.27 ***	-	-	-
											2010	-1.25 ***	-	-	1.19 ***	-	-	-	-	-	-
											2011	-0.70 **	-	-	0.78 *	-	-	-	-	-	-
2012	-	-	-	0.85 **	-	0.68 *	-0.68 *	-	0.56 *	-											
2013	-1.09 ***	-	-	0.59 *	-	-	-	-	-	-											
2014	-	-0.34 *	-	-	-	-	-	-	-	-											
2015	-0.68 **	-0.41 *	-	-	-	-	-	-	-	-											
2016	-0.99 ***	-	-	0.75 **	-	-	-1.17 ***	-	-	-											
2017	-0.64 **	-	-	0.61 *	-	-	-	0.60 *	0.52 *	-											
2018	-0.43 *		-	-	-	-	-0.87 *	-	-	-											
smooth terms																					
chla	-	-	-	-	-	-	0.79 *	0.80 *	-	-											
eastw_rms	1.66 **	-	-	-	1.80 *	-	-	-	-	-											
northw_rms	1.84 **	-	-	-	-	-	-	-	-	-											
sst	2.71 ***	-	0.80 *	1.24 *	-	-	0.87 **	-	3.33 ***	0.93 ***											
so_sst	1.95 **	-	-	1.68 **	0.89 **	-	1.52 **	-	3.14 ***	-											

Table 5 – Estimates from the best fit GAM models predicting abundance of each species and seasonality for passage migrants. * p < 0.05, ** p < 0.01, *** p < 0.001; - non-significant results.

smooth terms	Northern Gannet post- breeding	Northern Gannet pre- breeding	Balearic Shearwater	Common Scoter post- breeding	Common Scoter pre- breeding	Sandwich Tern post- breeding	Sandwich Tern pre- breeding	Mediterranean Gull	Razorbill	Great Skua
vo_sst	-	-	-	-	-	0.76 *	-	-	-	-
uo_sst	-	-	-	-	-	-	-	1.67 **	-	-
surf_down_east	2.13 ***	-	-	-	-	-	-	-	-	-
surf_down_north	-	-	-	1.72 ***	-	-	-	-	-	-
eastw_wind	-	0.90 **	-	0.89 **	1.40 *	0.83 *	-	0.74 *	-	-
northw_wind	0.99 *	-	-	-	-	-	-	-	-	-
wind_stress	-	0.89 **	3.07 **	-	-	-	-	0.88 **	-	-
NAO_Monthly	-	-	-	1.84 ***	-	-	0.85 **	-	1.67 **	-
NAO_Annual	-	-	2.61e-16 **	-	-	-	-	-	-	-
Location	4.01 ***	5.74 ***	5.83 ***	5.59 ***	3.37 **	4.22 ***	2.35 *	5.57 ***	5.27 ***	5.21 ***

Two contrasting patterns are explained in more detail. Species responded differently to the ocean mixed layer thickness, with Northern Gannet post-breeding being significantly more abundant as this variable increase, while the opposite was true for the other species (Fig. 4). Most of the species abundance increased when the eastward wind speed was high, except for the Sandwich Tern during the post-breeding migration (Fig. 5).

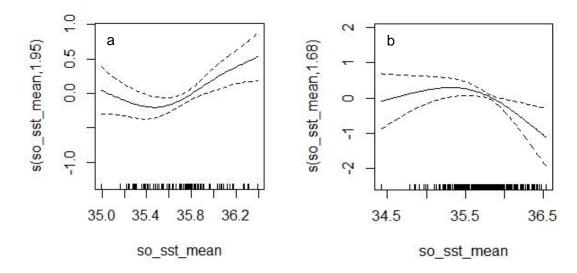


Figure 4 – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of (a) Northern Gannet post-breeding migration and (b) Common Scoter post-breeding migration. Density is represented as a function of the variable 'so_sst'. Dashed lines show 95% confidence intervals around the main effects.

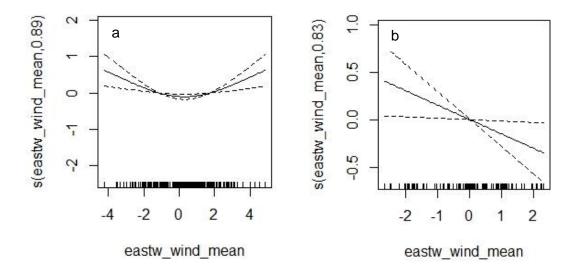


Figure 5 – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of (a) Common Scoter post-breeding migration and (b) Sandwich Tern post-breeding migration. Density is represented as a function of the variable "eastw_wind". Dashed lines show 95% confidence intervals around the main effects.

As a case study, we also present the variables that influenced the abundance of Balearic Shearwater in the Portuguese waters (Fig. 6). The sea surface temperature component showed a negative effect on Balearic Shearwater counts. Hence Shearwaters were more abundant with low values of sst, while they were scarcer under higher sea surface temperatures. The species abundance decreased when the wind stress values were small but with values higher than 0.08 the abundance was relatively constant. Regarding the NAO, the pattern was not clear although it seems that there was a higher effect when the NAO values were positive. Nevertheless, we cannot identify a trend.

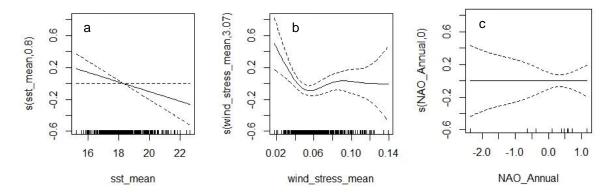


Figure 6 – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on the abundance of Balearic Shearwater. Abundance Density is represented as a function of the variables (a) "sst", (b) "wind_stress" and (c) "NAO" index. Dashed lines show 95% confidence intervals around the main effects.

Discussion

Here we undertook the first long-term study on the spatio-temporal patterns of migratory seabird species on the Portuguese coast from data gathered within the framework of a citizen science project – RAM Network. Our results showed that data obtained in initiatives such as RAM, together with large-scale open datasets for environmental variables, can be successfully applied to describe the migratory distribution and abundance of seabird species accurately. Although these large volumes of data may be hard to analyse and interpret, and relevant interpretations may be limited in scope, accurate information on the distribution of species during the migration period can be derived from these datasets.

Our data confirm the findings of Gomes et al. (2018) who reported that the entire Portuguese coastal zone shows a high ornithological value. Our observation sites were mainly located in the four main hotspot zones of significantly high biological value inside the continental shelf waters identified by Gomes et al. (2018): *i*) off Aveiro and expanding to the north; *ii*) off Cabo Carvoeiro; *iii*) the region off Cabo Raso and Setubal bay up to Arrábida bay and *iv*) the majority of the south region. These hotspots seem to coincide with large-scale topographic and oceanographic characteristics which can influence biodiversity and affect the dynamics of the whole ecosystem (Gomes et al., 2018). These areas are also strongly influenced by seasonal upwelling patterns and highly productive waters, determined by the bathymetry, coastal morphology, and local wind conditions (Relvas et al., 2007). Probably all these characteristics are the main reasons why the coast of Portugal is characterized as an important migratory corridor but also as a major wintering area for some seabird species.

The seasonal patterns detected in our study fit well with the phenological cycle of the seven species occurring in higher numbers and support data from previous authors (e.g. Catry et al., 2010; Magnusdottir et al., 2012; Meirinho et al., 2014; Perez-Roda et al., 2016; Grecian et al., 2019), except for the Mediterranean Gull. Previous data (Catry et al., 2010; Meirinho et al., 2014) refer to this species mainly as a passage migrant in Portugal. However, the Atlantic and Cantabrian regions of Iberia, particularly southern Portugal, became an important wintering area over the last two decades (Poot & Flamant, 2006; Cama et al., 2011). Our data showed that the Mediterranean Gull was present in large numbers between October and March and so we consider this a wintering species.

In general, the trim model was able to estimate the trend for all species, except for the Common Scoter during the pre-breeding migration. However, all these models should be interpreted with caution because the number of sites included in the analysis was small and the trend estimate may not be as reliable or robust, especially for species with fewer observations such as the Great Skua. Usually, for the species with a high number of records, such as the Northern Gannet or the Balearic Shearwater, the uncertainty values associated with each annual index were lower.

Overall, three out of 14 environmental predictors explained the variance in the abundance of the seven migrating seabird species

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Northern Gannet

Northern Gannet is the most common seabird in the Portuguese waters and its main concentration areas are in the southwestern coast, between Lisboa and Cabo São Vicente. The seasonality found for the Northern Gannet is a little different from the one described by Catry et al. (2010). Our data shows that the post-breeding migration starts one month later and the pre-breeding migration last one more month, only finishing in March. This change might be related to the trend observed for colonies in the northeast Atlantic to delay the breeding season. On average, Northern Gannets are breeding 6 days later in 2007 than in 1980 (Wanless et al., 2008). According to Wanless et al. (2008), the consistency of the temporal response across colonies may indicate a common factor operating outside the breeding season and changes in the over-wintering distribution may be related to this. All observations indicate that Northern Gannets now winter further south than previously. A southward extension of the wintering range, and hence increased return distance to the breeding colonies, might result in delayed breeding schedules (Wanless et al., 2008).

We found a contrasting population trend for the two migration periods. During the post-breeding migration, the data shows a moderate decrease while during the prebreeding the estimated trend is a moderate increase. Abundance has been fluctuating over the years and the highest numbers registered in both periods are very different. For instance, 2014 was the year when we observed one of the highest numbers of Northern Gannets during the post-breeding period but in contrast, 2015 was the year with the minimum value for the pre-breeding season. These changes might be related to environmental changes, shifts in prey distribution or other human-related factors, though the pattern is not clear. It's important to state that the bycatch of Northern Gannet in Portuguese waters is high and Oliveira et al. (2020) estimated the death of more than 15.000 individuals per year for the entire fishing fleet operating from Peniche harbour. This is in line with results reported by Calado et al. (2020) for the same fishing fleet, with Northern Gannets being the species bycaught in higher numbers, mostly on longliners.

Overall, findings indicate that Northern Gannets are essentially coastal shelf migrants and the number of individuals recorded during the pre-breeding migration tended to increase with eastward winds while during the post-breeding, the numbers decrease with northward winds. The causes underlying this pattern remains unclear but the birds may have responded to eastward winds by approaching the coast in proportion to the magnitude of wind intensity. Such a change in flight patterns could be a strategy to reduce energy costs because by approaching the coast the wind intensity was reduced by orographic factors. Under tailwind conditions (northward winds during post-breeding) seabirds tended to fly further from the coast, profiting from increasing winds further from shore (Mateos & Arroyo, 2011). Northern Gannet numbers during the post-breeding migration were also negatively affected by sea surface temperatures, which is a usual pattern from former studies since warmer waters are usually characterized by low productivity and prey-availability for top predators in general (e.g. Tremblay et al., 2009).

The differences obtained in both periods might be related to the lesser number of birds that are observed during the pre-breeding migration. Probably during this period birds migrate more offshore (Egunez et al., 2018). In future studies it would be interesting to evaluate these differences only considering the number of adult birds.

Balearic Shearwater

Our data supports previous studies (Guilford et al., 2012; Oppel et al., 2012) that reported that the Balearic Shearwater used the Portuguese Continental Waters as migratory flyways and stopover sites during the post-breeding season, although there are birds present all year round that probably are non-breeders (can include juveniles, failed breeders and adult birds taking a sabbatical year from breeding; Jones et al., 2014). Along the Portuguese coast, there is a higher density of birds in the northern region which is also in agreement with reports from Araújo et al. (2017) and Louzao et al. (2012).

Regarding the numbers of birds detected throughout the years, we find a similarity with results shown by Araújo et al. (2017), who reported that the lowest values of Balearic Shearwater sightings were observed in 2010 and the highest values were observed in 2012. The negative population trend detected is in agreement with previous estimates (e.g. Genovart et al., 2016; BirdLife International, 2020) however contrasts with the results obtained by Martín et al. (2019) that through coastal-land based counts of migrating birds passing in the Strait of Gibraltar (southern Spain) provided evidence that Balearic Shearwaters have been recently increasing in the Mediterranean Sea.

Sea surface temperature, wind stress and NAO index were the variables predicting Balearic Shearwater abundance decrease during migration. Sea surface

temperature in the Northern Hemisphere has been increasing since the 1980s (Morice et al., 2012). Probably this is the main reason explaining the northwards expansion of the species and increases in Balearic Shearwater abundance in the British Isles (Yésou, 2003; Wynn et al., 2007; Luczak et al., 2011; Martin et al., 2020). According to Luczak et al. (2011), this long-term change is also related to the increase of their fish prey, contrary to what is occurring in the Portuguese waters. The warming trend of the sea surface temperature and the NAO index positive phases have a significant impact on the intense and frequent upwelling events occurring off the Portuguese coast during winter (Santos et al., 2001; Borges et al., 2003). When winter upwelling events are much stronger than usual, they can impact negatively on the recruitment of Portuguese sardine by larval dispersal, limiting its success even if beneficial upwelling conditions occurring later during the summer (Santos et al., 2001). This may indicate that for the last decade the Balearic Shearwater has had less fish prey available to forage along the Portuguese coast.

Our findings may confirm that the decreasing numbers of Balearic Shearwater could be related with this northwards expansion and decrease in the fish stock, but we also have to consider that the breeding population also have a global negative trend. In relation to weather predictors, our findings are similar to Martin et al. (2020) who also found that temperature and wind were variables significantly affecting the abundance of migrating shearwaters. Also, in both studies the NAO index hardly contributed to explain the variance in abundance patterns.

Common Scoter

This is probably the species with the least documented information about its occurrence in Portugal. It is known that it occurs mainly in the central and northern regions of the country (Catry et al., 2010; Vingada & Eira, 2018) and that it inhabits shallow coastal waters with sandy bottoms (Meirinho et al., 2014), but besides the months it is present in our waters, there is not much more information. Our data also confirms that the species is more frequent from Cabo Carvoeiro to the north.

The numbers of Common Scoter have dramatically reduced in Ireland and Scotland since 1963 (Ruttledge, 1970). As reported by Catry et al. (2010), in which the species once seemed to have been much more abundant on the Portuguese coast, our results also confirm the strong decline in migratory birds during the post-breeding period. For the pre-breeding period, the estimated trend was uncertain. The trend of European populations is unclear, suspecting that the species may be in moderate decline or has altered patterns of spatial distribution, however, more data is needed to ascertain its status and possible conservation concerns (BirdLife International, 2020).

Regarding the influence of environmental variables, we found some similarities for both migration periods. The species abundance is negatively related to ocean mixed layer thickness but positively related with eastward winds. As these winds are less favourable to the migration, probably the birds come closer to the coast trying to be more sheltered in order to spend less energy. Our data shows that the postbreeding migration was influenced by other environmental variables such as the monthly NAO index and the surface downward northward wind stress. The species abundance was higher when monthly values of NAO were closer to zero and when the values of surface downward northward wind stress increased because these are tailwinds, which promote the migration to the south with less energy expenditure.

Sandwich Tern

The species prefers coastal areas and it's distributed along the Portuguese coast without main areas of concentration. The Sandwich Tern migrates almost exclusively along the coasts of Europe and Africa rather than heading out to sea (Møller, 1981). Møller (1981) also suggests that in Europe they normally travel in small groups, although occasionally in flocks of several hundred, just above the surface of the sea and within a few hundred metres of the coast.

Our results show that main migration passage periods seem a bit smaller than previously reported (Catry et al., 2010; Meirinho et al., 2014). These authors reported three months for the post-breeding migration (August to October) and four months for the pre-breeding period (March to June) while our findings indicate that in the last 10 years the migration has been concentrated in only four months (September and October for post-breeding migration; April and May for pre-breeding migration). This change might be related to the increase of sea surface temperatures in the Northern Hemisphere through the last decades (Morice et al., 2012). Stienen (2006) points out that in the German North Sea the breeding population changes from the 1980s onwards were probably related to shifts in food availability. Stienen (2006) found that the species closely followed fluctuations in the NAO index throughout the period 1969–2004, which was thus possibly altering the food supply over the years (e.g. Ottersen et al., 2001).

The *trim* model estimates a decrease in the abundance of the species, although stronger in the post-breeding period. According to BirdLife International (2020), the European population appears to be stable, despite having suffered declines in some countries. In the German North Sea, Garthe & Flore (2007) report on a significant decline in population numbers during recent years, in line with our results. As previously mentioned, this decline may be related to climate changes and subsequent changes in food availability.

Responses to the environmental parameters varied between species, but also between seasons within the same species. This was the case of the Sandwich Tern. During the post-breeding migration, the abundance was negatively related to eastward winds and sea surface height anomaly. This effect of eastward winds is probably related to the increased difficulty for birds to stay close to the coast and the avoidance of flying with such unfavourable winds. Our data shows that during the pre-breeding migration, the Sandwich Tern is strongly related to areas of higher productivity as it is shown by the negative relationship with the ocean mixed layer thickness. The NAO monthly values also play an important influence in the species numbers as it seems that the abundance is higher when values are very negative or positively high. As it was observed for some of the other species, sea surface temperature plays a negative effect on the Sandwich Tern abundance.

Mediterranean Gull

The regional distribution we found is similar to the one reported by Poot & Flamant (2006), with the main concentration areas being in Lisboa, Alentejo coast and Algarve. Our data shows that the lowest numbers of birds were detected in 2009, 2010 and 2012. Since then the numbers have been fluctuating but were always higher. The population trend obtained for the Mediterranean Gull is in agreement with the last estimates for wintering populations in the Mediterranean and Portuguese coasts (Poot & Flamant, 2006; Cama et al., 2011), which refers to a large increase in population numbers in recent decades. Several authors have reported on the dramatic and rapid change in distribution of this species in the recent decades, expanding northwestwards through most of Europe, including the North Sea and Atlantic coasts (e.g. Meininger & Beckhuis, 1990; Cramp & Simmons, 2004; Zielinska et al., 2007). However, our results are in contradiction to the global trend of the breeding population (BirdLife International, 2020).

Clearly, the abundance of the Mediterranean Gull is influenced by the wind field. The species avoid strong easterly winds but increase in numbers with westerly winds (reflected by the wind stress). According to Isemer & Hasse (1987), the prevailing winds in the west coast of the Iberian Peninsula during winter are mainly southwesterlies. The pattern observed is explained by the fact that Mediterranean Gull is a coastal seabird and easterly winds force the birds to go further away from the coast. Other environmental variables that positively influenced the annual numbers of this species were chlorophyll-a concentration and sea surface height above geoid. This means that the species prefered waters with more turbulence and consequently with higher levels of productivity. Although traditionally seen as a relatively stable season, winter is a period when significant mesoscale variability is superimposed on the climatological circulation (Relvas et al., 2007). Buoyant plumes associated with terrestrial runoff seem to play an important role in the nearshore oceanography, influencing stratification, phytoplankton patterns and larval fish survival (Santos et al., 2007). Upwelling events have been reported to occur also during winter (Relvas et al., 2007).

Razorbill

The Razorbill has a very strong seasonality, being present along the Portuguese coast only between November and April, with higher concentrations in the north region. During the non-breeding season, the Razorbills are restricted to the continental shelf probably due to the importance of shallow continental shelves as areas of high productivity (Stone et al., 1995).

Although this species has undergone a considerable decrease in its conservation status in the last 20 years (due to sharp decline in numbers of breeding couples in Iceland), going from Least Concern in the year 2000 to Near Threatened in 2015 (BirdLife International, 2020), our data only shows a moderate decrease in the last 10 years. Besides the influence of environmental variables, this decrease may be related with the evidence, in Portugal, of the occurrence of massive events of bycatch of Razorbill in fishing gear (Beja, 1989; Costa et al., 2019). In recent years, especially in winter, massive drowning events of this species have been recorded on the beaches of the central region of the country. The main cause for these events is the species entanglement in gillnets, illegally operated (Vingada et al., 2012).

In the study of Costa et al. (2019) the highest number of Razorbills found dead was in the year 2012 which is also the year we registered a significantly higher number of individuals. The year 2012 was the 10th warmest year since records began in 1880 with the annually-averaged temperature across global land and ocean surfaces 0.57°C above the 20th-century average (NOAA, 2013). Warmer-than-average temperatures occurred during 2012 for most of the world's surface. The record warmth was observed across much of central North America, central South America, parts of southern and Eastern Europe, much of the north-eastern coastal Atlantic Ocean, part of the southern Arctic Seas, and sections of the mid-latitude Southern oceans (NOAA, 2013). This increase in the temperature probably has affected the productivity and fish species distribution, including the pelagic fish to move deeper in the water column. These conditions may have forced the Razorbills to migrate further south looking for better foraging areas. This southward expansion was also noted in the North American Atlantic Coast (Iliff et al., 2012).

Sea surface temperature and ocean mixed layer thickness had a significant effect in explaining the variance in the abundance of Razorbills in Portuguese waters. The abundance of this species is limited by higher sea surface temperatures and thicker ocean mixed layer (which is indicative of less productive waters).

Great Skua

The Great Skua is the least common seabird species wintering in the Portuguese coast. Through the 10 years of study, only 2000 individuals were observed and the highest numbers were observed in the South region of the country. Probably this limited number of observations has conditioned the GAM models as well as the estimates of population trend. Actually, the strong decrease trend obtained with rtrim should be interpreted with caution, however, this data is supported by the ESAS (European Seabirds at Sea) counts in Portugal that also shows a strong decrease in the density of Great Skua since 2006 (Pereira & Oliveira, 2019).

The largest number of individuals registered in 2014 seems contradictory with regard to the failure of that year's breeding season in Bjørnøya, Svalbard, Norway in which no offspring survived more than 20 days (Jakubas et al., 2018). This failure appears to be related to the lack of food available that year due to changes in the fish stock, especially the polar cod *Boreogadus saida* (main prey), which distribution shifted northeastwards (Jakubas et al., 2018). This situation may have forced birds to migrate

further south to places with higher food availability. Although most of the birds from Bjørnøya winters in higher latitudes, some tracked individuals spent some months on the Iberian coast (Magnusdottir et al., 2012). Although we didn't find a relationship between the number of Great Skuas and the Annual NAO, the reduced number of birds observed in 2015 may have been related to a high NAO value (the highest value recorded in this 10 year period). Positive NAO index is typified by more intense and frequent storms in the vicinity of Iceland and the Norwegian Sea (Hurrell & Deser, 2010), which can hinder the migration of the species to lower latitudes.

The sea surface temperature was the only environmental variable significantly influencing the numbers of this species. Thus, the presence of Great Skuas seems to be limited by temperatures between 16 and 18°c.

Conclusions

Understanding the at-sea distribution and migration of seabirds is becoming increasingly important as pressures on the marine environments increase. Identifying seabird movements and use of areas where they are at risk from a range of marine threats is critical to ensure their conservation. The scarcity of information about migration movements and numbers of individuals, makes seabirds vulnerable in an era of global change, with fisheries impacting ever more the marine environment.

Citizen science projects recording seabirds from the coast may provide useful records for the monitoring of the species along its migratory route, completing the partial picture offered by geo-locators and vessel surveys. Direct observations of birds collected by volunteers are a cost-effective source of data and these massive datasets provide low-cost information on long-term temporal and large spatial extents. This allows us to identify spatio-temporal patterns from many different individuals belonging to several populations.

Seabird populations are in decline around the globe and our analysis contributes to this concerning trend, with four species presenting a strong decline in abundance and two species a moderate decline. A decline in Balearic Shearwater reflects the trend in breeding colonies (BirdLife International, 2020) but the negative trends for Common Scoter and Sandwich Tern are a surprise as, according to BirdLife International (2020), these species have an unknown (Common Scoter) or stable trend (Sandwich Tern). Time, and more data, will determine the extent to which these declines in abundance are indicative of species-wide declines, but the long-term trends identified here highlight motives for conservation concern for at least some seabird species.

Statistical models such as those developed in the present study will enable predictions, for example on the consequences of climate change. From the data shown here we can expect substantial effects of future climatic changes on the composition of the seabird community on the Portuguese coast, due to the link between relevant environmental parameters and seabird distribution. This is clear when most of the species presented a negative relationship with sea surface temperatures and the same species presents a negative trend. Our data indicates that population trends of species such as the Balearic Shearwater, Common Scoter or Sandwich Tern can be a consequence of changes in foraging areas in the non-breeding areas in general, but also on the Portuguese coast. Indeed, climate variations impact on individuals and populations may operate either directly through physiology (metabolic and reproductive processes) or indirectly through the ecosystem, including prey, predators, and competitors.

Our analysis improves the understanding of inter-annual variation in seabird distributions, interspecific differences in response to environmental conditions, and provides a basis for understanding how migratory seabirds may respond to climate change. This information is critical for effective conservation planning and for the design of future monitoring programs. As mandated by the recent Marine Strategy Framework Directive (2008/56/EC), all European states are required to regularly monitor and report on the state of the marine environment of their waters. The distribution range and the abundance of species are possible indicators to contribute to assessing the achievement of Good Environmental Status. This study could provide a baseline of the seasonal distribution of migratory seabirds in the Eastern North Atlantic and their relative abundance, complementary to the monitoring of breeding sites.

Acknowledgments

The authors would like to thank to all the observers who have ensured the counts in the different points of the coast during these 10 years. Special thanks to those responsible for the observation points that voluntarily guarantees the RAM counts: Leonel Rocha (Praia da Vagueira); Helder Cardoso, Pedro Ramalho, Ana Santos and Elisabete Silva (Cabo Carvoeiro); João Paulo Carvalho, Ricardo Guerreiro, Ana Meirinho and André Ferreira (Cabo Espichel); Carlos Santos (Cabo de Sines); Nuno Barros and Tiago Caldeira (Cabo de São Vicente); Miguel Mendes (Ilha do Farol). We appreciate the comments from Hany Alonso whose efforts improved our paper and Edward Cormac for the final English proofreading.

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Final Remarks

Understanding the at-sea distribution and migration of seabirds is becoming increasingly important as pressures on the marine environments increase. Identifying seabird movements and use of areas where they are at risk from a range of marine threats is critical to ensure their conservation. The scarcity of information about migratory movements and numbers of individuals, makes seabirds vulnerable in an era of global change, with increased and prevalent environmental stochasticity and fisheries impacting even more the marine environment.

The marine environment is highly dynamic and its conditions in a particular location are ever changing. Available global data from satellite imagery are frequently provided at high spatial and temporal resolutions, offering an excellent opportunity to model highly mobile migratory species by informing on the heterogeneity at different spatiotemporal scales affecting the habitat use. We show that this data, together with observations of seabirds collected in citizen science projects, such as the RAM Network, can be used to identify conservation concerns and targets at regional levels related to environmental changes such as global warming or fisheries, among others, which are difficult to track using traditional approaches.

Our abiotic and biotic predictors explained a large proportion of the overall variability in seabird abundance along the Portuguese coast. Statistical models such as those developed in the present study will enable predictions, for example on the consequences of climate change. From the data shown here we can expect substantial effects of future climatic changes on the composition of the seabird community on the Portuguese coast, due to the link between relevant environmental parameters, such as sea surface temperature and seabird distribution. Analysis shown here can be a powerful and cost-effective tool for the long-term spatial monitoring of the migratory patterns of sensitive marine species. However, count analysis must control for the effect of weather, and in this context future studies should try to obtain standardized indices of seabird counts. Accounting for the distance at which the birds are observed from each site is also recommended.

Our analysis improves understanding of inter-annual variation in seabird distributions, interspecific differences in response to environmental conditions, and provides a basis for understanding how migratory seabirds may respond to climate change. This information is pivotal for effective conservation planning and for the design of future monitoring programs, especially for those targeting species whose large part of the population uses the Portuguese waters during the non-breeding period. This data is also very important to complement the information regarding population estimates and trends of particular breeding colonies. This is a more comprehensive analysis but it can be an asset for monitoring a group that suffers enormous pressures and threats, both at sea and inland, and that in the case of some species, it can be very difficult to monitor at the breeding colonies.

Problem solving suggestions

Although this work is based on an extensive database, there are several gaps in it, namely the absence of counts in some observation points per year. For example, the cases of the Ilha do Farol and Praia da Vagueira that only were added to the observation network after, respectively in 2013 and 2016, or the case of Sines without observers to ensure the counts in 2017 and 2018. This census requires high skilled observers with availability to systematically ensure the counts, which unfortunately are lacking in Portugal, resulting in many gaps over the years.

Another difficulty that should be noted is that the observations should take into account the weather conditions, since adverse conditions such as strong swell, reduced visibility by rain or fog or the existence of strong tailwinds, can make it difficult to identify or detect species or even condition the birds' migration or foraging behaviours.

The difficulties presented above require that the interpretation of the effects of environmental variables on species abundance (GAM models) and the estimates of trends should be interpreted with caution.

Although in the scientific article we only present the population trends using trim, we tested another model – geeglm. The trim model is widely used for trend estimation of animal populations based on (possibly sparsely available) count data (Bogaart et al., 2020) and model 2 assumes that populations vary across sites but show the same growth everywhere and that growth rates are constant during specified time intervals. *Trim* takes the observed values whenever it is available and impute the missing values for sites without count in the given year (Bogaart et al., 2020). The imputed population size estimates produced by *trim* should be used with some caution because the estimation of missing counts using the year effect can lead to severe overestimations and large fluctuations that can be especially severe when the number of sites with actual counts is low. *GeegIm* from the package "geepack" (Højsgaard et al., 2019) fits

generalized estimating equations using the 'geese.fit' function for doing the actual computations and has a syntax similar to glm (General Linear model; Højsgaard et al., 2019). The *geeglm* is less used for estimating trends, but because we have a small number of observation sites, it could be more appropriate.

Looking at the results and graphs of the *geeglm* and *trim* we can see there is some consistency between both models although *trim* has managed to estimate the population trend for a greater number of species. In general, the species for which the *trim* estimated a sharp decline or increase, ended up showing a similar trend through *geeglm* (except for the Great Skua). When the population trends were moderate, the *geeglm* was unable to estimate them. This way it seems that the results of both analyses are in line, although those of *geeglm* are more conservative.

In the article we decided to present our results only with *trim* models and the *geegIm* results are presented in Appendix 3.

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Appendix 1 – Species trends. rTrim plots

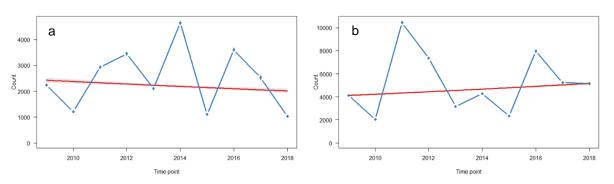


Figure I – rtrim model predictions of Northern Gannet (a) post-breeding migration and (b) prebreeding migration annual trends in abundance. Grey lines show 95% confidence intervals.

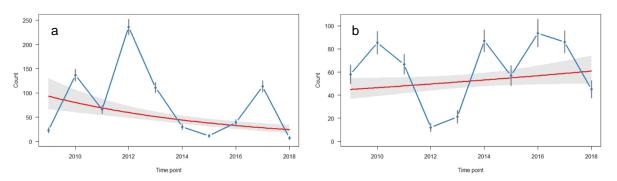


Figure II – rtrim model predictions of Common Scoter (a) post-breeding migration and (b) prebreeding migration annual trends in abundance. Grey lines show 95% confidence intervals.

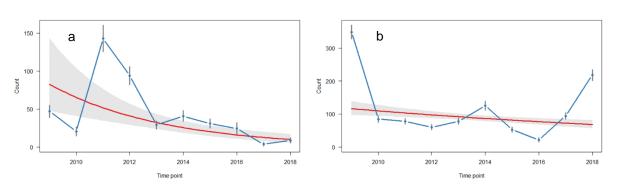
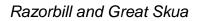


Figure III – rtrim model predictions of Sandwich Tern (a) post-breeding migration and (b) prebreeding migration annual trends in abundance. Grey lines show 95% confidence intervals.

Common Scoter

Sandwich Tern

Northern Gannet



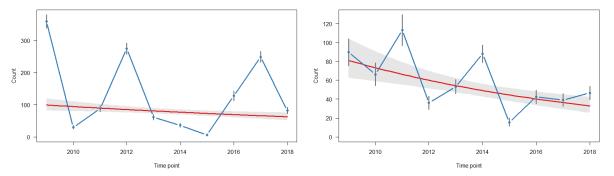


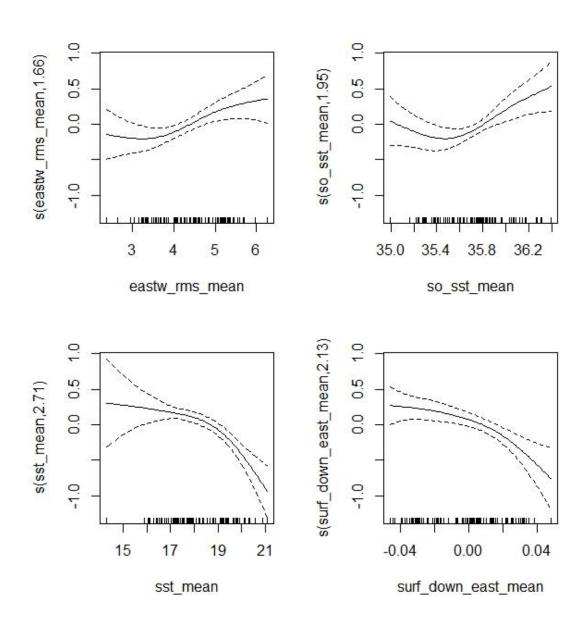
Figure IV – rtrim model predictions of annual trends in seabird abundance (a) Razorbill and (b) Great Skua. Grey lines show 95% confidence intervals.

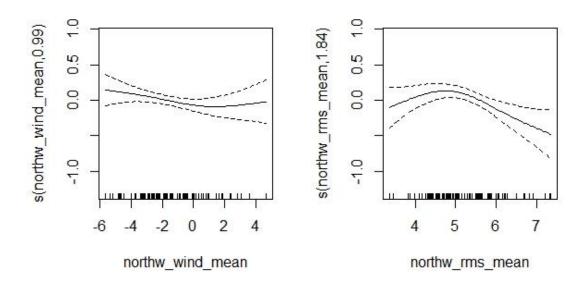
Appendix 2 – Generalised additive model (GAM) results

Northern Gannet post-breeding migration

Table A - Best fit model predicting the abundance of Northern Gannet during the post-breeding migration

Model	AIC	Deviance
		explained
Counts ~ Year + s(eastw_rms) + s(northw_rms) +	595.8128	72%
s(so_sst) + s(sst) + s(surf_down_east) +		
s(northw_wind) + s(uo_sst) + s(NAO_Monthly) +		
s(NAO_Annual) + s(Location)		







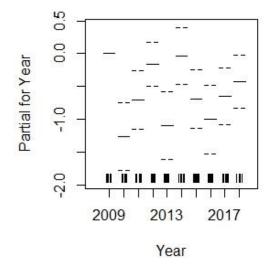
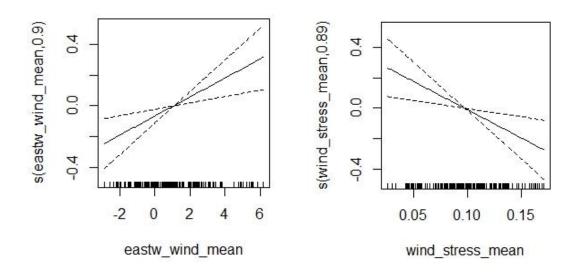


Figure I – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of Northern Gannet during the post-breeding migration.

Northern Gannet pre-breeding migration

Table B - Best fit model predicting the abundance of Northern Gannet during the pre-breeding migration

Model	AIC	Deviance
		explained
Counts ~ Year + s(chla) + s(eastw_rms) + s(eastw_wind) +	1128.003	59%
s(sst) + s(northw_wind) + s(uo_sst) + s(vo_sst) +		
s(wind_stress) + s(NAO_Monthly) + s(NAO_Annual) +		
s(Location)		





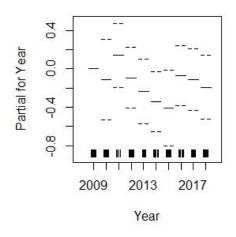


Figure II – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of Northern Gannet during the pre-breeding migration

Balearic Shearwater

Model	AIC	Deviance
		explained
Counts ~ Year + s(shla) + s(so_sst) + s(sst) +	1325.816	49%
s(surf_down_east) + s(surf_down_north) + s(uo_sst) +		
s(wind_stress) + s(NAO_Monthly) + s(NAO_Annual) +		
s(Location)		

Table C - Best fit model	predicting the abund	ance of Balearic Shearwater

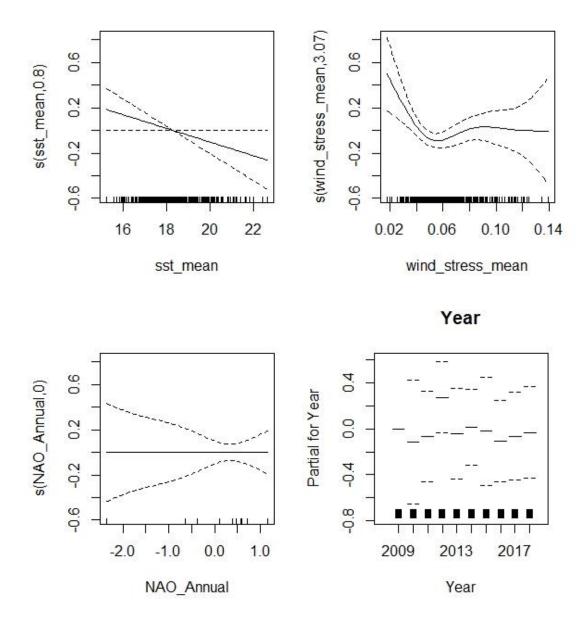
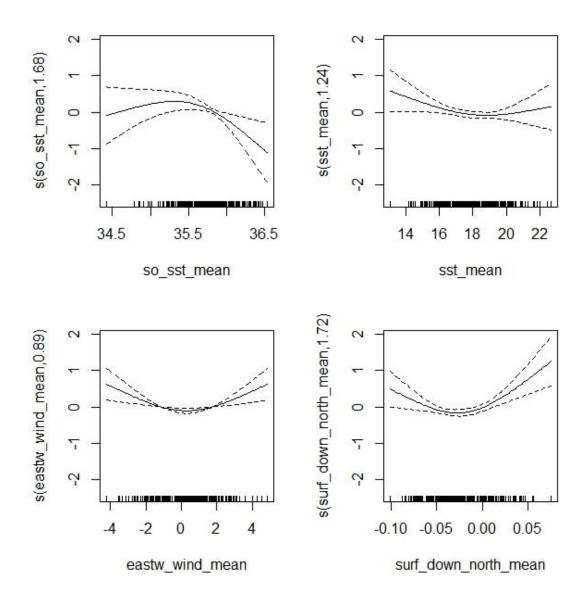


Figure III – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Balearic Shearwater

Common Scoter post-breeding migration

Table D - Best fit model predicting the abundance of Common Scoter during the post-breeding migration

Model	AIC	Deviance
		explained
Counts ~ Year + s(shla) + s(eastw_rms) +	826.6092	57%
s(northw_rms) + s(so_sst) + s(sst) + s(eastw_wind) +		
s(surf_down_north) + s(uo_sst) + s(vo_sst) +		
s(NAO_Monthly) + s(NAO_Annual) + s(Location)		



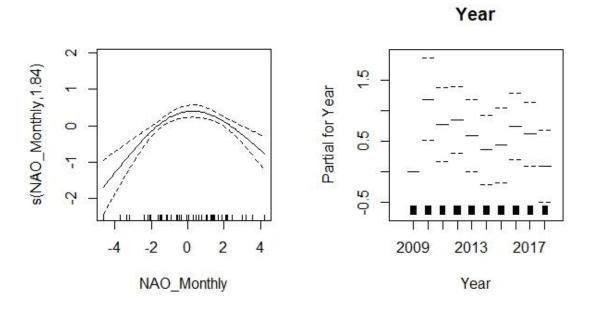


Figure IV – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Common Scoter during the post-breeding migration

Common Scoter pre-breeding migration

Table E - Best fit model predicting the abundance of Common Scoter during the pre-breeding migration

Model	AIC	Deviance
		explained
Counts ~ Year + s(shla) + s(eastw_rms) +	402.679	47%
s(northw_rms) + s(so_sst) + s(sst) + s(eastw_wind) +		
s(uo_sst) + s(vo_sst) + s(NAO_Monthly) +		
s(NAO_Annual) + s(Location)		

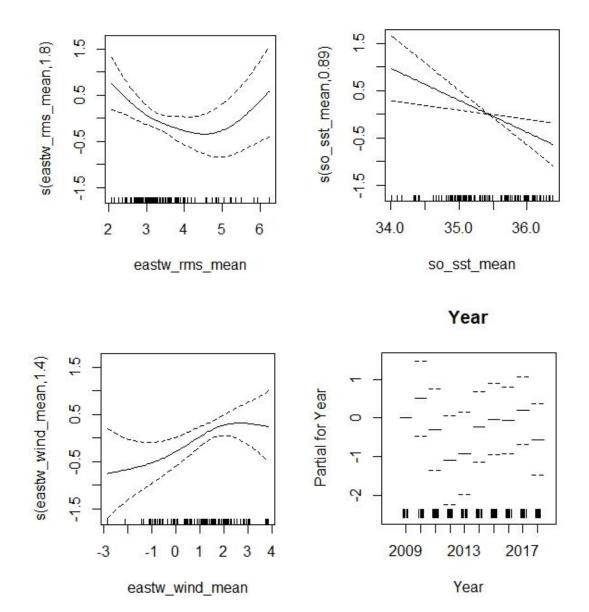
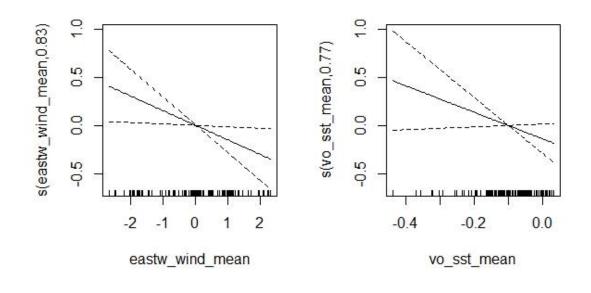


Figure V – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Common Scoter during the pre-breeding migration

Sandwich Tern post-breeding migration

Table F - Best fit model predicting the abundance of Sandwich Tern during the post-breeding migration

Model	AIC	Deviance
		explained
Counts ~ Year + s(so_sst) + s(eastw_wind) +	407.2859	27%
s(northw_wind) + s(uo_sst) + s(vo_sst) +		
s(NAO_Monthly) + s(Location)		



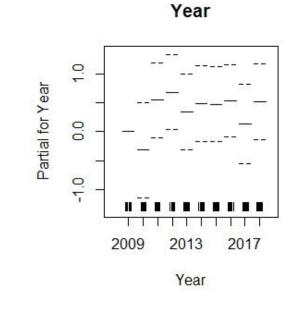
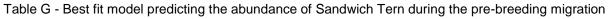
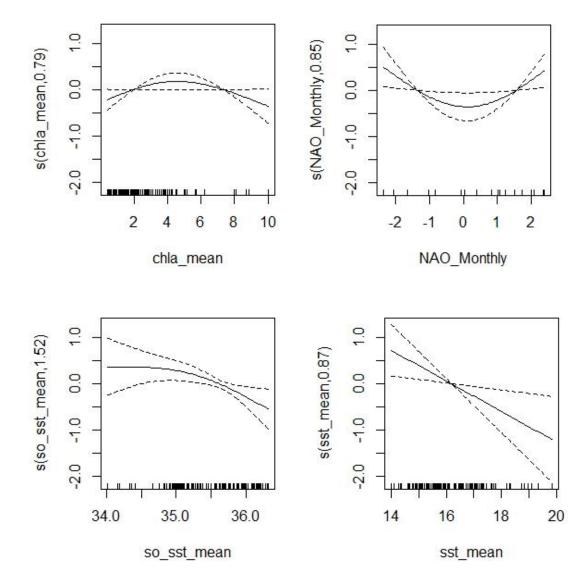


Figure VI – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Sandwich Tern during the post-breeding migration

Sandwich Tern pre-breeding migration

Model	AIC	Deviance
		explained
Counts ~ Year + s(chla) + s(eastw_rms) + s(so_sst) +	448.005	47%
s(sst) + s(northw_wind) + s(uo_sst) + s(vo_sst) +		
s(wind_stress) + s(NAO_Monthly) + s(Location)		





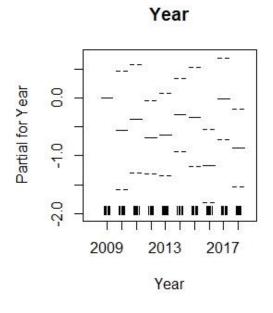
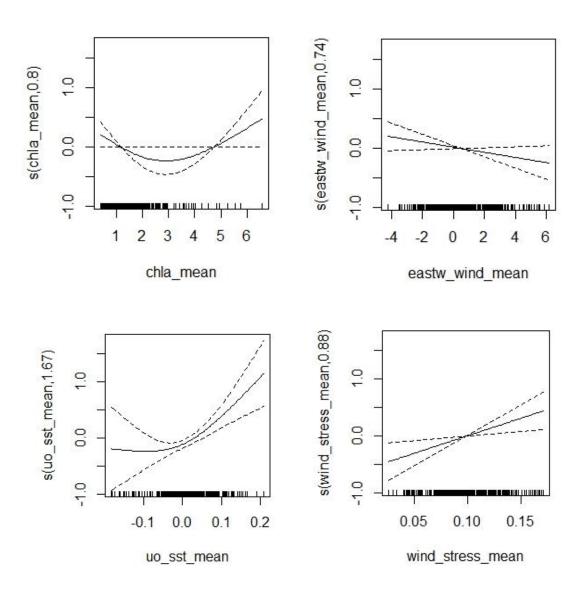


Figure VII – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Sandwich Tern during the pre-breeding migration

Mediterranean Gull

Model	AIC	Deviance
		explained
Counts ~ Year + s(chla) + s(northw_rms) +	893.9239	44%
s(eastw_rms) + s(so_sst) + s(sst) + s(eastw_wind) +		
s(northw_wind) + s(uo_sst) + s(vo_sst) +		
s(wind_stress) + s(NAO_Monthly) + s(NAO_Annual) +		
s(Location)		

Table H - Best fit model predicting the abundance of the Mediterranean Gull



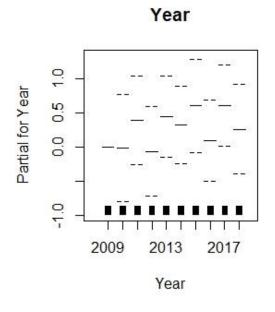


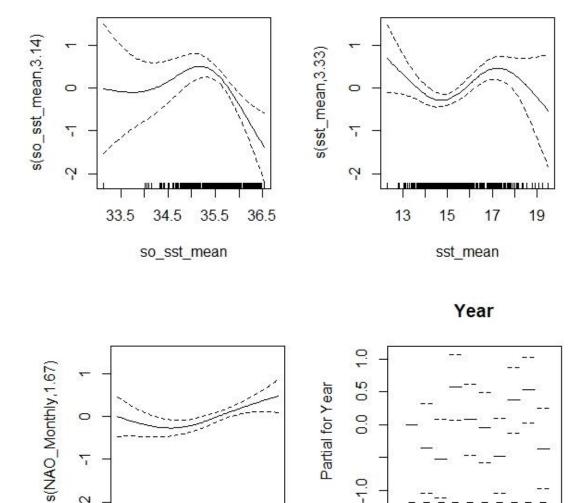
Figure VIII – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Mediterranean Gull

Razorbill

2

Model	AIC	Deviance
		explained
Counts ~ Year + s(so_sst) + s(sst) + s(vo_sst) +	1036.363	41%
s(NAO_Monthly) + s(Location)		

Table I - Best fit model predicting the abundance of the Razorbill



0

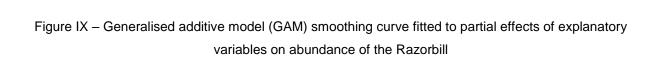
NAO_Monthly

2

4

-2

-4



-1.0

2009

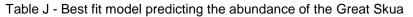
2013

Year

2017

Great Skua

Model	AIC	Deviance
		explained
Counts ~ Year + s(chla) + s(eastw_rms) +	718.9852	25%
s(northw_rms) + s(so_sst) + (sst) + s(eastw_wind) +		
s(uo_sst) + s(vo_sst) + s(NAO_Monthly) + s(Location)		



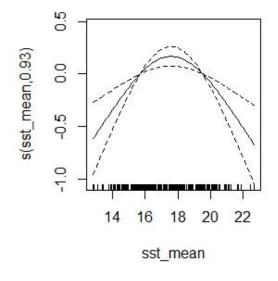


Figure X – Generalised additive model (GAM) smoothing curve fitted to partial effects of explanatory variables on abundance of the Great Skua

Appendix 3 – Fit Generalized Estimating Equations (geegIm) results

Table A – Estimated trend using geeglm for each species and seasonality for passage migrants between 2009 and 2018. Estimate values, standard error and significance (p) are also presented. Significant values are in bold.

Species	Estimate	SD	Significance	Trend
			(<i>p</i>)	
Northern Gannet post-breeding	-0.01	0.03	0.72	Uncertain
Northern Gannet pre-breeding	0.02	0.003	0.55	Uncertain
Balearic Shearwater	-0.06	0.02	<0.05	Decrease
Common Scoter post-breeding	-0.07	0.03	<0.05	Decrease
Common Scoter pre-breeding	0.003	0.03	0.93	Uncertain
Sandwich Tern post-breeding	-0.16	0.04	<0.001	Decrease
Sandwich Tern pre-breeding	-0.07	0.08	0.33	Uncertain
Mediterranean Gull	0.12	0.02	<0.001	Increase
Razorbill	-0.08	0.08	0.30	Uncertain
Great Skua	-0.006	0.07	0.93	Uncertain

Northern Gannet

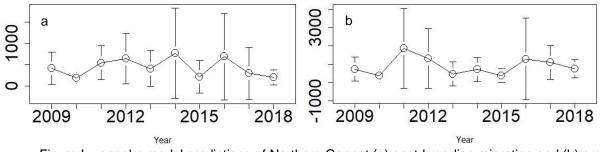


Figure I – geeglm model predictions of Northern Gannet (a) post-breeding migration and (b) prebreeding migration annual trends in abundance.

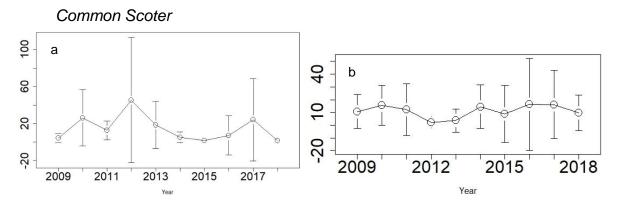


Figure II – geeglm model predictions of Common Scoter (a) post-breeding migration and (b) prebreeding migration annual trends in abundance.

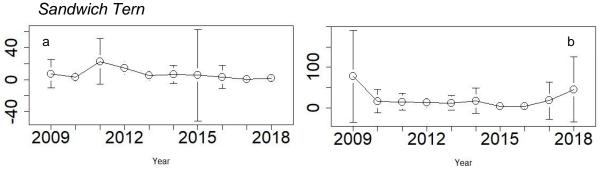


Figure III – geeglm model predictions of Sandwich Tern (a) post-breeding migration and (b) prebreeding migration annual trends in abundance.

Balearic Shearwater and Mediterranean Gull

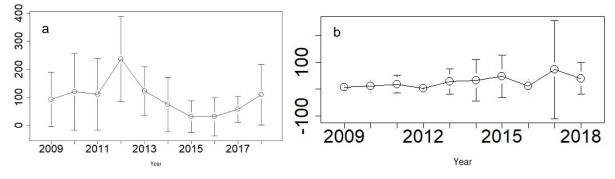


Figure IV – geeglm model predictions of annual trends in abundance of seabirds (a) Balearic Shearwater and (b) Mediterranean Gull.

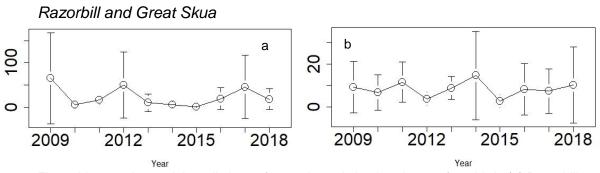


Figure V – geegIm model predictions of annual trends in abundance of seabirds (a) Razorbill and (b) Great Skua.