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Meta-Analysis of United States Seabird Populations Based on Ocean Biodiversity Information System (OBIS) Records (1965–2018)

by

Savannah Hartman

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
with a concentration in Biological Oceanography
College of Marine Science
University of South Florida

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June 23, 2023

Key Words: shorebirds, environmental change, open-access databases, *Puffinus griseus*, *Gavia immer*, and *Phoebastria nigripes*

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DEDICATION

This work is dedicated to my parents, Keith, Jennifer, and Michelle Hartman and to my loving and patient husband, Nicholas Barrales, for providing me with the support I needed to complete this degree as a first-generation student.

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ABSTRACT

Understanding the distribution of organisms is an important priority for society as we live through ecosystem transformations that threaten the well-being of all organisms. I have approached the dynamic and complex issue of studying biodiversity by using open-access seabird data collected along the Americas since the 1960s. I explained how these data have changed over time and space, how certain species populations could have shifted over time, and possible correlations between this potential geographic change and select environmental variables.

In Chapter 2 I evaluated the suitability of the open-access data archive Ocean Biodiversity Information System (OBIS) for supporting detailed inquiry into multi-decadal-scale geographic distributions of sea- and shorebird species in the Americas. The study included more than 680,000 occurrence records of 210 species collected between 1965 and 2018, evaluating them by marine ecoregion. I found that while OBIS contained a significant amount of data, the majority of records were from North American marine ecoregions, specifically from the Puget Trough/Georgia Basin and the Gulf of Maine/Bay of Fundy. Only a small portion of the data covered South America, the majority of which was collected in the Channels and Fjords of Southern Chile ecoregion. This study concluded that North American ecoregions could be used for future research, but that the community should share additional observations via OBIS to

enable comprehensive, large-scale and detailed meta-analyses of spatial and temporal trends in marine and shorebird biodiversity.

In Chapter 3, I used OBIS occurrence (presence only) records from 1980–2018 for common loons (*Gavia immer*), sooty shearwaters (*Puffinus griseus*), and black-footed albatross (*Phoebastria nigripes*) to see how locations of these field-observations changed over time. The objective was to see how these changes illustrate the possibility of populations shifting northward or southward correlating with sea-surface temperatures, among other variables. These species were selected because of the larger volume of records available over the four-decade period compared to other seabird species. Records available for each of the four decades made these taxa useful for my study. Records for other taxa were too sparse to address changes over multi-decadal time scales. Results show that the average centroids of the distributions of sooty shearwater and black-footed albatross observations off the west coast of the United States of America (USA) moved northward by ~450 and 270 kilometers over 40 years, respectively. In contrast, the average centroids of the sooty shearwater and common loon observation distributions on the east coast of the USA moved southward by ~140 and 260 kilometers, respectively, over this period. However, these results have high uncertainty, and it is not possible to assign these changes to processes such as climate change at this time. Using the modelled Copernicus Global Ocean Physics Reanalysis (GLORYS12V1) environmental data product, I examined correlations between species' geographic locations and abiotic factors (e.g., sea-surface temperatures, salinity, mixed-layer depth, northward and eastern current velocities, and sea-surface height).

The statistical analyses indicated that changes between decades in the average population distributions of common loons computed for any one season off the east coast of the USA were

largely associated with sea-surface temperature changes in all seasons except spring. Locations of observations of sooty shearwaters on the east coast actually occurred such that records were matched to progressively cooler sea-surface temperature from decade to decade (~7°C across 40 years), and leading to an apparent southward location of the spring centroids over time. For observations in autumn and summer, locations were associated with warmer waters (an increase of ~2.5°C over 40 years, also corresponding to southward location of the bulk of shearwater observations). On the west coast, sooty shearwater observation distributions were positively associated with both temperature and salinity in spring, and negatively correlated in summer and autumn. Population observation distribution of black-footed albatross positively correlated with sea-surface temperature and salinity in spring, summer and autumn. Summer centroid temperatures for sooty shearwaters and black-footed albatross observations on the west coast increased by 1°C and 0.5°C over the 40-year period, respectively. In all cases except for common loons, records from winter seasons provided insufficient data for meaningful analyses. The results included numerous artifacts due to an uneven availability of records of species observations across years and from decade to decade.

Chapter 4 argues for the importance of integrating our communities, exploring scientific inquiry, and improving communication skills to bridge the gap between scientists and the public. This chapter presents four case studies from various parts of the Americas, including Brazil, Argentina, and Canada, which demonstrate diverse approaches such as technological applications, websites, community engagement activities, and events. The examples encompass a mobile “app” designed to reduce bycatch in shrimp fishing, participatory workshops utilizing graphic facilitation to raise awareness about environmental change, and an academic group that conducts accessible laboratory experiments to explain geophysical fluids. This chapter

emphasizes the potential of these strategies to inform environmental management and everyday decision-making while fostering positive societal transformations. This can be easily applicable to, and was useful in, my seabird research. Clear and accessible communication between the scientific community and the public can raise awareness about the conservation needs of seabirds and promote community engagement.

Chapter 5 is a summary of the dissertation findings with recommendations for future work. Overall, my work highlights that even the most numerous seabird species records at present are insufficient to conduct robust temporal and spatial analyses and comprehensive assessments. The OBIS platform provides a foundation to understand sea- and shorebird distributions throughout North American marine ecoregions. However, to enable comprehensive analyses of spatial and temporal trends in marine and shorebird communities and their biodiversity, the temporal and geographic coverage of OBIS must be augmented with many more observations. Sharing observations via open-access databases such as OBIS can support monitoring and ecological analyses within and across marine ecoregions and contribute to future conservation efforts.

It is clear that there can be more coordinated efforts in capacity development and training in data management and use at the level of graduate study programs. Standardized, open databases are an essential component of creating, compiling and spreading knowledge. Using such information helps establish best practices for taxonomic and environmental observations, ultimately expanding and improving the availability of data on sea- and shorebirds. Furthermore, supporting scientific understanding and environmental interest in local communities can contribute to a more comprehensive and effective understanding of these species and their role in marine ecosystems.

CHAPTER 1:

INTRODUCTION

The overarching question that inspired my dissertation stems from Sutherland et al. (2013): how does the distribution in marine species change with latitude at different spatial and temporal scales? Stein et al. (2014) hypothesized that environmental heterogeneity increases the number and types of environmental gradients, which then increase the range of habitat types, resources, and structural complexity. In principle, however, an increase in heterogeneity may lead to compression or disappearance in habitats. I am interested in how environmental change may be affecting the populations of seabirds along the coasts of the Americas and focused on the populations of common loons (*Gavia immer*), sooty shearwaters (*Puffinus griseus*), and black-footed albatross (*Phoebastria nigripes*) off the coasts of the United States.

Relevance

Seabirds are excellent biomonitors that span trophic levels and their presence may indicate health of ecosystems including availability of prey (Furness and Camphuysen, 1997; Mallory et al., 2010; Larsen et al., 2012; Oro, 2014; Rajpar et al., 2018). Seabirds connect the ecology of the land with the oceans. According to Croxall et al. (2012), more than half of the seabird species are threatened. Insight is needed to understand seabird biodiversity of the Americas to guide conservation efforts (Sherman, 1991). A priority is to determine if species can

be examined in a systematic manner across various spatial and temporal scales; for this there needs to be sufficient data to support research.

The goals of this study were to:

- Goal 1: Determine what bird-occurrence data are available in the data platform Ocean Biodiversity Information System (OBIS) and document the challenges and need for additional data sharing to support research and enhance conservation actions.
- Goal 2: Assess latitudinal distribution of sooty shearwater, common loon, and black-footed albatross off the coasts of the United States over four decades, 1980–2018.
- Goal 3: Determine whether changes in sea-surface temperature and other ocean parameters, including salinity, northward current velocity, eastward current velocity, sea-surface height, and mixed-layer depth, may have affected latitudinal distributions of selected populations.

Highlights

Chapter 2:

The OBIS platform (Klein et al., 2019) currently can provide baseline data for sea- and shorebird distributions to support future studies for several North American marine ecoregions (Spalding et al., 2007). Preliminary examination included multiple datasets (e.g. OBIS, GBIF, ebird). Data from other platforms were largely redundant; moreover, OBIS has stricter criteria creating a more robust dataset to conduct meta-analyses. More than 680,000 occurrence records of 210 species, collected between 1965 and 2018, were located and evaluated by marine ecoregion. The Puget Trough/Georgia Basin marine ecoregion, along the United States/Canadian border, and the Virginian marine ecoregion on the United States' east coast, dominated

occurrences, each with more than 100,000 records, while the Gulf of Maine/Bay of Fundy had the most years of records (42). Most records from South America (~29,000) came from the Channels and Fjords of Southern Chile, collected across 16 different years. More than 90% of the recorded data were collected since 1983, and more than 95% of the records were from North American marine ecoregions. More data from Central and South American ecoregions, as well as those from the Caribbean Sea, must be shared via open-access databases like OBIS to enable monitoring and ecological assessments.

Chapter 3:

This chapter focuses on the spatial distribution of populations of common loons, sooty shearwaters, and black-footed albatross, because their OBIS records covered the largest temporal range compared to other seabirds. Sooty shearwaters and black-footed albatrosses are global species listed as near-threatened by the International Union for Conservation of Nature (IUCN). Insight concerning these populations can be useful for species protections. The study found that the population distributions of common loons, sooty shearwaters, and black-footed albatross documented in OBIS changed over a 40-year period, with the population centers of sooty shearwater and black-footed albatross observations on the west coast moving northward and sooty shearwater and common loon observations on the east coast moving southward. There is uncertainty associated with this movement since it is based upon data that does not cover the entire geographic range of each population. Changes in the population distributions of common loons were largely associated with sea-surface temperature changes over this period for decadal average seasons except spring, while the population distributions of sooty shearwaters were affected by both sea-surface warming and cooling. On the west coast, sooty shearwater distributions were positively associated with decadal-scale changes in temperature and salinity in

decadal average spring variables, and negatively correlated in summer and autumn. Population distributions of black-footed albatross were positively correlated with sea-surface temperature and salinity in decadal average spring, summer and autumn.

Chapter 4:

This chapter explores the issue of research outcomes being limited to academic circles and proposes fun and innovative ways to spread scientific knowledge to and engage the public, focusing on ocean and coastal ecosystems. Emphasizing the importance of integrating communities, exploring scientific inquiry and improving communication skills to bridge the gap between scientists and the public, this chapter presents four case studies in the Americas ranging from Brazil and Argentina to Canada, showcasing different methods such as technological applications, websites, community engagement activities. These initiatives aim to promote environmental education, raise awareness, and encourage behavioral change.

Gilchrist et al. (2005) emphasized the potential value of local ecological knowledge in identifying population declines and relocation that was undetected by western science. Engaging with community members, such as fishers or coastal residents, can provide important information for understanding seabird habitats and potential threats they face (Reyes-Arriagada et al., 2015).

Fostering collaborations between scientists and the public can enhance data collection efforts. Citizen science projects have proven successful in seabird research, with community members contributing to monitoring programs and collecting valuable data on seabird populations (Martín et al., 2020). Effective communication is vital in conveying research findings and their implications to the wider public, and studies have shown that clear and

accessible communication can raise awareness about conservation needs and promote public engagement (Kobori et al., 2016).

Chapter 5:

In this chapter, I emphasize the need for more comprehensive and consistent data reporting worldwide and highlight the gaps in knowledge for ecologically important taxa. I acknowledge the importance of contributing to the available data and recommend future studies that focus on the relationships between biotic factors, such as productivity and phytoplankton abundance, and population distribution of sooty shearwaters and common loons on the east coast of the United States. Future species distribution models should contain biotic factors and fisheries activity to identify foraging hotspots and marine habitats that require appropriate management and protection.

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CHAPTER 2:

OBLIGATION TO ENHANCE OBIS DATA ON SEA- AND SHOREBIRDS OF THE AMERICAS

Note to reader:

This chapter was published in the December 2022 issue of *Diversity* with co-authors, Drs. Pamela Hallock and Frank Muller-Karger. The paper is included in this dissertation, and its corresponding online supplement is included as Appendix A in this dissertation. Open access policy of MDPI included as Appendix B.

Reference:

Hartman, S., Hallock, P., & Muller-Karger, F. (2022). Obligation to Enhance OBIS Data for Sea- and Shorebirds of the Americas. *Diversity*, 14(12), 1099. https://doi.org/10.3390/d14121099.

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Supplementary material related to this article can be found in the online version at https://www.mdpi.com/article/10.3390/d14121099/s1.

CHAPTER 3:

CHANGES IN THE GEOGRAPHIC DISTRIBUTION OF THE SEABIRDS *GAVIA IMMER, PUFFINUS GRISEUS,* AND *PHOEBASTRIA NIGRIPES* ALONG THE EAST AND WEST COASTS OF THE USA OVER FOUR DECADES (1980-2018): INFERENCES FROM ENVIRONMENTAL-CHANGE ANALYSIS

Abstract

This study examines the geographic distribution of observations of three species of seabirds along the east and west coasts of the United States of America (USA) from 1980 to 2018. Seasonal changes in distribution were examined in the context of select surface-ocean environmental variables. Specifically, I examined the spatial distributions of occurrence records of common loons (*Gavia immer*), black-footed albatrosses (*Phoebastria nigripes*), and sooty shearwaters *(Puffinus griseus*) using observations curated by the Ocean Biodiversity Information System (OBIS). The geographic distribution of observations of each of these species was averaged seasonally to show centroids at decadal scales (1980–1989, 1990–1999, 2000–2009, 2010–2018). The Copernicus Global Ocean Physics Reanalysis (GLORYS12V1) product was used to evaluate the possible effects of sea-surface temperature, salinity, northward current velocity, eastward current velocity, sea-surface height, and mixed-layer depth on the seasonal population distributions averaged over each decade of these seabirds using a classical redundancy analysis with Akaike information criterion for each season. The average centroids of

the distributions of sooty shearwater and black-footed albatross observations on the west coast of the USA moved northward by ~450 and 270 kilometers over 40 years, respectively. In contrast, the average centroids of the sooty shearwater and common loon observation distributions on the east coast of the USA moved southward by ~140 and 260 kilometers over this period. These results have high uncertainty, and it is not possible to assign these changes to processes such as climate change at this time. However, statistical analyses suggest that decadal-scale changes in population distributions of common loons were largely associated with sea-surface temperature changes in all seasons averaged across the decades, except spring. Population distributions of sooty shearwaters on the east coast experienced sea-surface temperature cooling over the decades (~7°C) coinciding with southward movement of the spring centroids over time. Temperatures in average autumn and summer increased by ~2.5°C over the four decades, also corresponding to southward movement of the shearwaters. On the west coast, sooty shearwater distributions were positively associated with both temperature and salinity in decadal average spring, and negatively correlated in average summer and autumn. Population distribution of black-footed albatross were positively correlated with sea-surface temperature and salinity in the average spring, summer and autumn. However, these results could be an artifact of years when data were available. In all cases except for common loons, insufficient data for meaningful analyses were found in records from winter seasons, even seeking to aggregate data over decades.

Introduction

Environmental changes are influencing the geographic range of many organisms, with some population distributions shifting poleward (Walther et al., 2002; Root et al., 2003; Hickling et al., 2006; Chen et al., 2011; Anderson et al., 2023; Martínez-Ruiz et al., 2023). Climate

change is driving a rise in average atmosphere, ocean, and land temperatures. Sea level is rising and complex changes in weather are occurring that may affect habitat preference and availability of food for many bird populations. For many seabirds, there is also relatively little known about their life history. Such information is crucial because marine and coastal seabirds are consistently used for assessments of ocean health (Oro, 2014; Thibault et al., 2019; Velarde et al, 2019). In this study, I examined the average seasonal geographic distribution of three seabird species along the east and west coasts of the United States of America (USA) over a period of nearly 40 years (1980–2018). Specifically, I utilized occurrence records curated in the Ocean Biodiversity Information System (OBIS) for the common loon (*Gavia immer)*, sooty shearwater (*Puffinus griseus)*, and black-footed albatross (*Phoebastria nigripes*) to make inferences about changes in their population distributions. These three species were selected because they have the longest temporal records available in OBIS, with data available for each decade since the 1980s.

Both sooty shearwaters and black-footed albatrosses are global species listed as near-threatened by the International Union for Conservation of Nature (IUCN) (BirdLife International, 2019; 2020). In contrast, common loons are found throughout the northeastern portion of the USA (Paruk et al., 2021). The common loon is one of five loon species found worldwide (Evers et al., 2010), and is listed as not threatened by the IUCN. All three seabird species are recognized as indicators of aquatic ecosystem health; yet how their populations respond to climate change is not known (Bianchini et al., 2020; Carboneras et al., 2020; Piper et al., 2020).

Sooty shearwaters are the most common seabirds in the world and are the most common of their genus *Puffinus*. Breeding pairs migrate to the northern Atlantic and Pacific Oceans in mid-April. They return to breeding areas in the southwest regions of their respective ocean

basins off Australia, New Zealand, and the Tierra del Fuego archipelago of Chile and Argentina sometime between August and January (Carboneras et al., 2020). Non-breeders are suspected of moving across the entire length of their respective ocean basins in a figure-of-eight loop pattern, residing at higher northern latitudes between March and October (Spear and Ainley, 1999). Approximately 75% of the global population is made up of non-breeders (Brooke, 2004). In their breeding and non-breeding locales, shearwater abundances track forage-fish distribution and abundances (Lyverl et al., 1999; Humphries and Möller, 2017; Bonnet-Lebrun et al., 2020).

Black-footed albatrosses are the only albatross species regularly observed off the North American coast. They range from the coast to the shelf break and slope of the western United States in the California Current region (Hyrenbach et al., 2006; Yen et al., 2006). Population distributions for this species are strongly related to temperature, and abundance increases in local cold-water conditions reflect upwelling and higher ocean productivity (Hyrenbach and Veit, 2003; Antão et al., 2020). However, how climate change is affecting distributions and other population characteristics remains unknown (Tickell, 2000; Awkerman et al., 2020).

Here I focused on the changes observed in the spatial distributions of observation records of these species over four decades. My assumption is that the distribution of observation records can be used to make inferences about seasonal bird distributions. My working hypothesis was that sea-surface temperature would affect latitudinal distributions of these seabird populations over the four decades considered. I also examined the seabird observation locations with time series of ocean parameters gridded through a reanalysis product. This included salinity, northward current velocity, eastward current velocity, sea-surface height, and mixed-layer depth. The goal was to determine if the reported distributions of the seabird populations in their transient, non-breeding habitats were correlated with any of these environmental parameters.

Methods

Seasonal and Decadal Shifts

Presence only, field-observation data (hereby referred to as occurrence data) archived at the Ocean Biodiversity Information System (OBIS) (Grassle, 2000; Klein et al., 2019) were used to examine the average population distributions of common loons, sooty shearwaters, and black-footed albatrosses off the east and west coasts of the United States by seasons and years between 1980 and 2018. Data were quality controlled using methods described in Hartman et al. (2022). Data were spatially plotted using a World Geodetic System 1984 projection (Department of Defense, 2003) and statistics were derived using geographic information system software (ArcGIS Pro; Scott and Janikas, 2010). Each data point represented one seabird occurrence record indicating presence at that location. Centroids representing mean location, calculated using the 'Mean Center' spatial statistics tool in ArcGIS, were created for these species for each season averaging all observations in those seasons across each decade. These centroids were used to estimate general geographic position changes of the observations over time using the 'Linear Directional Mean' tool in ArcGIS. Of particular interest was the detection of any general north- or southward trend in the central geographic distribution of each population from decade to decade, so a fundamental assumption in the analysis of results is that the general distribution of observations represents population distribution – this is an assumption that leads to major uncertainties in the results.

Environmental Predictors and Response

I used the Global Ocean Physics Reanalysis product "GLORYS12V1" from Copernicus (e.g., Jean-Michel et al., 2021) to determine if species locations were related to specific environmental parameters. The Copernicus GLORYS12V1 is a model output product that

includes monthly means for sea-surface temperature, salinity, northward and eastward current velocities, sea-surface height, and mixed-layer depth. The global ocean surface output raster files were available on a regular grid at a 1/12° spatial resolution from 16 January 1993 to 16 December 2018. The GLORYS12V1 product has been used to support seasonal forecasting of ocean conditions and to study past ocean states (Jean-Michel et al., 2021). The Sentinel Application Platform software (SNAP; Zuhlke et al., 2015) was used to export modelled environmental data for the location (latitude and longitude) of each occurrence record for common loons, sooty shearwaters, and black-footed albatrosses. Data for each environmental parameter at all corresponding record locations were averaged seasonally (i.e., summer: July, August, and September; autumn: October, November, and December; winter: January, February, and March; and spring: April, May, and June) per year across decades for each season from 1993–2018 using SNAP. The Copernicus product did not include results for years prior to 1993, so we could not include earlier seabird observations from OBIS in the statistical comparison analyses. However, I did use the pre-1993 OBIS data to examine the mean-location centroids of the population observation records, hereafter simply referred to as centroids.

Using the package [vegan] in R (version 4.0.2), I created classical redundancy analyses (RDA) with the Akaike information criterion for each season, using species location and the environmental model output (McClanahan and Hicks, 2010; Borcard et al., 2011; Zhang et al., 2021). This multivariate, multiple linear regression used the Copernicus GLORYS12V1 seasonal average model output as the explanatory variables, while the response variables were the latitudes and longitudes for each occurrence record for each species. ArcGIS Pro software was used to obtain sea-surface temperature ranges and averages within a two-degree square buffer

around the centroids. This allowed me to observe potential sea-surface temperature changes about the centroids for each average decadal season.

Important Data Uncertainties and Assumptions

1. Uncertainty in each centroid of observation records, as well as seasonal and decadal movement, was high due to inconsistent sampling. To retain as many records as possible, data were not randomly subsampled. For example, the east coast sooty shearwater centroid for the spring of the 1990s was off the coast of North Carolina, which is an artifact of heavy sampling off Cape Hatteras. Data could not be organized/subsampled in a way that would provide spatial or temporal consistency.
2. Environmentally modelled data were assumed to be correct due to validation and integration of in situ measurements (Jean-Michel et al., 2021). Resulting correlations of environmental data with geographic position were based upon relatively insignificant changes in the salinity, sea-surface height, and northward and eastward current velocities over time.

Results

Occurrence Records

OBIS occurrence records are relatively few for black-footed albatrosses and sooty shearwaters during some seasons and decades (Tables C1 and C2). For example, an average of only 11 records per year were found for the black-footed albatross for 2010–2018, where eight of the records occurred in winter seasons. For sooty shearwaters, only two observations on the east coast and six observations on the west coast were found for the winter seasons of the 2010–2018

period. Most other seasonal and decadal data sets included hundreds to thousands of observations.

Figures 3.1–3.4 illustrate the location of centroids for each seabird population for each decadal-average season across decades and decade. The red arrows indicate the distance and direction of the average shift in the centroid of the population's distribution location over the nearly 40-year time period. Records for the common loon extended from North Carolina to Massachusetts (Fig. 3.1). Data for the average decadal spring season showed minimal displacement of the population distribution over the past four decades. During summers, an overall southwestward shift was apparent in the observation records, suggesting a small shift in population distribution since the 1980s. During autumn and winter, the centroids were furthest south in the 1980s and then again in the 2010s, with northward shifts in the 1990s and 2000s. Except for spring, movement distance of the centroid was similar among seasons for each decadal period (average shifts >250 kilometers).

The range of sooty shearwaters along the east coast of the USA extends from Florida to Maine, but OBIS records were only available from North Carolina to Massachusetts (Fig. 3.2). Data for three seasons were found for all four decades. During summer and autumn seasons, southward shifts in the population distributions of sooty shearwaters exceeded ~140 kilometers. Spring population shifts were not included because data for this species during the 1990s were biased. Data are distributed in a way that does not cover the full population distribution range randomly and does not allow for the assessment of differences in the linear directional mean over the past four decades. However, the largest displacements between decades were seen in spring (Fig. 3.2; Appendix Fig. C1). Data for winter were only available for the 2010s.

Sooty shearwaters are generally observed along the entire west coast of the United States, but OBIS records ranged only from the San Francisco Bay region (California) to northern Washington State. Substantial gaps exist in the OBIS data for spring and autumn in the 2000 and 2010 decades, and in winters of the 1990s and the 2010s (Fig. 3.3), precluding meaningful analyses of those intervals. However, the available data suggest a north/northwestward shift averaging ~450 kilometers since the 1980s for most seasons except autumn, which showed a small southeastern displacement from the 1980s–1990s.

Major data gaps also inhibited analyses of black-footed albatross distributions (Fig. 3.4), notably from the spring of the 2000s and 2010s, autumn from the 2000s, and winters for the 1990s, 2000s, and 2010s. Despite the lack of data over the 21st century for the spring and winter, a north/northwestward shift of hundreds of kilometers was evident in the field observations of the population distributions since the 1980s for spring and summer. Change in the location of the average population distribution in the autumn across decades was minimal, on the order of 100 km.

Redundancy Analyses

The results of the redundancy analyses for the common loon during the winter and sooty shearwaters on the east coast of the United States during the spring are shown in Figures 3.5 and 3.6. All occurrence records are indicated within the ordination space of panel (a) in these Figures, where each decade is represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively. Ellipses are color-matched to the corresponding decade. The black lines represent different environmental variables in the redundancy analysis ordination [abbreviations: salinity (Sa), sea-surface temperature (SST), sea-surface height (SSH), northward (NV) and eastward current velocities (EV), and mixed-layer depth (ML)]. The degree of

explanation of the modelled environmental data is indicated by the length of the black line attaching a particular label to the center of the plot; a longer line indicates a stronger correlation between a particular environmental parameter and observation-record location. The length of the line is not related to the scaling of parameters.

The redundancy analysis model for wintering common loons along the east coast had ~81% of the variance explained along the x-axis (i.e., latitude). The y-axis variance, representing longitude, was insignificant (<1%). Larger variance across latitudes shows that the common loon population moves farther north-south than east-west with each season and across decades. In general, the strongest positively associated predictor variables were sea-surface temperature (0.91) and salinity (0.84), and northward current velocity (-0.69) was correlated with distribution of the population (Fig. 3.5; Table C3). In this case, as the population moved south and the Gulf Stream moved north, this simply shows the current direction and the population's response to it.

For sooty shearwaters along the east coast during the spring (Fig. 3.6, Table C4), latitude accounted for ~87% of the variance, with longitude explaining only ~4% of the variance of all six environmental parameters. Field observations of shearwaters during the 1990s were taken at lower latitudes at the location where the Gulf Stream separates from the coast, so there is a higher correlation with eastward current velocity. In contrast, these birds were observed over a much greater section of the coast, including at relatively higher latitudes, during the 2000s and 2010s; however, the distribution is likely an artifact of sampling effort and does not promote a simple understanding of the effects of the Gulf Stream and the currents North of Cape Hatteras. A sooty shearwater's latitudinal location during the spring was also heavily influenced by mixed-layer depth (0.95), salinity (0.65), and inversely by sea-surface height (-0.74) (degree of explanation indicated by the length of the black line, Fig. 3.6a).

More than half of the latitudinal variance (52–99%) for all species was explained by sea-surface temperature (Tables C3–C6; Figs. C2–C5), heavily influencing observed seasonal population distributions for 11 out of the 14 seasons for which data were available (14 = four groups of species by four seasons, minus winter data for west coast species). Outliers included common loons during the spring and summer, and sooty shearwaters on the east coast during the spring. All outliers had a significant portion of their latitudinal variance explained by salinity and sea-surface height, and distributions of sooty shearwaters were correlated strongly with mixed-layer depth during the spring and autumn as well.

Decadal average sea-surface temperatures around common loon centroids increased ~3°C (standard deviation ±2.5) for the autumn and ~3.5°C (standard deviation ±1.6) for the summer, which negatively correlated with southward population movement over the decades (Figs. 3.1 and 3.7). When northward movement was observed in the spring, locations coincided with lower sea-surface temperature changes over the four decades (~2°C; standard deviation ±2.9, Fig. 3.7). Sooty shearwaters on the east coast experienced sea-surface temperature cooling from decade to decade in spring (~7°C, standard deviation ±3.6) coinciding with southward movement of the spring centroids over time. Temperatures in summer and autumn increased by ~2.5°C (standard deviation ±1.7), corresponding to southward movement of the shearwater centroids. Figure 3.8 suggests that there were minimal changes in the average sea-surface temperature around sooty shearwater and black-footed albatross centroids on the west coast over decades from 1993 to 2018. Isotherms for 15°C–16°C along the west coast shown at -130º longitude expanded by about one latitudinal degree during the summer season when comparing decadal averages of the 1990s and the 2010s (Fig. 3.9).

The latitudinal variance for all species off the east and west coasts was also associated with seasonal salinity (65–99%, Tables C3–C6; Figs. C2–C5), for 13 out of the 14 seasons for which data were available. In the three cases for which latitudinal variance was not strongly associated with temperature (e.g. spring for common loons, spring and autumn for sooty shearwaters on the east coast), latitudinal variance was strongly associated with salinity. The only weak association with salinity (-0.24) was for the quite limited winter data for sooty shearwaters on the east coast.

Discussion

Limitations

Several important limitations are inherent in this meta-analysis:

a) Seabird data sets are the occurrence records documented by individuals and surveys reporting on seabird sightings. Most studies covered only limited periods of time and only portions of the known historical distribution range of these seabirds. Only two studies were conducted over multiple years, the International Pacific Halibut Commission Seabird Survey of 2002–2011 and the United States Geological Society Patuxent Wildlife Research Center Seabirds Compendium dataset from 1906–2013 (Geernaert, 2012; Perry, 2016). However, these studies did not collect data regularly enough throughout the year to understand species' populations distributions and dynamics. The International Pacific Halibut Commissions Seabird Survey had up to two regular collection events during summers, and the United States Geological Society Patuxent Compendium was made up of 70 individual data records, which inconsistently sampled seabird data over space and time. Therefore, the results reported only provide a general understanding of the seabirds at specific locations of observation.

b) Number of occurrence records available in OBIS. Records of black-footed albatross sightings were not available for entire seasons and decades: spring 2000s, 2010s; autumn 2000s; winter 1990s, 2000s, 2010s. The autumn 1990s centroid plotted outside of the species' habitat (Fig. 3.4), as albatrosses are not known to venture inland. Similarly, very limited numbers of sooty shearwater records from the east coast of the United States during the winters of the 1980s, 1990s, and 2000s prevented interpretations of winter distributions.

c) The linear or parallel patterns of occurrence records apparent in the RDA plots (Figs. C4; C5) are likely artifacts of sampling during research cruises and probably reflect the cruise tracks.

d) The redundancy analysis models linear relationships among response variables and predictors, so nonlinear relationships may not be detected (Capblacq and Forester, 2021).

Such data and analysis limitations on results and implications are common in meta-analyses investigations, and can inform planning of future studies (e.g., Cabral et al., 2019; Burgess et al., 2021).

Latitudinal Shifts

Population ranges of the seabirds studied appeared to be shifting towards higher latitudes (i.e., northward) along the west coast of the USA, while the ranges along the east coast revealed reversals from decade to decade, but generally suggested a trend towards lower latitudes (southward) by the 2010s. All three species showed strong latitudinal displacement with season. This is consistent with our understanding that populations are influenced by parameters that vary with latitude seasonally and across longer timeframes (Tables C3–C6; Figs. C2–C5). The summer centroids for common loons and sooty shearwaters on the east coast plotted near each other, but whether these similarities are associated with oceanographic processes or availability

of data (i.e., sampling and reporting effort) is not presently understood (Figs. 3.1–3.2). An analysis of the distribution of observations of sooty shearwaters for spring off the east coast was not possible because of the lack of records (Fig. 3.2; Appendix Fig. C1).

Sea-surface Temperature and Population Distribution

Decadal average sea-surface temperatures in Figures 3.7 and 3.8 had large error bars for every species, which indicate the long-term variation in temperature could be insignificant, but redundancy analyses show that changes in population distributions of common loons were positively correlated with sea-surface temperature in autumn and winter season (RDA1>0.9), while summer correlation was still positive but weaker (RDA1=0.47) (Table C3). Shearwater distributions on the east coast positively correlated with sea-surface temperature in summer (RDA1=0.87) and winter (RDA1=0.99), and negatively in autumn (RDA1=−0.66) (Table C4).

The sooty shearwater and black-footed albatross populations showed general movement northward from 1980–2018 along the coastlines of California, Oregon, and Washington states. The northward latitudinal population shift in the decadal average summer and autumn seasons was correlated with sea-surface temperature (Figs. 3.3 and 3.4). However, the limited occurrence data were not sufficient to determine how robust the influence of sea-surface temperature may be on seasonal population distributions across decades despite seeing sea-surface temperatures increase within their range through the decades (Figs. C2-C8). Population distributions of shearwaters were negatively correlated with sea-surface temperature in summer (RDA1=−0.97) and autumn (RDA1 =−0.99) (Table C5), while black-footed albatross distributions positively associated with sea-surface temperature in spring (RDA1=0.9), summer (RDA1=0.85) and autumn (RDA1 =0.96) (Table C6). The difference in summer sea-surface temperature as a predictor parameter for the two species (negative for shearwaters and positive for albatrosses)

may be an artifact of years when data were available. To determine if the populations were indeed moving northward with changes in sea-surface temperatures, ocean temperature data from monthly averages were combined to show seasonal and decadal isotherms (Figs. 3.9–3.11, Appendix Figs. C6–C14). Figure 3.9 displayed a slight latitudinal expansion by one degree at -130º longitude for the isothermal range 15°C–16°C during the summer. NOAA (2023) states that El Niño-Southern Oscillation events have the strongest influence on USA seasonal climate during the winter, which we then use to assume the summer would have the weakest influence and be the time of the year that would show movement least influenced by El Niño and the exaggerated effects of the warm blob on El Niño-Southern Oscillation (Yeo and Kim, 2014; Tseng et al., 2017). This slight thermal expansion indicates that sooty shearwater and black-footed albatross population movement northward by hundreds of kilometers may be exaggerated and an artifact of inconsistent sampling. Additional information is required to determine whether these populations moved northward as sea-surface temperatures increased over that period (Figs. C2-C8).

Sea-surface temperature was a useful predictor for distributions of sooty shearwaters and common loons off the east coast, especially in autumn and winter (Table C3, C4). Redundancy analyses showed that temperature was not a useful predictor for population distributions of either species during the spring. Ultimately, we understand this as the smaller correlations between spring sea-surface temperature and species distribution are likely caused by highly variable spring conditions, possibly in combination with inconsistent collection.

The apparent southward movement of sooty shearwaters and common loons in the 2010s is not clearly understood. Observations recorded in OBIS noted shifts in population locations, as have previous studies of common loon populations in the northeast United States (Spagnuolo,

2014; Paruk et al., 2021). No reports were found detailing sooty shearwater population movement around New England and the mid–Atlantic. More occurrence data are needed to understand if these populations are shifting southward; however, sea-surface temperatures <26°C along the east coast (Figs. 3.9–3.11, Appendix Figs. C6–C14) are covering relatively larger geographic areas, particularly during the summer season between 25°C–40º latitude and -80º to -70º longitude, where both species have been documented. The slight expansion of this thermal range within temperate North Atlantic waters, using the GLORYS12V1 environmental data product, could provide additional habitat for the species. This, in conjunction with other variables outside of the scope of this study, could potentially be why these populations appear to be moving southward.

The results show that there was latitudinal variance associated with salinity for all species (0.65–0.99, Tables C3–C6; Figs. C2–C5). Salinity varies along coastlines, over decade-long time periods, with upwelling and advection of water masses (Yu et al., 2021). At the spatial resolution and decadal-scale averages of the data, perhaps the most marked changes would have been due to observations being collected in different water mass locations (such as within or outside upwelling areas off the west coast, or waters within or outside the Gulf Stream off the east coast). Variability in salinity over time and space can reflect changes in ocean stratification, with potential influence on seabird habitat/prey. Additional analyses are recommended to understand the correlation between salinity regimes and seabird location.

No other parameters emerged as strong predictors (>0.5) of population distributions over time (Table C3-C6). Mixed-layer depth showed some predicting power in nine of 14 seasons, six of which were for east-coast seabird populations. Sea-surface height seemed strong in eight cases, equally split between coasts and between positive or negative predictors. Eastward current

velocity was a strong predictor in half (7 of 14) the species/season matrices, and six were positive predictors. Northward current velocities were also strong predictors in half the species/seasons, and were primarily negative correlations. However, more data and analyses are needed to understand how robust these correlations may be and what the ecology driving these patterns may be.

Comparing the geographic distributions by species with RDA plots provides additional insight into trends over time and space (e.g., Figure 3.5, 3.6 Appendix Figs. C2-C5). For example, Figure 3.5 illustrates the locations of observations of common loons along the east coast of the United States in winter for each decade. Figure 3.5a indicates that the wintering loons in the 2000s were influenced by northward current velocity at higher latitudes; however, changes in northward current velocities over time were negligible. Loons at lower latitudes were generally observed during the 2010s and were more influenced by sea-surface temperature and salinity. Average sea-surface temperatures for wintering loons increased >1°C from 1993 to 2018, with no discernable changes in salinity. Figure 3.6 similarly shows the location of observations of sooty shearwaters on the east coast of the United States during the spring for each decade. Individuals documented in the 1990s within the red ellipses were found at lower latitudes, associated with eastward current velocity where the Gulf Stream separates from the coast, while birds located at relatively higher latitudes during the 2010s were more correlated with northward current velocity.

Future Work

Meta-analyses are useful in identifying research gaps. This study demonstrated that much more data collection and analyses are needed to understand which environmental conditions may define essential habitat for these seabird species, and how this is changing with seasons and

across decades. Ideally, data collections should be carried out with seasonal and spatial consistency and consider biotic factors such as life histories of groups of birds and changes in biotic factors, ocean chemistry, air quality, and pollution that could influence seabird abundances and distributions. Better understanding of net primary productivity and secondary productivity that influence food resources for seabirds during specific times of the year are essential (Grémillet and Boulinier, 2009). Proxies for biotic factors, such as phytoplankton abundance using ocean-color data are available starting in the mid-1990's (McClain, 2009). Additionally, detailed studies of the biological and ecological needs and constraints associated with each species would contribute to more robust interpretations of the influence of specific environmental parameters.

Conclusion

Sea-surface temperature is an important factor that influences the distribution of many organisms, including seabirds (Croxall et al., 2002; Irons et al., 2008). This paper explored the relationship between the distribution of three species of seabirds and oceanographic variables including sea-surface temperature, salinity, northward and eastward current velocities, sea-surface height, and mixed-layer depth along the east and west coasts of the United States. The hypothesis that sea-surface temperature is a strong factor contributing to latitudinal changes in the distribution of seabirds was supported for three species (common loons, sooty shearwaters, and black-footed albatross). Salinity emerged as a strong predictor of these OBIS derived field observations; however, this could be an artifact of seabirds occupying different salinity regimes as they migrate.

Despite finding hundreds of thousands of records for seabird species in OBIS, the data were only sporadically collected and reported over the four decades examined. This prevented a more in-depth exploration of seasonal and decadal trends for species along the west coast of the United States. Yet, the limited data show northward population shifts of the black-footed albatross and sooty shearwater records, and these were correlated with increases in sea-surface temperature. These correlations may not show causality. Hartman et al. (2022), shows that additional observations should be shared via open-access databases like OBIS to facilitate monitoring and robust ecological analyses. Without frequent reporting of observations, understanding how and why these species react to environmental change is hard to understand. With more complete data sets, additional analyses can be conducted that explore the influence of biotic factors, such as productivity and phytoplankton abundance, on population distribution over the 21st century. Due to ongoing rapid changes in the Earth's climate, studies of seabird population dynamics can play a critical role in future management and conservation activities.

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Figures

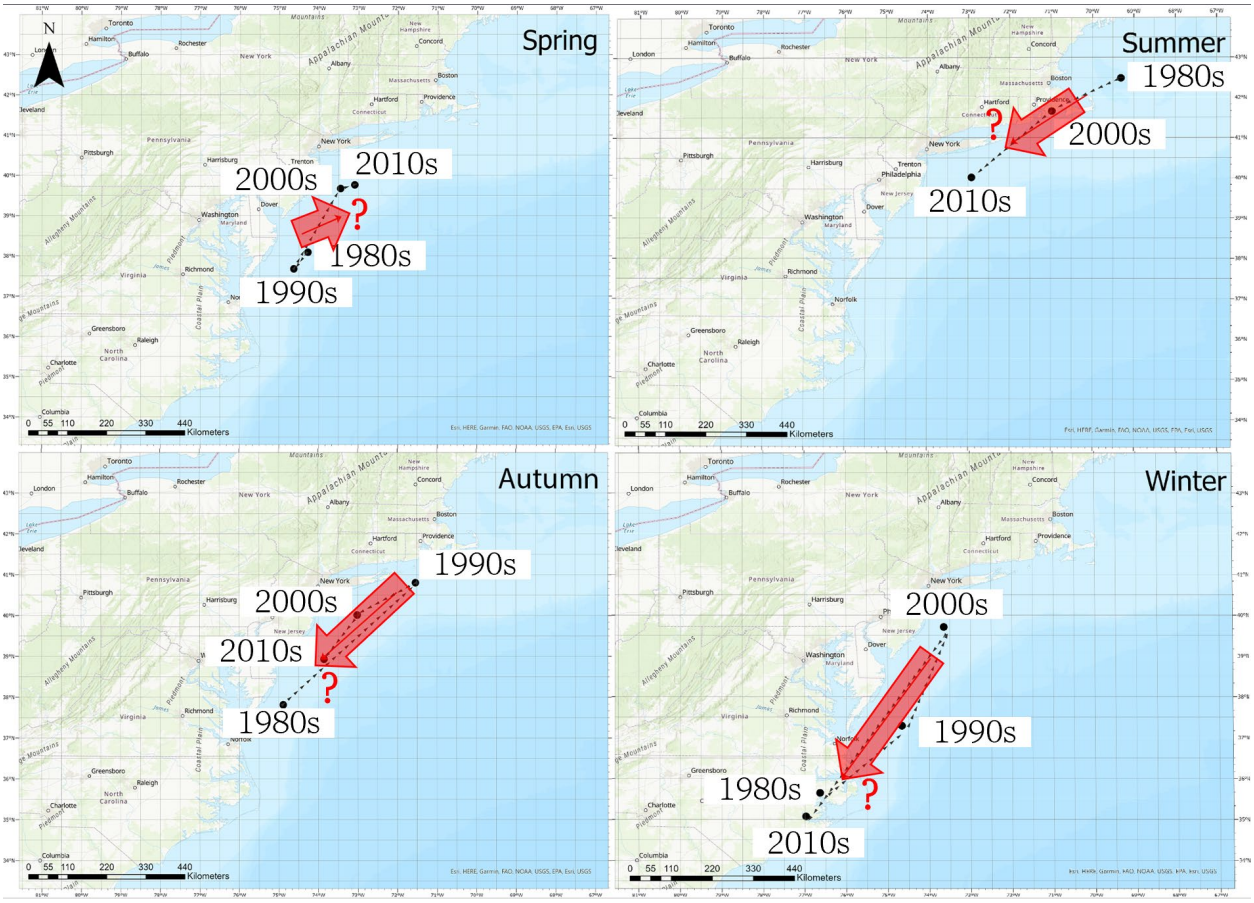


Figure 3.1. Common loon average of OBIS record locations suggesting seasonal population movement from the 1980s to the 2010s along the northeastern coastline of the United States. The centroids for each decade are shown as black circles. The dashed black lines indicate decadal changes. The red arrows indicate average long-term trends (the distance and direction of the average shift) and question marks emphasize that results have high uncertainty.

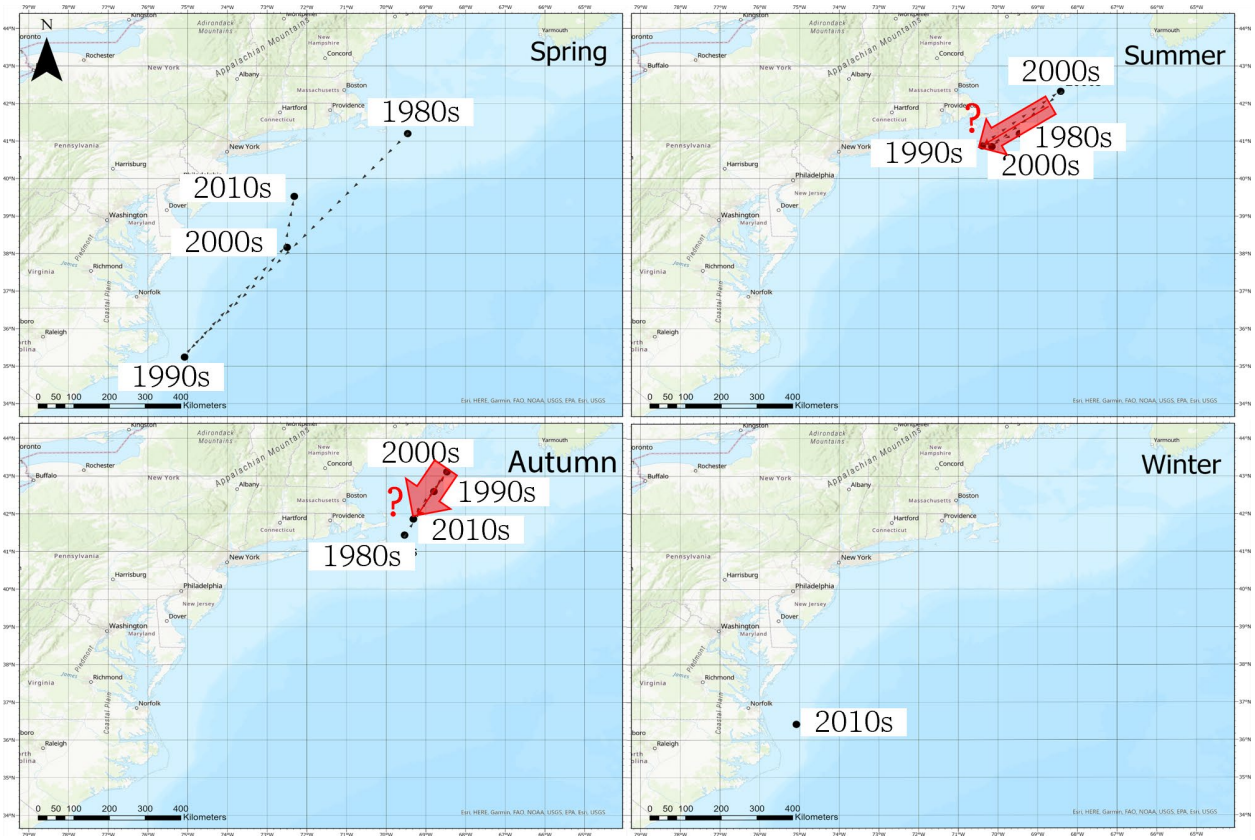


Figure 3.2. Sooty shearwater average of OBIS record locations suggesting seasonal population movement from the 1980s to the 2010s along the northeastern coastline of the United States. The centroids for each decade are shown as black circles. The dashed black lines indicate decadal changes. The red arrows indicate average long-term trends (the distance and direction of the average shift) and question marks highlight the high uncertainty of results. No red arrow was documented in the spring season, because occurrence records for the 1990s were not sampled consistently over the apparent geographic range of the seabirds, skewing long-term trends results.

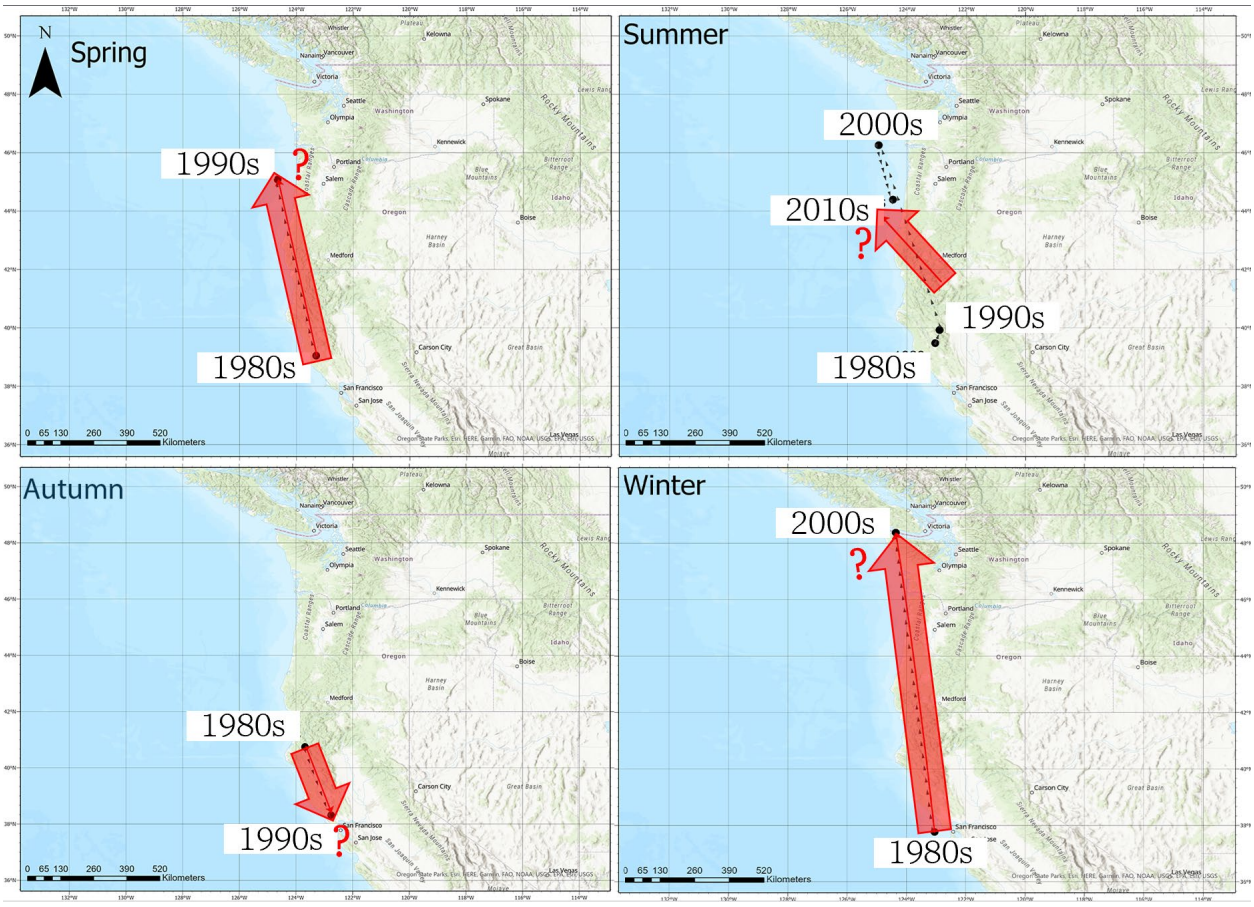


Figure 3.3. Sooty shearwater average of OBIS record locations suggesting seasonal population movement from the 1980s to the 2010s along the Pacific coast of the United States. The centroids for each decade are shown as black circles. The dashed black lines indicate decadal changes. The red arrows indicate average long-term trends (the distance and direction of the average shift) and question marks emphasize that these trends have high uncertainty (see Figure C1).

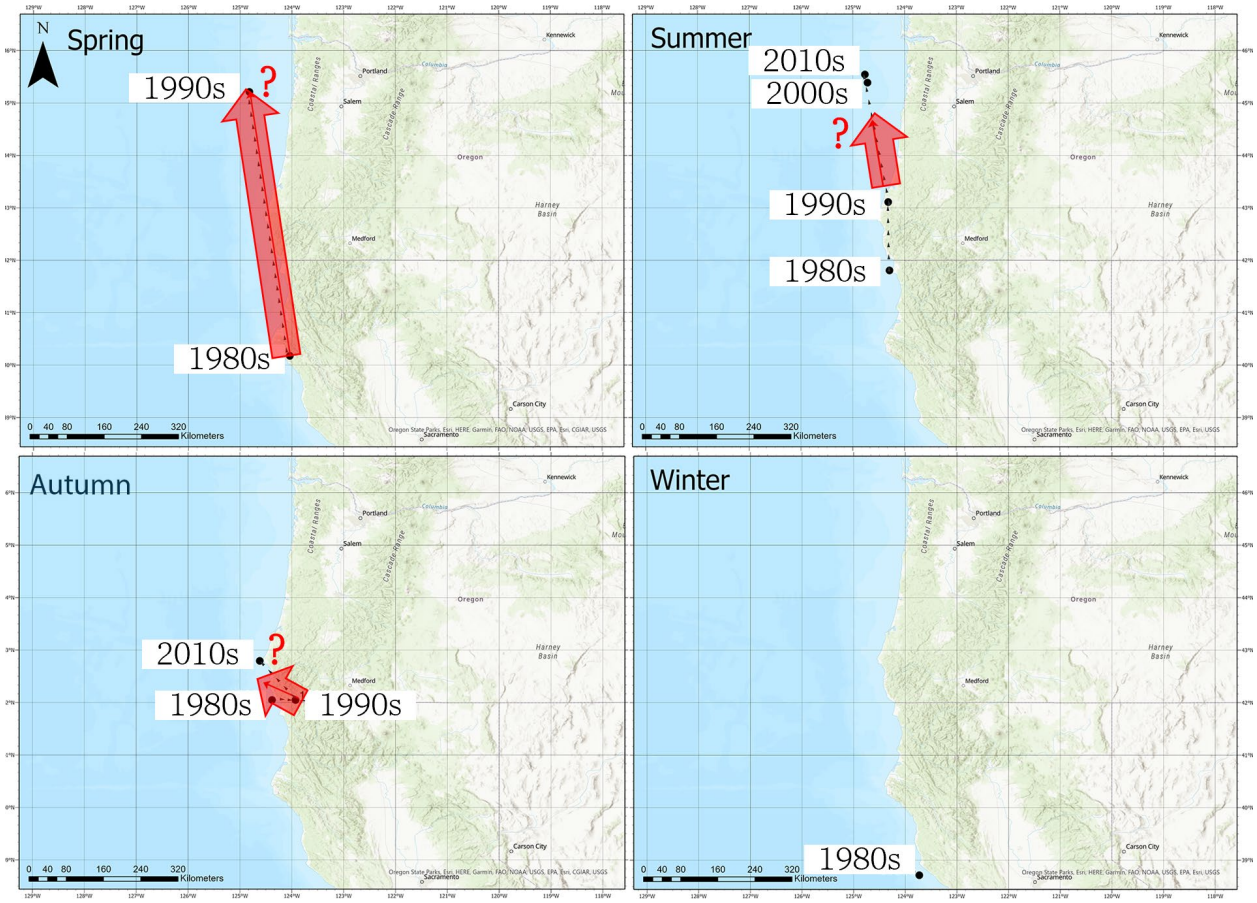


Figure 3.4. Black-footed albatross average of OBIS record locations suggesting seasonal population movements from the 1980s to the 2010s along the Pacific coast of the United States. The centroids for each decade are shown as black circles. The dashed black lines indicate decadal changes. The red arrows indicate average long-term trends (the distance and direction of the average shift) and question marks emphasize that these trends have high uncertainty based on the distribution of documented records in OBIS.

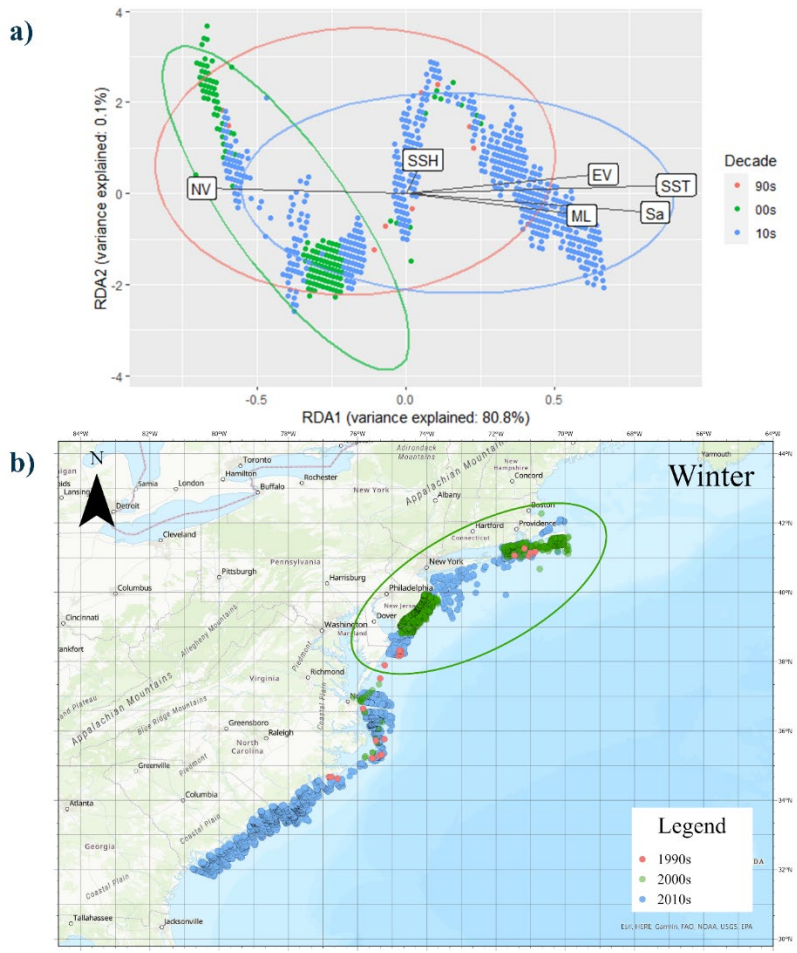


Figure 3.5. a) Redundancy analysis occurrence data for wintering common loons on the east coast of the USA. Latitudinal changes in occurrence records can be seen along x-axis and longitudinal changes along the y-axis. NV = northward current velocity, SST = sea-surface temperature, SSH = sea-surface height, ML = mixed-layer depth, EV = eastward current velocity, Sa = salinity. b) Geographic spread of occurrence records. Decades are represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively. Ellipses are color matched with their respective decades and show the region for which there is 90% confidence that the centroids observed in Figure 3.2 were located within the centers of the ellipses.

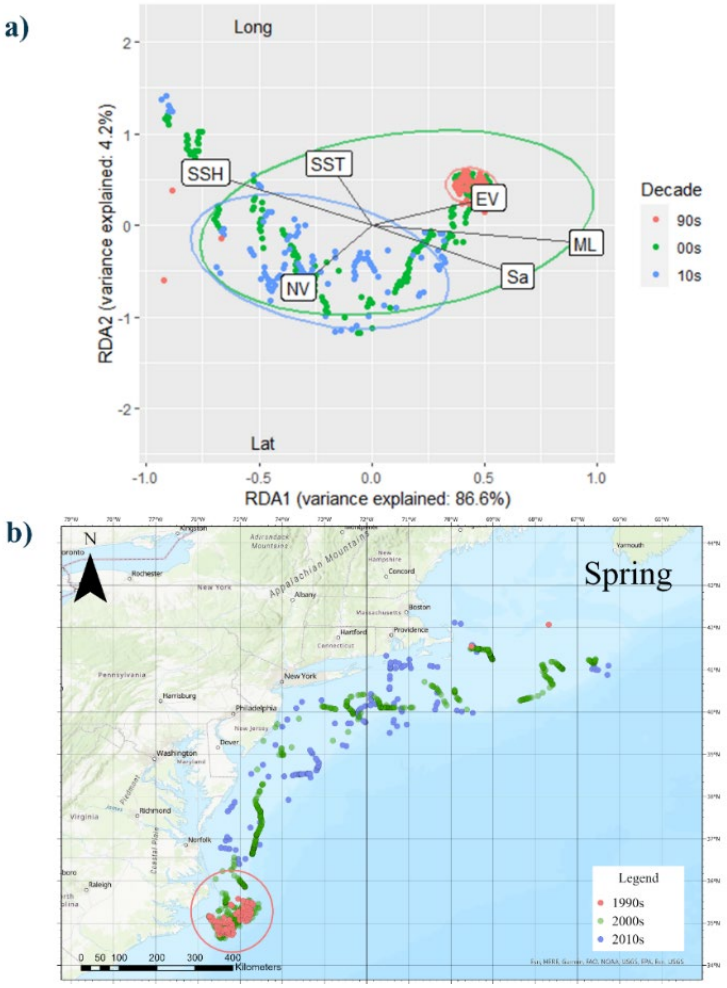


Figure 3.6. a) Redundancy analysis occurrence data for sooty shearwaters on the east coast of the USA during the spring. Latitudinal changes in occurrence records can be seen along x-axis and longitudinal changes along the y-axis. NV = northward current velocity, SST = sea-surface temperature, SSH = sea-surface height, ML = mixed-layer depth, EV = eastward current velocity, Sa = salinity. b) Geographic spread of occurrence records. Decades are represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively. Ellipses are color matched with their respective decades and signify that there is 90% confidence that the centroids observed in Figure 3.2 were located within the centers of the ellipses. Red ellipses in (a) and (b) are focused on in the discussion.

a) b)

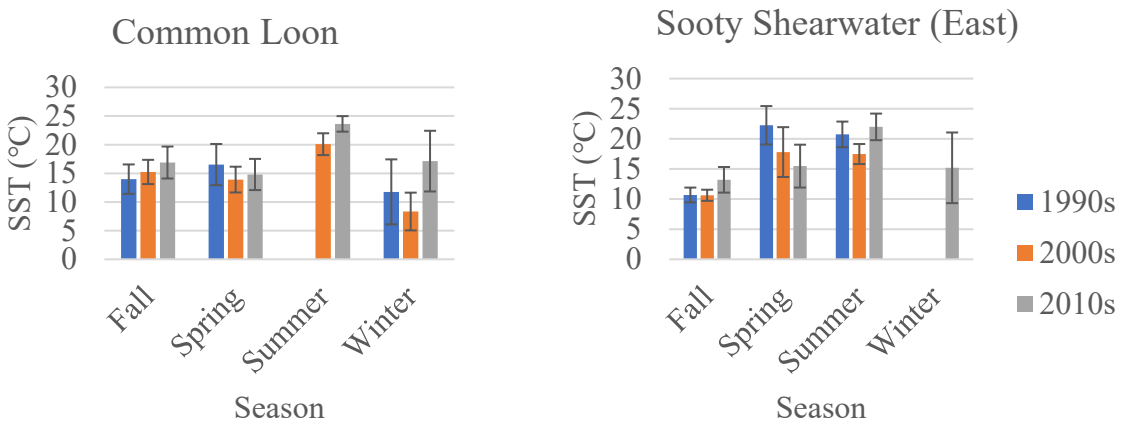


Figure 3.7. Average sea-surface temperature for the centroids of a) common loons, b) sooty shearwaters on the east coast, for each decadal average season. Sea-surface temperatures were taken within a two-degree square buffer around the centroid. Standard deviations about the two-degree square of the average decadal gridded seasonal fields are shown.

a) b)

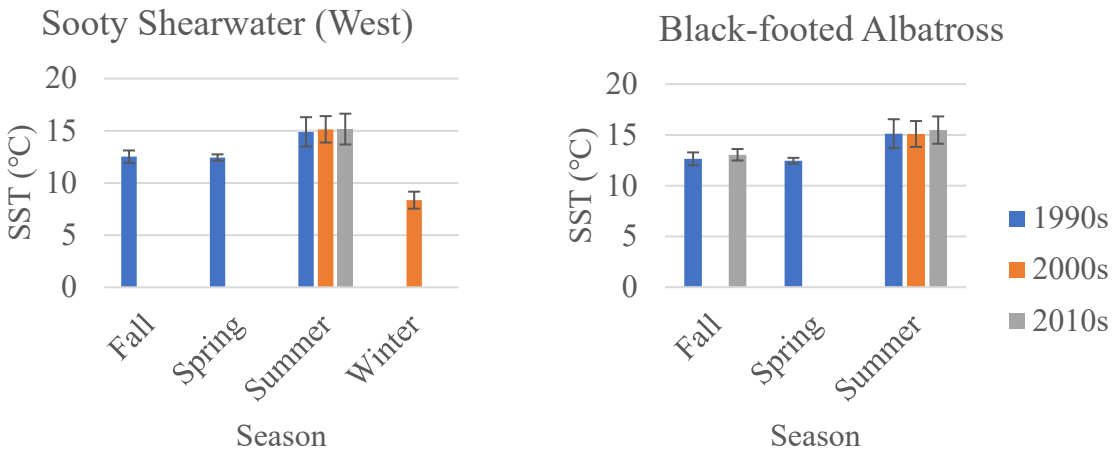


Figure 3.8. Average sea-surface temperature for the centroids of a) sooty shearwaters on the west coast, b) black-footed albatross, for each decade and season. Sea-surface temperatures were taken within a two-degree square buffer around the centroid. Standard deviations about the two-degree square of the average decadal gridded seasonal fields are shown.

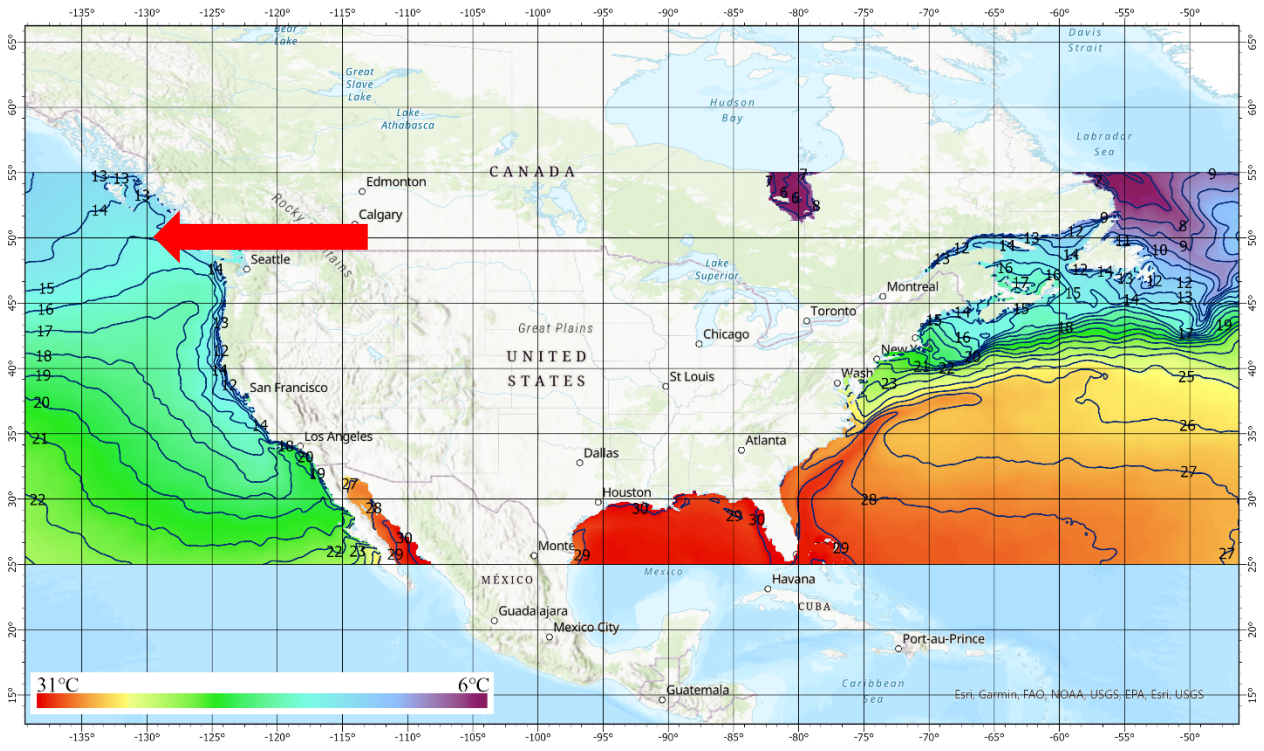


Figure 3.9. Average summer, decadal sea-surface temperatures off the coasts of the United States (a: 1990s, b: 2000s, c: 2010s). Isotherms indicate variation of 1°C. Red arrows show 1º expansion of 15°C-16°C at 50º latitude and -130º longitude when comparing decadal averages to the 2010s (Figure 3.11).

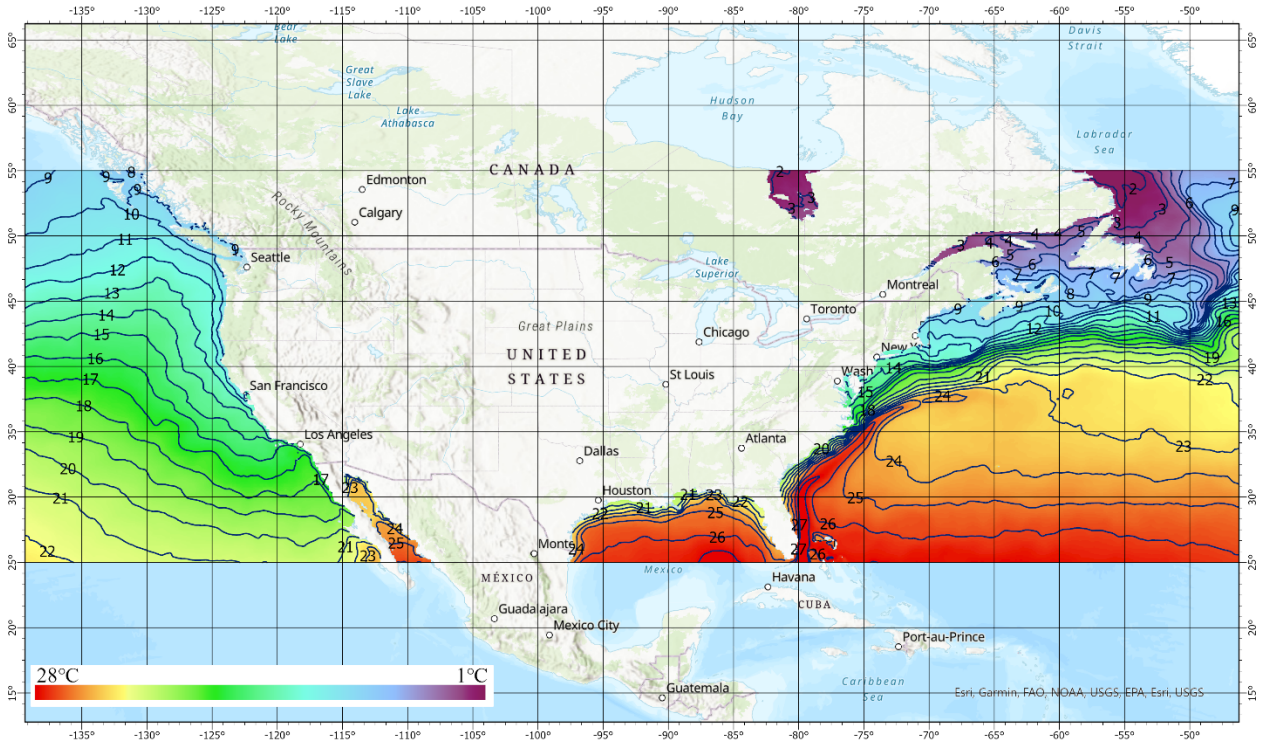


Figure 3.10. Average summer, decadal sea-surface temperatures off the coasts of the United States during the 2000s. Isotherms indicate variation of 1°C.

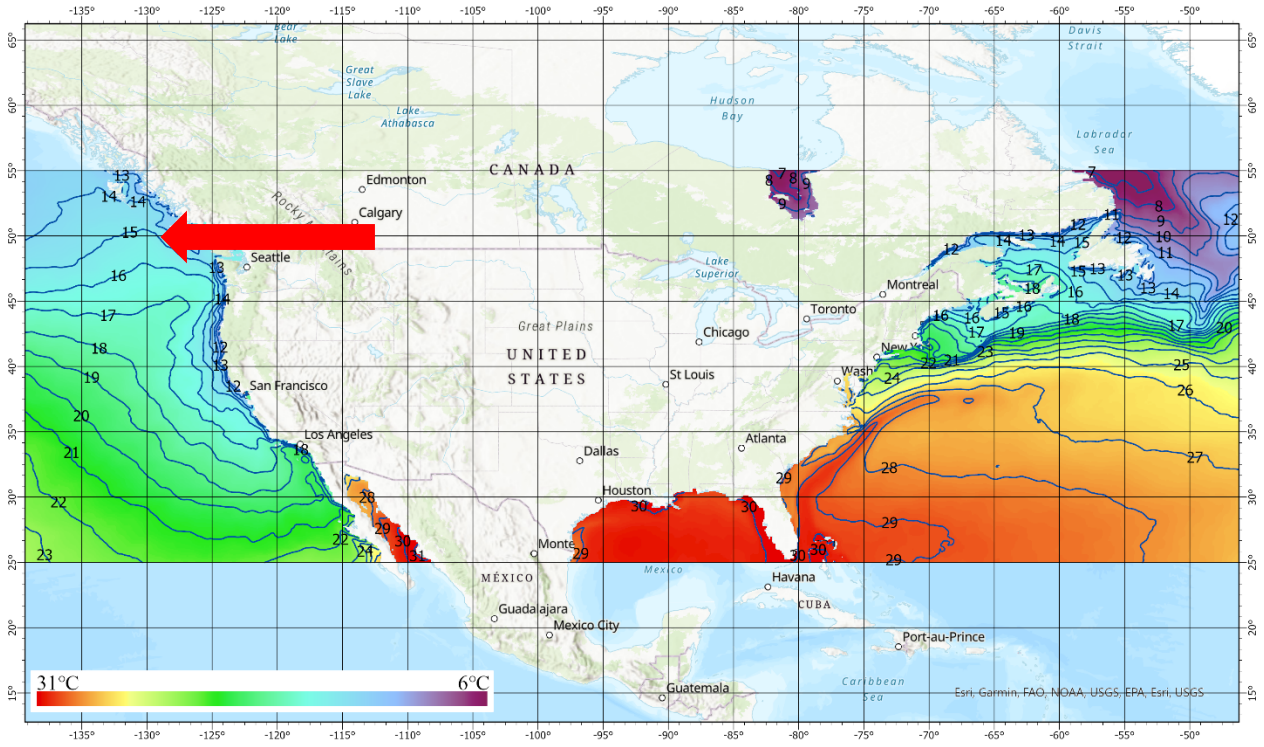


Figure 3.11. Average summer, decadal sea-surface temperatures off the coasts of the United States during the 2010s. Isotherms indicate variation of 1°C. Red arrow show 1º expansion of 15°C-16°C at 50º latitude and -130º longitude when comparing decadal averages to the 1990s (Figure 3.9).

CHAPTER 4:

USEFUL TOOLS FOR ENVIRONMENTAL EDUCATION: SPREADING KNOWLEDGE IN INNOVATIVE AND ENGAGING WAYS

Note to reader:

This chapter was published on November 23, 2022 through the University of São Paulo Institute of Advanced Studies with co-authors, Drs. Ana Carolina Esteves Dias, Loreley Lago, and Lorena Lopes Almeida, as well as Dragana Paleček, Juan Pardo, and Thaís Rech. The paper is included in this dissertation, and its corresponding online supplement is included as Appendix D in this dissertation. Creative Commons License is included as Appendix E.

Reference:

Dias, A.C.E., D. Paleček, J. Pardo, S. Hartman, L. Lago, T. Rech, and L.L. Almeida. "Useful Tools for Environmental Education: Spreading Knowledge in Innovative and Engaging Ways." Challenges in Ocean Governance in the Views of Early Career Scientists – Achievements of the São Paulo School of Advanced Science on Ocean Interdisciplinary Research and Governance (SPSAS Ocean), edited by Bruno Meirelles de Oliveira, Juan Carlos Farias Pardo, and Alexander Turra, Institute of Advanced Studies, Sao Paulo, Brazil., November 2022, pp. 209-235. Doi: 10.11606/9786587773384

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CHAPTER 5:

CONCLUSIONS

The meta-analysis conducted in Chapter Two provided an opportunity to understand the scale and abundance of available records of seabirds in the Ocean Biodiversity Information System along the Pacific and Atlantic margins of the Americas. Over 680,000 records were found to be robust and of good quality for study. Yet, most data were collected in waters around North America. Despite there being more than 655,000 records on the east and west coasts of the United States, data documentation and collection activity has varied substantially for each species over the past few decades. This work highlights that more data need to be reported from all over the world for robust conclusions to be made about species of interest (in this case seabirds). Data already collected should be made available in open access platforms. For the future, initiatives should be undertaken that facilitate consistent data collection over every season for specific geographic ranges.

According to a literature review conducted by Bernard et al. (2021), 363 seabirds have been analyzed to some degree. When considering threatened species, out of "113 threatened species only 10 had both high tracking effort (more than 100 individuals tracked) and good coverage (>50% of the range)" (Bernard et al., 2021, p. 11), and only a dozen more species were documented as having "sufficient coverage". My research further documented that more work needs to be done concerning these elusive, yet ecologically important taxa.

My dissertation research suggests many new questions and directions for future research. For example, the strong correlations of the seabird distributions with sea-surface temperature and salinity suggest that there are testable hypotheses regarding how these physical parameters influence biotic factors. Untangling these factors from biases due to observation location would be a challenge. Further, historical remote sensing and field data on phytoplankton and zooplankton abundances should be examined in the context of seabird distribution data (e.g., Grémillet and Boulinier, 2009). Creating detailed species distribution models incorporating biotic factors, in combination with fisheries activity, could also be useful for understanding foraging hotspots and particular marine habitats that should be protected/ managed appropriately in the future.

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APPENDICES

Appendix A: Obligation to Enhance OBIS Data for Sea- and Shorebirds of the Americas

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Obligation to Enhance OBIS Data for Sea- and Shorebirds of the Americas

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Abstract: The distributions of many sea- and shorebird species span large geographic areas, making them ideal candidates as biomonitors of ecosystem perturbations and long-term environmental trends. The basic question examined in this study was: Does a major open-access data archive contain sufficient temporal- and spatial-scale data to support more detailed inquiry into multi-decadal-scale responses in geographic distributions of specific taxa? The global-scale open-access data platform, Ocean Biodiversity Information System (OBIS), was searched to compile data on bird distributions of the Americas, including the Caribbean Sea. More than 680,000 occurrence records of 210 species, collected between 1965 and 2018, were located and evaluated by marine ecoregion. The Puget Trough/Georgia Basin marine ecoregion, along the United States/Canadian border, and the Virginian marine ecoregion on the US east coast, dominated occurrences, each with more than 100,000 records, while the Gulf of Maine/Bay of Fundy had the most years of records (42). Most records from South America (~29,000) came from the Channels and Fjords of Southern Chile, collected across 16 different years. More than 90% of the recorded data were collected since 1983, and more than 95% of the records were from North American marine ecoregions. We urge additional observations to be shared via OBIS to allow comprehensive large-scale and detailed meta-analyses of spatial and temporal trends in marine and shore-bird communities and their biodiversity.

Keywords: biodiversity; biogeography; biomonitoring; marine ecoregions; open-access data; meta-data analyses; Ocean Biodiversity Information System (OBIS); birds

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1. Introduction

Sea and shorebird taxa are relatively well known, but their distributions and responses to environmental perturbations deserve further investigation. These taxa can serve as monitors of marine ecosystems because many species span large geographic ranges, inhabit different coastal and oceanic regimes, and feed on prey at various trophic levels. Changes in species occurrences and abundances, as well as changes in numbers and health of individuals within populations, can indicate changes in temperature, food supply, exposure to environmental contaminants, and other environmental and biological factors [1–3]. Sea- and shorebird populations are also widely-observed, making them ideal candidates to provide data on community composition and population distributions for biogeographic and macroecological analyses [4–6].

The Ocean Biodiversity Information System (OBIS) is a global, open-access data archive [7] that originated from the Census of Marine Life [8] and was adopted as a project of the Intergovernmental Oceanographic Data and Information Exchange of UNESCO. OBIS uses the Darwin Core Biodiversity Standard [9,10] to record observations related to individual species, including location, time of observation, and any other related measurements or facts. The system can also be used to document specimens and taxonomic information derived from museum collections, other taxonomic information (e.g., derived from genetic analyses, acoustics, imaging or other methods), and other historical observations documented in the literature. OBIS was established to provide access to historical and

recently collected observations, all submissions require rigorous quality-control procedures that must be met prior to data being archived [7]. This platform ideally can be used in a multitude of ways, ranging from determining if an unusual observation is indeed unprecedented, to meta-data analyses of geographic distributions. Additionally, there are databases such as eBird [11] and the Seabird Tracking Database [12] which contain a multitude of seabird data; however, these databases, including OBIS, inevitably have gaps in coverage.

For this study, we examined records of sea- and shorebird occurrences in the Americas using data from the OBIS archive collected over the past ~50 years. The specific goals of this study were to (a) determine what bird-occurrence data are available in the major data platforms; (b) assess the available data with respect to when and where data were collected; and (c) document the challenges and need for additional data sharing to support research and enhance conservation actions.

2. Methods

Occurrence records for sea- and shorebirds were acquired from OBIS [7]. Records identified from latitudes 49°N–60°S within the EEZ of each country in the Americas and the Caribbean region were acquired from the OBIS platform on 7 August 2019. The overwhelming majority (~98%) of the records were based on field observations. Records based on preserved specimens were few in number and therefore excluded from further analyses, as were data from remote images that were analyzed using machine learning and artificial intelligence software. Data were quality controlled using [robis] and [obistools] from R programming (R version 4.0.2) [9]. Duplicates and organisms that were not identified to the species level were removed, as were species designated as purely terrestrial (<1% from OBIS data for North American EEZs). Occurrence records with a geographical coordinate located inland or seaward within 1 km of the coastline were also excluded from the analysis for standardization purposes.

Each OBIS record was standardized using coverage-based rarefaction. This method normalizes data across various datasets and allows for comparability [13]. Sampling effort could not be accounted for because numerous records did not discuss standardization methods a priori or include effort for post hoc standardization. The lead author attempted contact with collection agencies but was unsuccessful in obtaining necessary information. Data that were collected outside of a specific collection event, meaning they had no collection event identification or could not be identifiable as part of an overall project, were retained only for the analysis of South American data. If those had been excluded, there would be far fewer data available for much of South America. Data from North America were ultimately aggregated by collection event and then compared regionally, while data from South America were simply compared regionally due to sparce collection-event records. We used the detailed marine-ecoregions classification of Spalding et al. [14] to examine biogeographic distributions of OBIS records. Occurrence data were spatially joined with marine ecoregions using GIS [15]. Data collected in international waters (beyond 200 nm from a coast) were excluded from the analyses, resulting in the exclusion of approximately 2000 additional occurrence records.

3. Results

Seabird-occurrence records were found for 29 of 43 marine ecoregions of the Americas between 49° N and 60° S (Figures 1–3). After screening, 685,454 bird-occurrence records were compiled from the OBIS (2019) database for the years 1965–2018 (Figure 2). No data were available for 1960–64, 1966–68, 1974, 1976, 1979, 2015, and 2016. In 1979–1982, ~20,000 records/year were found, then many fewer in the subsequent decade of 1983–1992. In 1993–2004 and 2008–10, 20,000–30,000 occurrence records were found per year. In 2018, nearly 100,000 records were entered into OBIS from the 'U.S. Outer Continental Shelf Option Year 1' and 'Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy—OPA 2016 datasets' [16,17].

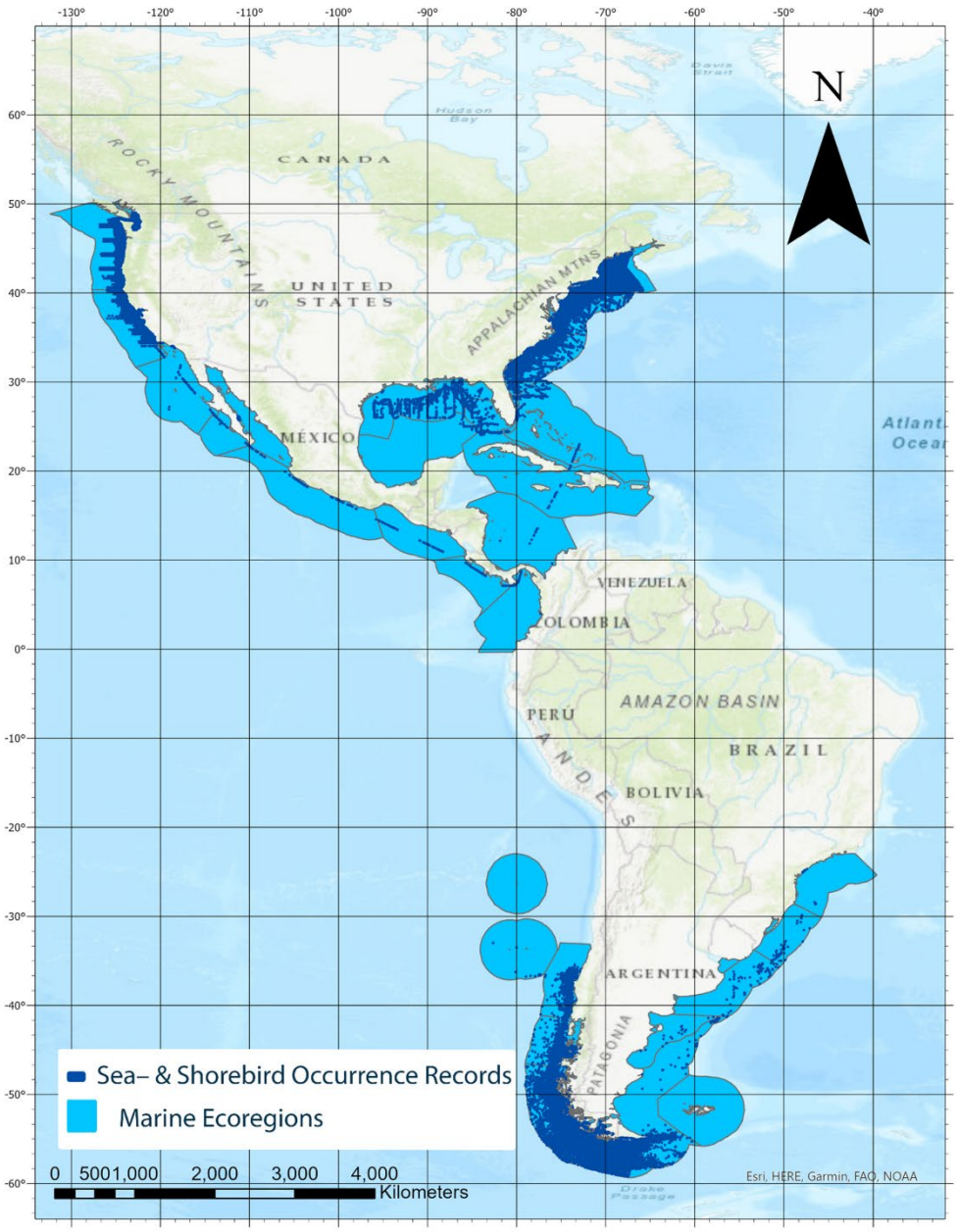


Figure 1. Relevant marine ecoregions of the Americas (based on [14]) used to evaluate sea- and shorebird records found in OBIS ([7]; accessed 7 August 2019). OBIS records found are noted by blue dots, and all marine ecoregions and occurrence records are located off the coast. Marine ecoregions where no seabird records were found in OBIS are not shown. Dashed line along western Central America and across to the Caribbean Sea indicate that observations were recorded along a cruise track [18,19].

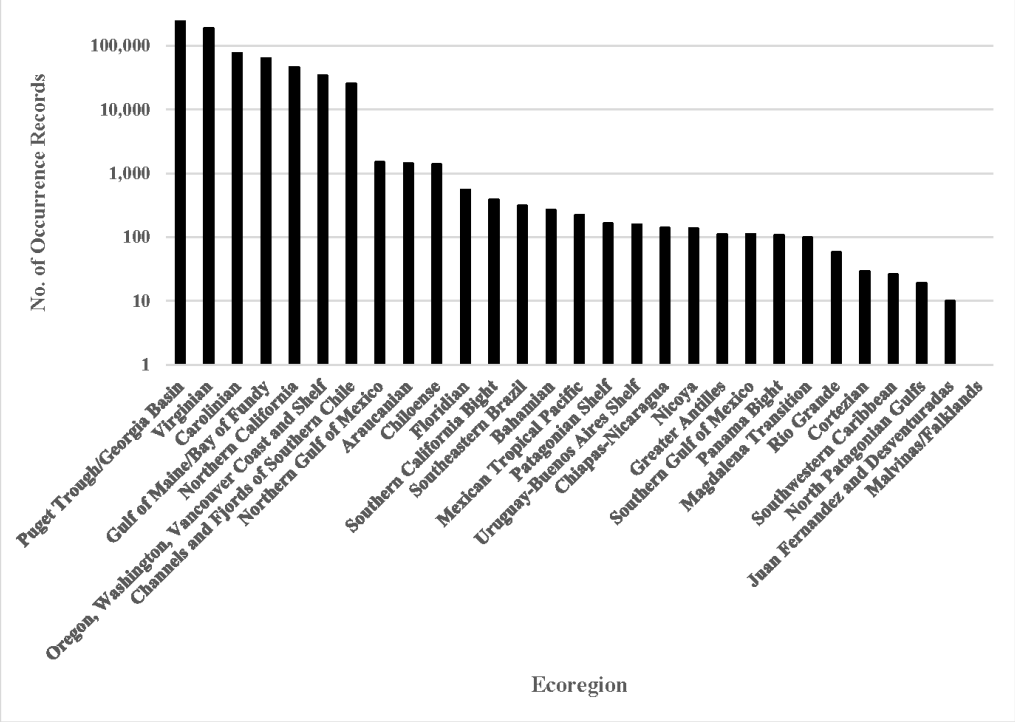


Figure 2. Sea- and shorebird-occurrence records in OBIS [7] (accessed 7 August 2019) for Marine Ecoregions of the Americas [14]. Most records are from North American ecoregions, especially the coastlines of the United States. Only one occurrence record was found for the Malvinas/Falkland Islands marine ecoregion.

The number of years when data were reported for individual ecoregions ranged from 0–42 (Figure 3). More than 20 years of data were available for only four ecoregions, all in North American waters. Considering the number of years and the 29 ecoregions for which data were found, North American ecoregions averaged 11 years (median 8 years) with documentation, while South American ecoregions averaged 6 years (median 4.5 years).

Approximately 96% of the occurrence records were from North America, as were ~83% (n = 47) of the documented collection events. The majority of South American records are attributed to one ecoregion, the high latitudes of the Channels and Fjords of Southern Chile. This ecoregion was the only South American marine ecoregion for which >10,000 occurrence records were found in the OBIS archive. In contrast, more than 100,000 occurrence records were acquired for each of two North American ecoregions, Puget Trough/Georgia Basin and Virginian Ecoregion. More than 10,000 records were available for each of four other North American ecoregions: Carolinian; Gulf of Maine/Bay of Fundy; Northern California; and the Oregon, Washington, Vancouver Coast and Shelf. More than 1000 records were found for only three additional ecoregions, the Northern Gulf of Mexico (NA), Araucanian and Chiloense (SA) ecoregions. Fewer than 1000 records were found for 18 remaining ecoregions (Figure 2), including those from Central America, the Caribbean, and South American coastlines outside of Chile. No records were found for 14 of the ecoregions in the Americas (Figure 1) [14].

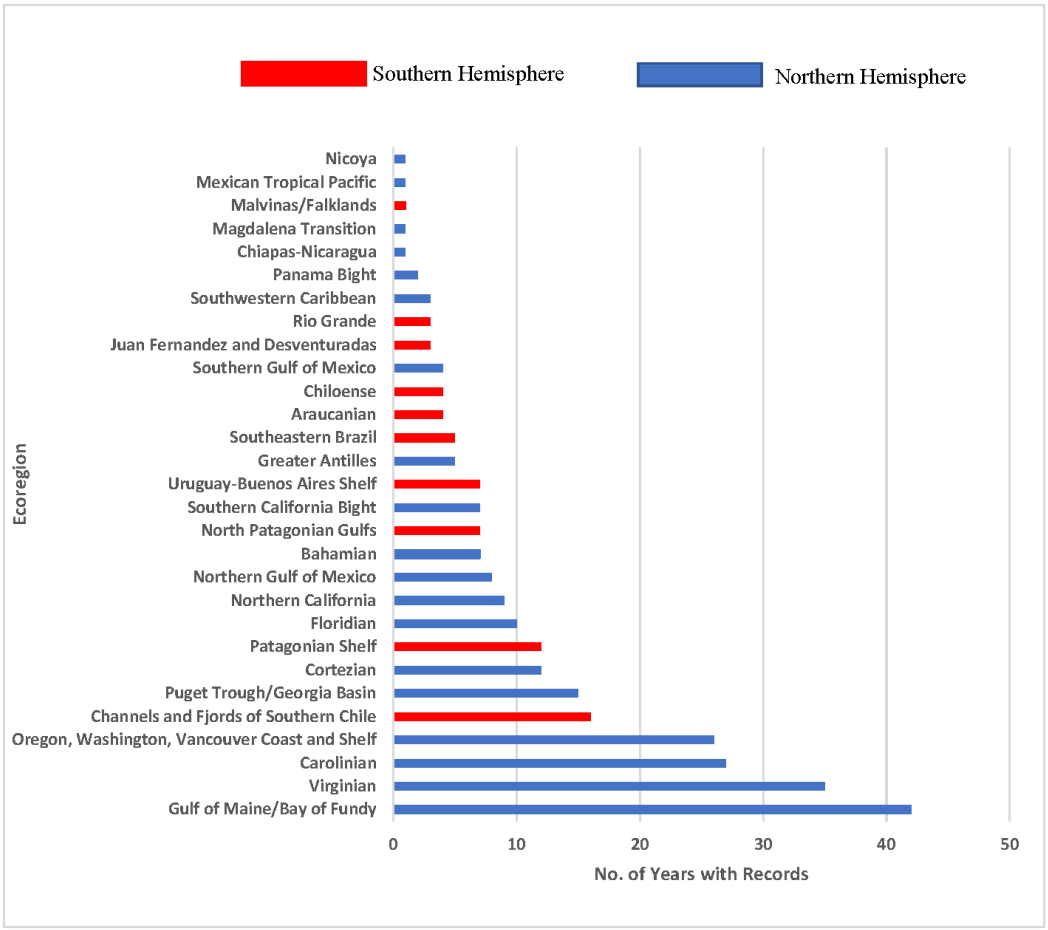


Figure 3. Marine ecoregions of the Americas [14] and the number of years from 1960–2018 for which the OBIS database [7] contained sea- and shorebird data.

The dataset for sea- and shorebird occurrences included 210 species across 25 taxonomic families, primarily Anatidae, Procellariidae, Laridae, Scolopacidae, Alcidae, Hydrobatidae, Sternidae, and Diomedeidae (Table 1; Figure 4). More than 150,000 occurrence records were found for each of two families, the Anatidae (ducks and geese) and Laridae (gulls), accounting for 45% of the records. Supplementary Tables S1 and S2 show the five most abundant species per ecoregion and decade for which it was found. The most common species found for Anatidae were *Melanitta fusca*, *Melanitta perspicillata*, *Mergus serattor*, *Melanitta nigra*, and *Somateria mollissima*; Laridae species documented most frequently were *Onychoprion fuscatus*, *Onychoprion anaethetus*, *Larus atricilla*, *Larus argentatus*, and *Rissa tridactyla*. Between 10,000 and 100,000 records of occurrences of species from ten families were found, 100 to 1000 records were found for species in three families, with fewer than 100 occurrences recorded for five families.

Table 1. Sea- and shorebird families, common names, general habitat, number of species recognized based on ([20–40] and occurrence records within the OBIS database [7]). The ecoregions with records were alphabetically assigned numbers (1–29) to show where records for each family were found: 1 Araucanian, 2 Bahamian, 3 Carolinian, 4 Channels and Fjords of Southern Chile, 5 Chiapas-Nicaraguan, 6 Chiloense, 7 Coretezian, 8 Floridian, 9 Greater Antilles, 10 Gulf of Maine/Bay of Fundy, 11 Juan Fernandez and Desventuradas, 12 Magdalena Transition, 13 Malvinas/Falklands, 14 Mexican Tropical Pacific, 15 Nicoya, 16 North Patagonian Gulfs, 17 Northern California, 18 Northern Gulf of Mexico, 19 Oregon, Washington, Vancouver Coast and Shelf, 20 Panama Bight, 21 Patagonian Shelf, 22 Puget Trough/Georgia Basin, 23 Rio Grande, 24 Southeastern Brazil, 25 Southern California Bight, 26 Southern Gulf of Mexico, 27 Southwestern Caribbean, 28 Uruguay-Buenos Aires Shelf, 29 Virginian.

Family Name	Common Name/s	Habitat	# Species	# spp in OBIS	# Occurrence Records	No. of Each Marine Ecoregion with Records
Anatidae	Ducks, Geese	Coastal/inland	174	33	158,392	3, 10, 17, 19, 22, 29
Laridae	Gulls	Coastal/inland	51	26	150,416	2, 3, 5, 7–10, 12, 14, 15, 17–20, 22, 24–27, 29
Procellariidae	Petrels, Shearwaters	Pelagic	96	30	72,975	2–5, 7–12, 14–22, 25–29
Alcidae	Auks, Murres, Puffins	Cold water, coastal	25	15	72,386	3, 10, 17, 19, 22, 25, 29
Sulidae	Boobies, Gannets	Pelagic	10	5	44,381	2, 3, 5, 7–10, 14, 15, 18 20, 26, 27, 29
Gaviidae	Loons	Coastal/inland	5	3	42,642	3, 10, 17, 19, 22, 29
Diomedeidae	Albatrosses	Pelagic	15	10	29,730	1, 4, 6, 11–13, 16, 17, 19, 21, 23–25, 28
Hydrobatidae	Northern Storm Petrels	Pelagic	18	12	28,277	2–5, 7–10, 12, 14, 15, 17–20, 25–29
Phalacrocoracidae	Cormorants, Shags	Coastal & pelagic	40	6	20,867	3, 8, 10, 17–19, 22, 29
Podicipedidae	Grebes	Coastal/inland	22	5	20,680	3, 17, 19, 22, 29
Phalaropodidae	Phalaropes	Shorebirds	3	2	16,425	3, 10, 14, 17, 19, 22, 25, 29
Sternidae	Terns	Inland, coastal & pelagic	45	11	10,318	2, 3, 8–10, 14, 15, 17–20, 22, 24, 26, 29
Ardeidae	Herons, Egrets, Bitterns	Shorebirds	68	2	7,526	3, 8, 10, 17, 19, 20, 22, 29
Stercorariidae	Skuas	Cold water, coastal	7	5	3,202	2, 3, 8–10, 14, 17–19, 22, 25, 26, 28, 29
Scolopacidae	Sandpipers	Shorebirds	97	22	2,373	3, 10, 17, 19, 20, 22, 27, 29
Accipitridae	Hawks, Eagles, Kites	Mostly terrestrial	250	1	2,224	10, 19, 22, 29
Pelecanidae	Pelicans	Coastal/inland	8	2	1,104	7, 8, 17–20, 22, 25, 26, 29
Spheniscidae	Penguins	Southern cold waters	18	3	712	4, 21
Charadriidae	Plovers, Lapwings	Coastal/inland	68	8	549	3, 7, 10, 19, 20, 22, 24, 29
Phaethontidae	Tropicbirds	Islands & pelagic	3	2	157	2, 3, 5, 7, 8, 10, 14, 15, 26, 29
Rynchopidae	Skimmers	Coastal	3	1	65	24, 29
Fregatidae	Frigatebirds	Coastal & pelagic	5	1	27	2, 3, 5, 8, 14, 15, 20, 27
Recurvirostridae	Stilts, Avocets	Coastal/inland	9	2	17	3, 17
Alcedinidae	Kingfishers	Coastal/inland	118	1	7	3, 10, 27
Threskiornithidae	Ibises, Spoonbills	Shorebirds	36	1	2	3, 27

When the recorded families were compared to the number of observed species for each taxonomic group found in the Americas, all known species were recorded at least once for three families: Rynchopidae, Phaethontidae, and Phalaropidae (Figure 5). More than half the recognized species were recorded for an additional 11 families, while occurrences for the other 11 families included <50% of possible species (Figure 5), including one of the most abundant shorebird families, Charadriidae. Shorebird family Scolopacidae was

documented at 50%. Families with fewer than 10 species tended to be documented at higher percentages (i.e., Rynchopidae, Phaethontidae, Phalaropidae, Gaviidae, Stercorariidae, Sulidae, Pelecanidae, and Recurvirostridae), though three such families had <30% of species documented (i.e., Spheniscidae, Fregatidae, and Alcedinidae, see Table 1).

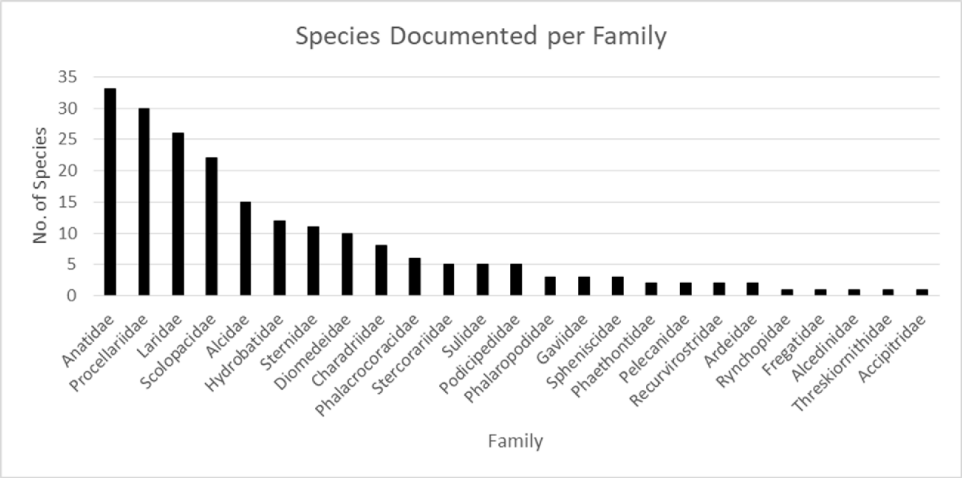


Figure 4. The number of species documented by family in OBIS [7] from 1960–2018 for the ecoregions assessed. Common name equivalents can be found in Table 1.

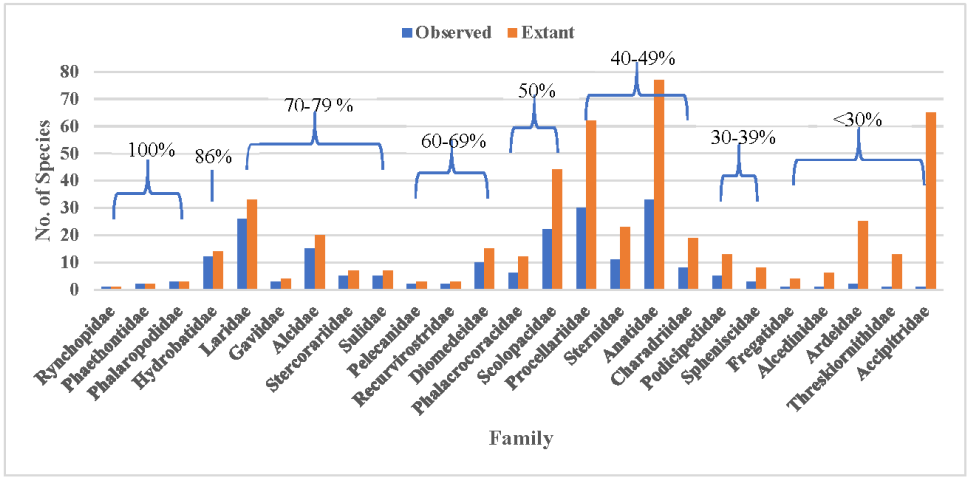


Figure 5. Number of species documented in OBIS [7] (accessed 7 August 2019) by family from 1960-2018 in the Spalding et al. [14] marine ecoregions of the Americas, plotted from highest (left) to lowest (right) percentages for each family (source of extant species data is [41]; common name equivalents can be found in Table 1).

The most widely recorded family was Procellariidae (petrels and shearwaters), which was documented in 24 of the 29 ecoregions for which data were found. The Hydrobatidae (northern storm petrels, 20 ecoregions) and Laridae (seagulls, 20), and Sternidae (terns, 17),

were also widely recorded. Families whose species distributions were more restricted included the cold-water Alcidae (auks, murres, and puffins in 7 ecoregions) and Spheniscidae (penguins, 2). Families with species found in freshwater as well as marine environments, or that typically occur nearshore, included Anatidae and Gaviidae (ducks and geese, 6 species, and loons at 6), Podicipedidae (grebes, 5), Alcedinidae (kingfishers, 3), Recurvirostridae (stilts and avocets, 2), Rynchopidae (skimmers, 2), Threskiornithidae (ibises and spoonbills, 2), and Accipitridae (ospreys, 1) (Table 1).

In eleven South American ecoregions for which observations were recorded in OBIS [7], occurrence records for fewer than six families were found (Table 1), though all eleven ecoregions contained records for the family Diomedeidae (albatrosses). In contrast, in several North American ecoregions, the majority of species for each family were documented. Representatives of 63% of all avian families found in the study were recorded in the "Cold, Temperate Northeast Pacific" province, and more than half of the species of those families were recorded within the Puget Trough/Georgia Basin ecoregion. In the "Cold, Temperate Northwest Atlantic" province, representatives of 67% of the families were recorded the Gulf of Maine/Bay of Fundy ecoregion, 73% in the Virginian ecoregion and 81% in the Carolinian ecoregion.

4. Discussion

Sea- and shorebird occurrence records were found in OBIS for just over half of the marine ecoregions along the Americas and documented for 46 years. Almost half of the records were from Anatidae and Laridae families, but the Rynchopidae, Phaethontidae, and Phalaropodidae families were documented "completely", meaning that 100% of the species in their families were documented. The Procellariidae family were documented in the most marine ecoregions (Table 1), while Laridae, in addition to Procellariidae, have the longest temporal record (Figure 6). The most abundant shorebird families, Scolopacidae and Charadriidae, are documented approximately half of the years of the study and seen over various marine ecoregions (Supplementary Table S3). Overall, the highest number of species recorded in the OBIS database has been recorded from the Puget Trough/Georgia Basin marine ecoregion (Figure 2).

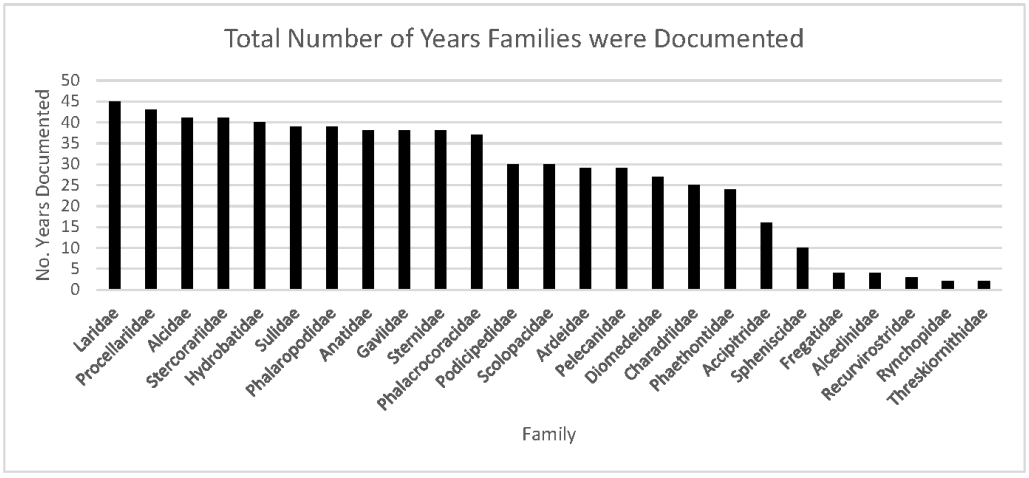


Figure 6. The total number of years each family was documented. Laridae and Procellariidae were documented for the most years (45 and 43 years, respectively). Rynchopidae and Threskiornithidae were documented the least, 2 years (common name equivalents can be found in Table 1).

OBIS is the "world's largest scientific knowledge base on the diversity, distribution and abundance of marine organisms" and strives to provide "an integrated and standardized format" for data [42]. While there are other databases that could provide additional information, notably Global Biodiversity Information Facility, eBird, and the Seabird Tracking Database [8,11,12], authors decided to focus their search within OBIS as a brief foray into the realm of seabird records. Data from eBird is updated annually and made available through GBIF [43], and OBIS and GBIF share many similarities; however, OBIS uses the World Register of Marine Species as its taxonomic backbone, unlike GBIF. Additionally, OBIS requires geographic latitudes and longitudes of an organism's occurrence to be reported and allows for researchers to input environmental data associated with the sampling events. GBIF data simply records occurrence. This sets OBIS up as a valuable platform for biogeographic study and complement to the eBird/GBIF databases. If data in future studies wish to focus on data outside of the marine ecoregions, the addition of the omitted OBIS records in conjunction with the Seabird Tracking Database could be invaluable.

Our results demonstrate the need for more data to be provided to OBIS, especially from ecoregions in the Caribbean, and Central and South America. This assessment is consistent with previous analyses of data available for other marine organisms that were based on OBIS data [44–51]. The majority of previous bird studies focused on a limited number of species or dealt extensively with terrestrial taxa [52–55]. We found that sea- and shorebird data available from OBIS are relatively sparse in many ecoregions, and both spatially and temporally fragmented. This reveals a vast need and an opportunity for data collection and archiving, to provide additional contributions that can improve the applicability of sea- and shorebird observations to address changes in coastal and marine environments.

Our study was originally designed to focus on seabirds, accounting for decision to exclude data recorded within 1 km of the coastline. However, when Anatidae (ducks and geese) and Laridae (gulls) accounted for 45% of the records, and many other families include taxa that utilize or migrate through a range of terrestrial and marine habitats (Table 1), we included shorebirds in our analyses. The five primarily pelagic families, and the three families with pelagic representatives, represent ~32% of the species records and more than 10,000 records were found for six of those eight families. Thus, our results do provide a substantial dataset for primarily pelagic species.

Many observations and data archives have been lost or forgotten [56,57]; therefore, it is important to share data via standardized and open databases, like OBIS, before data collection effort is wasted. If FAIR (i.e., Findable, Accessible, Interoperable, and Reusable) data principles are utilized in future, automated data input/collection and management can facilitate meta-data analyses and other reuse by individuals, agencies, and others [58]. Ideally, all collected data should be included in standardized biodiversity databases [59]. Building institutional and professional capacity is critical for providing data to specific open-access databases, such as OBIS.

Croxall et al. [60] noted that the total number of seabird species recorded within EEZ waters represents a key area of interest for ecological studies and for resource management. The data collected from EEZs can be used to specify goals for interregional collaboration and to designate mainland jurisdiction for conservation purposes. With the exception of the Channels and Fjords of Southern Chile Ecoregion, OBIS data from marine ecoregions in the Caribbean Sea and Central and South America are too sparse for detailed analyses. In contrast, OBIS data from marine ecoregions along the United States coastline can provide a sources of information for establishing conservation goals, especially considering the Puget Trough/Georgia Basin, Gulf of Maine Bay of Fundy, and Virginian marine ecoregions. While seabird species are found outside of EEZs, data from the high seas were excluded from this analysis, because they could complicate the interpretation of data used for country stewardship, since no country has sole responsibility for the management of those areas. While there is fragmented governance of international waters, there is a fluidity when it comes to environmental protection and management.

Families Fregatidae, Alcedinidae, and Threskiornithidae had the lowest percentages of species documented in the OBIS database. These include many species found along the coastlines of Central and South America [25,30,31]. Similarly, other families within the Americas with relatively few extant species, such as Spheniscidae, were poorly documented. The lack of documented studies on these taxa, specifically among tropical species, leads to the low percentages of species documented compared to better known temperate and boreal species.

Previous studies have observed higher avifaunal diversity along the equator compared to higher latitudes [54,61–66]. In contrast, Chown et al. [67] reported that pelagic seabird orders, such as Procellariiformes, have greater species richness at higher latitudes. Chown et al. [67] attributed this diversity to location along fishing routes and availability of prey from these anthropogenic interactions with the environment. Additional seabird studies from equatorial ecoregions may help address these questions. We recommend that any such studies share data via OBIS.

The abundance of occurrence records submitted to OBIS, as well as the diverse assemblages of recognized sea- and shorebird taxa, indicate that population-distribution analyses may be conducted for the Gulf of Maine/Bay of Fundy, and Oregon, Washington, Vancouver Coast and Shelf marine ecoregions. Data for other ecoregions were too limited for meaningful meta-analyses as of 2019.

5. Conclusions

1. The OBIS platform can provide baseline data for sea- and shorebird distributions in future studies for several North American marine ecoregions.
2. More observations, especially from Central and South American ecoregions and from the Caribbean Sea, should be shared via open-access databases like OBIS for monitoring and ecological analyses within and across those marine ecoregions.
3. Capacity development focused on best practices for seabird and environmental observations, including standardized meta-data formatting and sharing of observations via open databases like OBIS is important to improve the scientific understanding of sea- and shorebirds, as well as providing opportunities for scientists to contribute to the growth and well-being of open-access data initiatives.

Supplementary Materials: Please confirm if the following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d14121099/s1, Table S1: Anatidae species documented per marine ecoregion per decade; Table S2: Laridae species documented per marine ecoregion per decade; Table S3: Shorebird families Scolopacidae and Charadriidae and the marine ecoregions in which they were documented

Author Contributions: Conceptualization; Investigation; Data curation; Validation; Writing—review and editing, S.H., P.H. and F.M.-K.; Formal analysis, Savannah Hartman; Funding acquisition, F.M.-K.; Methodology, S.H.; Project administration, F.M.-K.; Software, S.H.; Supervision, P.H. and F.M.-K.; Visualization, S.H. and P.H.; Writing—original draft, S.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Occurrence records publicly available on OBIS. Computer code necessary to reproduce this work can be found on the lead author's Github: (https://github.com/hart2/AvesOBIS (last accessed on 9 December 2022).

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Conflicts of Interest: The authors declare no conflict of interest.

Biosketch: Savannah Hartman is a Ph.D. candidate at the Institute of Marine Remote Sensing (IMaRS), College of Marine Science, University of South Florida, USA. Her current research focuses on marine biodiversity, specifically biogeography and its connection to climate change using species distribution modelling.

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Supplementary Table S1. Anatidae species documented per marine ecoregion per decade. Species are listed from greatest to smallest abundance.

	Carolinian	**Gulf of Maine/ Bay of Fundy**	**Northern California**	**Oregon, Washington, Vancouver Coast and Shelf**	**Puget Trough/ Georgia Basin**	**Virginian**
70s	NA	*Branta bernicla, Somateria mollissima*	NA	NA	NA	NA
80s	*Melanitta nigra, Mergus serattor, Anas discors*	*Somateria mollissima, Melanitta fusca, Clangula hyemalis, Melanitta nigra, Mergus serattor*	*Melanitta perspicillata, Melanitta fusca, Mergus serattor*	*Melanitta perspicillata, Melanitta fusca, Melanitta nigra*	NA	*Melanitta fusca, Melanitta nigra, Clangula hyemalis, Somateria mollissima, Mergus serattor*
90s	NA	*Melanitta fusca*	*Melanitta perspicillata, Bucephala albeola, Melanitta fusca, Aythya valisineria, Anas platyrhynchos*	*Melanitta perspicillata, Bucephala albeola, Melanitta fusca, Melanitta nigra, Mergus serattor*	*Bucephala albeola, Anas americana, Bucephala clangula, Branata bernicla, Bucephala islandica*	*Melanitta nigra*
00s	*Aix sponsa*	*Somateria mollissima, Melanitta fusca, Melanita nigra, Melanitta perspicillata, Anas rubripes*	NA	*Bucephala albeola, Melanitta perspicillata, Mergus serattor, Melanitta fusca, Bucephala clangula*	*Bucephala albeola, Melanitta perspicillata, Bucephala clangula, Mergus serattor, Melanitta fusca*	*Clangula hyemalis, Somateria mollissima, Melanitta perspicillata, Melanitta fusca, Melanitta nigra*
10s	*Melanitta americana, Mergus serattor, Melanitta fusca, Aythya marila, Aythya affinis*	*Melanitta fusca, Somateria mollissima, Melanitta nigra, Mergus serattor, Clangula hyemalis*	NA	NA	NA	*Mergus serattor, Melanitta fusca, Melanitta nigra, Melanitta perspicillata, Somateria mollissima*

Supplementary Table S2. Laridae species documented per marine ecoregion per decade. Species are listed from greatest to smallest abundance.

	Bahamian	Carolinian	Chiapas-Nicaragua	Cortezian	Floridian	Greater Antilles	Gulf of Maine/Bay of Fundy	Magdalena Transition	Mexican Tropical Pacific	Nicoya	Northern California	Northern Gulf of Mexico	Oregon, Washington, Vancouver Coast and Shelf	Panama Bight	Puget Trough/Georgia Basin	Southeastern Brazil	Southern California Bight	Southern Gulf of Mexico	Southwest Caribbean	Virginian
60s	NA	NA	NA	NA	NA	NA	*Larus argentatus, Larus marinus, Rissa tridactyla, Larus atricilla, Larus philadelphia*	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
70s	*Onychoprion fuscatus, Sternula albifrons*	NA	*Onychoprion fuscatus, Onchoprion fuscatus*	NA	NA	*Onychoprion fuscatus*	*Larus argentatus, Larus marinus, Rissa tridactyla*	*Xema sabini*	*Onychoprion fuscatus, Xema sabini*	*Onychoprion fuscatus, Onychoprion anaethetus*	*Larus occidentalis*	NA	*Larus glaucescens, Larus occidentalis, Rissa tridactyla*	*Onychoprion anaethetus, Onychoprion fuscatus*	NA	NA	*Rissa tridactyla, Larus argentatus, Larus occidentalis, Larus californicus*	NA	*Onychoprion fuscatus*	*Larus argentatus, Rissa tridactyla, Larus marinus, Larus hyperboreus*
80s	*Onychoprion anaethetus, Larus atricilla*	*Larus argentatus, Larus articilla, Onychoprion anaethetus, Larus philadelphia, Onychoprion fuscatus*	NA	*Larus heermanii, Larus livens*	*Sternula albifrons, Larus atricilla, Larus argentatus, Onychoprion anaethetus*	NA	*Larus argentatus, Larus marinus, Rissa tridactyla, Larus atricilla, Larus delawarensis*	NA	NA	NA	*Larus occidentalis, Larus californicus, Rissa tridactyla, Larus argentatus, Larus philadelphia*	*Larus atricilla*	*Larus occidentalis, Larus californicus, Rissa tridactyla, Larus argentatus, Larus glaucescens*	NA	NA	NA	*Larus californicus, Larus occidentaiis, Larus heermanni, Larus philadelphia*	NA	NA	*Larus argentatus, Larus marinus, Rissa tridactyia, Larus atricilla, Larus hyperboreus, Larus delawarensis*
90s	*Onychoprion fuscatus*	*Onychoprion anaethetus, Onychoprion fuscatus, Larus argentatus, Rissa tridactyla, Larus philadelphia*	NA	*Larus heermanii, Larus livens*	*Onychoprion fuscatus, Larus atricilla, Larus argentatus, Onychoprion anaethetus, Sternula antillarum*	*Onychoprion fuscatus, Onychoprion anaethetus, Larus atricilla*	*Larus marinus, Larus argentatus, Rissa tridactyla, Larus fuscus*	NA	NA	NA	*Larus occidentalis, Larus californicus, Larus heermanni, Larus argentatus, Larus glaucescens*	*Larus atricilla, Onychoprion fuscatus, Larus argentatus, Onychoprion anaethetus, Larus delawarensis*	*Larus glaucescens, Larus occidentalis, Larus californicus, Larus argentatus, Larus heermanni*	NA	*Larus glaucescens, Larus canus, Larus philadelphia, Larus heermanni, Hydroprogne caspia*	NA	*Larus occidentalis, Larus heermanni*	*Larus atricilla, Onychoprion fuscatus, Onychoprion anaethetus, Sternula antillarum*	NA	*Onychoprion anaethetus, Onychoprion fuscatus, Rissa tridactyia, Larus argentatus, Larus marinus*
00s	*Onychoprion fuscatus, Onychoprion anaethetus, Larus atricilla*	*Onychoprion fuscatus, Onychoprion anaethetus, Larus atricilla, Sternula albifrons, Xema sabini*	NA	*Larus heermanii*	*Onychoprion fuscatus, Onychoprion anaethetus, Sternula antillarum, Hydroprogne caspia*	*Onychoprion fuscatus*	*Larus marinus, Larus argentatus, Larus atricilla, Rissa tridactyla, Larus philadelphia*	NA	NA	NA	NA	*Larus atricilla, Onychoprion fuscatus, Onychoprion anaethetus, Hydroprogne caspia*	*Larus glaucescens, Larus canus, Larus argentatus, Larus heermanni, Rissa tridactyla*	*Larus atricilla*	*Larus glaucescens, Larus canus, Larus philadelphia, Larus argentatus, Larus delawarensis*	*Larus dominicanus*	NA	*Onychoprion fuscatus, Larus atricilla, Onychoprion anaethetus*	NA	*Larus argentatus, Larus atricilla, Larus marinus, Larus philadelphia, Rissa tridactyla*
10s	NA	*Larus philadelphia, Larus argentatus, Larus atricilla, Larus marinus, Larus fuscus*	NA	NA	*Onychoprion fuscatus, Onychoprion anaethetus, Sternula antillarum*	NA	*Larus argentatus, Larus marinus, Rissa tridactyla, Larus atricilla, Larus philadelphia*	NA	NA	NA	NA	NA	*Larus argentatus, Larus argentatus, Larus heermanni, Xema sabini*	NA	*Larus argentatus*	NA	NA	NA	*Larus atricilla, Onychoprion fuscatus*	*Larus argentatus, Larus philadelphia, Larus marinus, Rissa tridactyla, Larus atricilla*

Supplementary Table S3. Shorebird families Scolopacidae and Charadriidae and the marine ecoreg which they were documented.

Marine Ecoregions	Shorebird Presence (Concerning Families Charadriidae, Scolopacidae)
Carolinian	Charadriidae, Scolopacidae
Cortezian	Charadriidae
Gulf of Maine/Bay of Fundy	Charadriidae, Scolopacidae
Northern California	Scolopacidae
Oregon, Washington, Vancouver Coast and Shelf	Charadriidae, Scolopacidae
Panama Bight	Charadriidae, Scolopacidae
Puget Trough Georgia Basin	Charadriidae, Scolopacidae
Southeastern Brazil	Charadriidae
Southwestern Caribbean	Scolopacidae
Virginian	Charadriidae, Scolopacidae

Appendix B: *Diversity* Open Access Policy

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Appendix C: Supplementary Tables and Figures for Chapter 3

Table C1. Average number of occurrence records per season for black-footed albatross, sooty shearwater, and common loon species.

Species	Season	Average No. Records per Season
Black-footed albatross	Winter	8
	Spring	123
	Summer	370
	Autumn	19
Sooty shearwater (east coast)	Winter	2
	Spring	345
	Summer	370
	Autumn	35
Sooty shearwater (west coast)	Winter	6
	Spring	713
	Summer	1422
	Autumn	336
Common Loon	Winter	3227
	Spring	1137
	Summer	73
	Autumn	434

Table C2. Number of occurrence records per year, averaged per decade for black-footed albatross, sooty shearwater, and common loon species.

Species	Decade	Average No. Records per Year
Black-footed albatross	1980s	303
	1990s	36
	2000s	109
	2010s	11
Sooty shearwater (east coast)	1980s	223
	1990s	62
	2000s	379
	2010s	88
Sooty shearwater (west coast)	1980s	1902
	1990s	568
	2000s	5
	2010s	3
Common Loon	1980s	215
	1990s	700
	2000s	1498
	2010s	2458

Table C3. RDA values of the environmental predictor variables for the common loon.

	Spring		Summer		Autumn		Winter	
Predictors	**RDA1**	**RDA2**	**RDA1**	**RDA2**	**RDA1**	**RDA2**	**RDA1**	**RDA2**
Salinity	0.93	-0.17	0.73	0.04	0.82	0.32	0.84	-0.42
Mixed Layer Depth	0.03	0.01	0.61	0.48	0.58	0.45	0.60	-0.48
Sea-Surface Height	-0.63	0.50	-0.46	-0.80	0.28	-0.82	0.06	0.74
Sea-Surface Temperature	-0.28	0.55	0.47	-0.77	0.93	-0.22	0.91	0.19
Eastward Current Velocity	0.18	0.34	0.24	-0.24	0.66	0.20	0.66	0.42
Northward Current Velocity	-0.53	-0.19	-0.38	-0.10	-0.60	-0.46	-0.69	0.12

Table C4. RDA values of the environmental predictor variables for the sooty shearwaters on the east coast. Values with NaN were excluded from RDA using Akaike Criterion.

	Spring		Summer		Autumn		Winter	
Predictors	**RDA1**	**RDA2**	**RDA1**	**RDA2**	**RDA1**	**RDA2**	**RDA1**	**RDA2**
Salinity	0.65	-0.55	0.72	0.15	-0.89	-0.21	-0.24	-0.57
Mixed Layer Depth	0.95	-0.19	0.79	-0.51	-0.93	-0.20	0.05	-0.82
Sea-Surface Height	-0.74	0.58	-0.09	0.40	0.82	0.37	0.89	-0.17
Sea-Surface Temperature	-0.19	0.68	0.87	0.37	-0.66	0.65	0.99	0.04
Eastward Current Velocity	0.52	0.30	-0.10	0.05	-0.43	-0.26	NaN	NaN
Northward Current Velocity	-0.32	-0.68	0.25	-0.25	0.38	0.45	NaN	NaN

Table C5. RDA values of the environmental predictor variables for the sooty shearwaters on the west coast. Values for the winter were insufficient for RDA analysis.

	Spring		Summer		Autumn	
Predictors	**RDA1**	**RDA2**	**RDA1**	**RDA2**	**RDA1**	**RDA2**
Salinity	0.95	-0.27	-0.98	0.14	-0.99	0.02
Mixed Layer Depth	0.87	0.16	0.39	0.15	-0.85	0.39
Sea-Surface Height	0.33	0.56	-0.88	-0.33	-0.98	-0.07
Sea-Surface Temperature	0.92	0.36	-0.97	-0.22	-0.99	-0.04
Eastward Current Velocity	0.56	-0.20	-0.46	0.42	-0.84	0.10
Northward Current Velocity	-0.85	0.04	0.73	-0.20	0.60	0.41

Table C6. RDA values of the environmental predictor variables for black-footed albatross on the west coast. The values for the winter were insufficient for RDA analysis, and values with NaN were excluded from RDA using Akaike Criterion.

	Spring		Summer		Autumn	
Predictors	**RDA1**	**RDA2**	**RDA1**	**RDA2**	**RDA1**	**RDA2**
Salinity	0.97	0.19	0.94	0.10	0.91	-0.30
Mixed Layer Depth	0.77	-0.49	-0.07	-0.10	NaN	NaN
Sea-Surface Height	0.44	-0.57	0.74	-0.48	0.95	-0.30
Sea-Surface Temperature	0.90	-0.36	0.85	-0.25	0.96	-0.23
Eastward Current Velocity	0.79	0.52	0.35	0.18	0.76	-0.06
Northward Current Velocity	-0.46	-0.42	-0.70	-0.39	-0.03	0.45

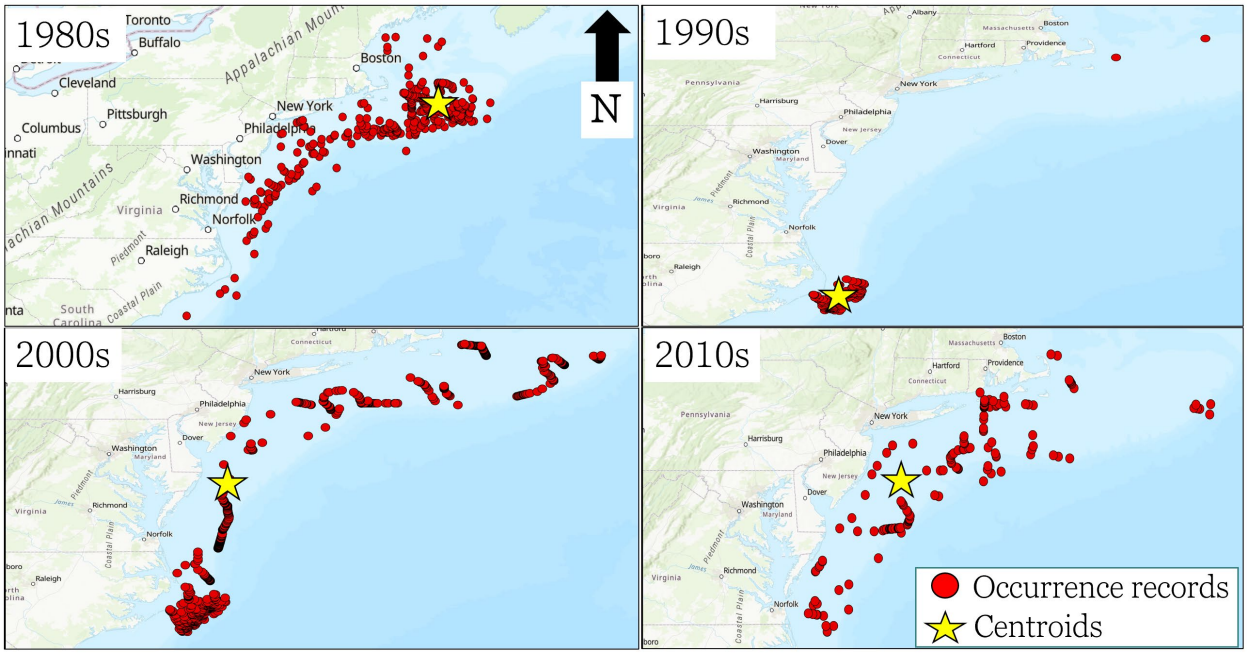


Figure C1. Decadal occurrence records (presence-only observations) for sooty shearwaters on the east coast of the United States. Mean centroids are based on the spread and density of records. The 1990s centroid is located off the coast of North Carolina, due to a prevalence of records obtained in this area at this time. The occurrence records off Cape Cod suggest that there is a wide distribution of this species during this time period, but the centroid is skewed to Cape Hatteras and this would also bias the overall linear directional mean of the presumed population distribution over the four decades examined.

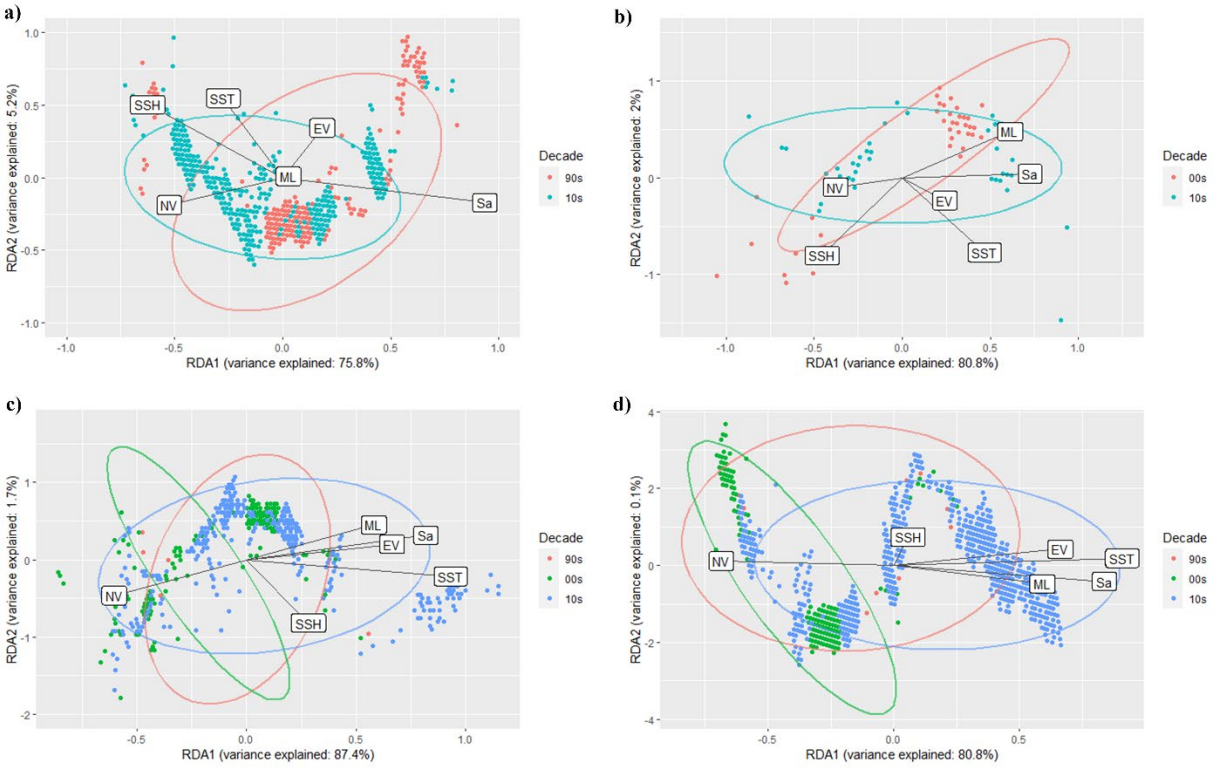


Figure C2. Redundancy analysis occurrence data for common loons on the east coast of the USA (a: spring, b: summer, c: autumn, d: winter). Decades are represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively, and each season is represented by a different-shaped marker. Ellipses are color coordinated with their respective decades and signify that there is 90% confidence that the weighted centroids observed in Figure 3.2 were located within the centers of the ellipses. Latitudinal changes in occurrence records can be seen along x-axis and longitudinal changes along the y-axis. NV = northward current velocity, SST = sea-surface temperature, SSH = sea-surface height, ML = mixed-layer depth, EV = eastward current velocity, Sa = salinity

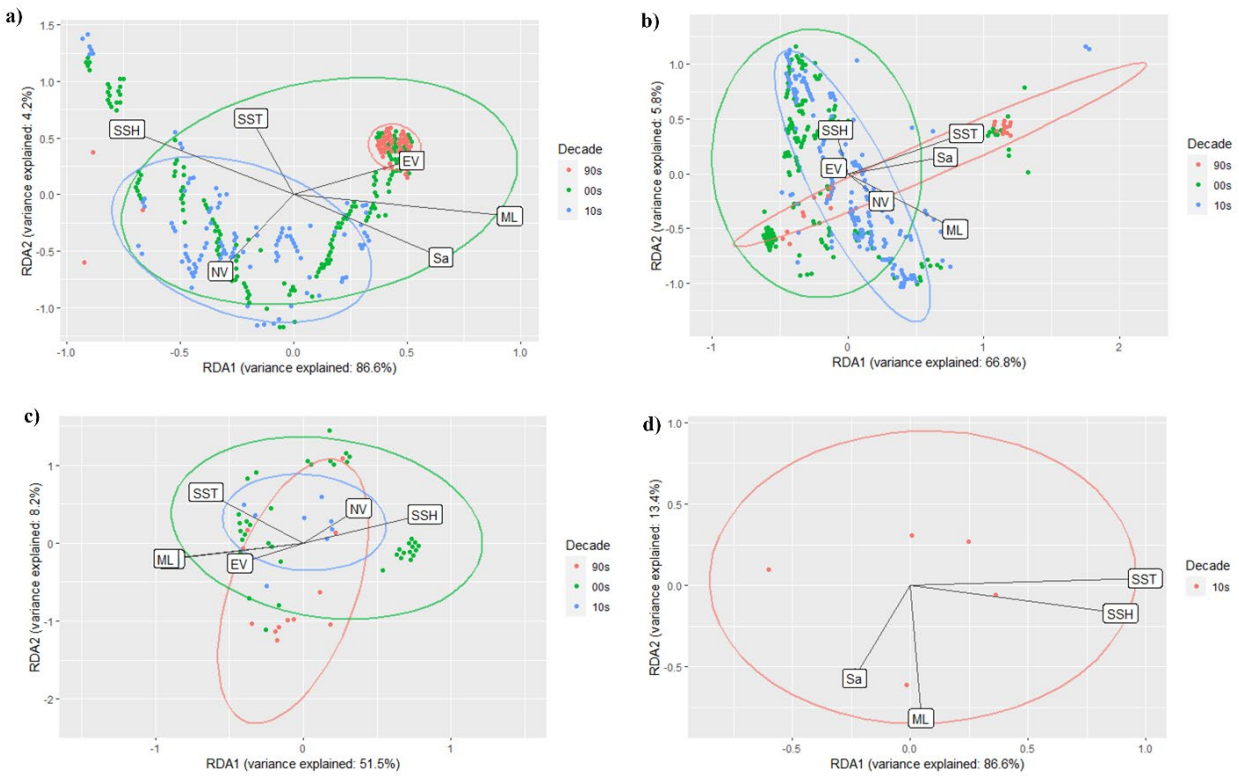


Figure C3. Redundancy analysis occurrence data for sooty shearwaters on the east coast of the USA (a: spring, b: summer, c: autumn, d: winter). Decades are represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively, and each season is represented by a different-shaped marker. Ellipses are color coordinated with their respective decades and signify that there is 90% confidence that the weighted centroids observed in Figure 3.2 were located within the centers of the ellipses. Latitudinal changes in occurrence records can be seen along x-axis and longitudinal changes along the y-axis. NV = northward current velocity, SST = sea-surface temperature, SSH = sea-surface height, ML = mixed-layer depth, EV = eastward current velocity, Sa = salinity

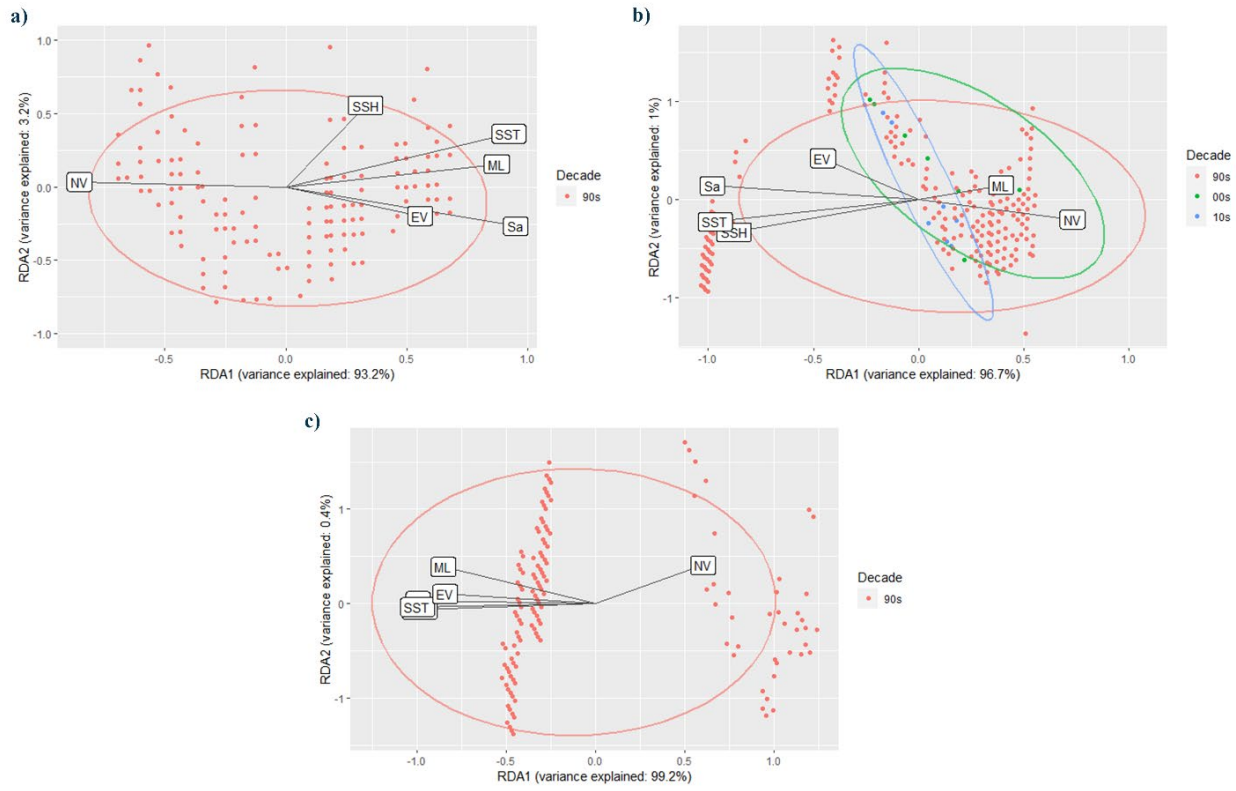


Figure C4. Redundancy analysis of occurrence data for sooty shearwaters along the west coast of the USA (a: spring, b: summer, c: autumn). Decades are represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively, and each season is represented by a different-shaped marker. Ellipses are color coordinated with their respective decades and signify that there is 90% confidence that the weighted centroids observed in Figure 3.3 were located within the centers of the ellipses. Latitudinal changes in occurrence records can be seen along x-axis and longitudinal changes along the y-axis. NV = northward current velocity, SST = sea-surface temperature, SSH = sea-surface height, ML = mixed-layer depth, EV = eastward current velocity, Sa = salinity

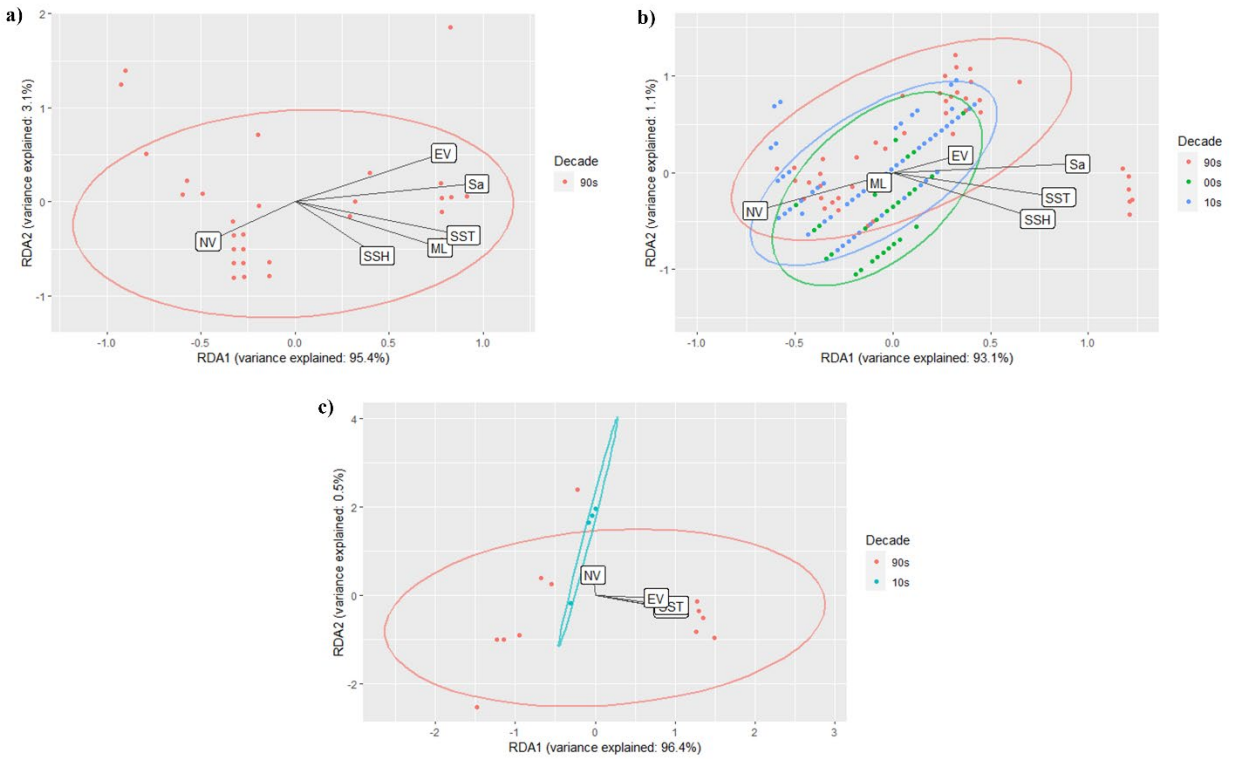


Figure C5. Redundancy analysis of occurrence data for black-footed albatrosses on the west coast of the USA (a: spring, b: summer, c: autumn). Decades are represented by red, green, and blue markers for the 1990s, 2000s, and the 2010s, respectively, and each season is represented by a different-shaped marker. Ellipses are color coordinated with their respective decades and signify that there is 90% confidence that the weighted centroids observed in Figure 3.4 were located within the centers of the ellipses. Latitudinal changes in occurrence records can be seen along x-axis and longitudinal changes along the y-axis. NV = northward current velocity, SST = sea-surface temperature, SSH = sea-surface height, ML = mixed-layer depth, EV = eastward current velocity, Sa = salinity

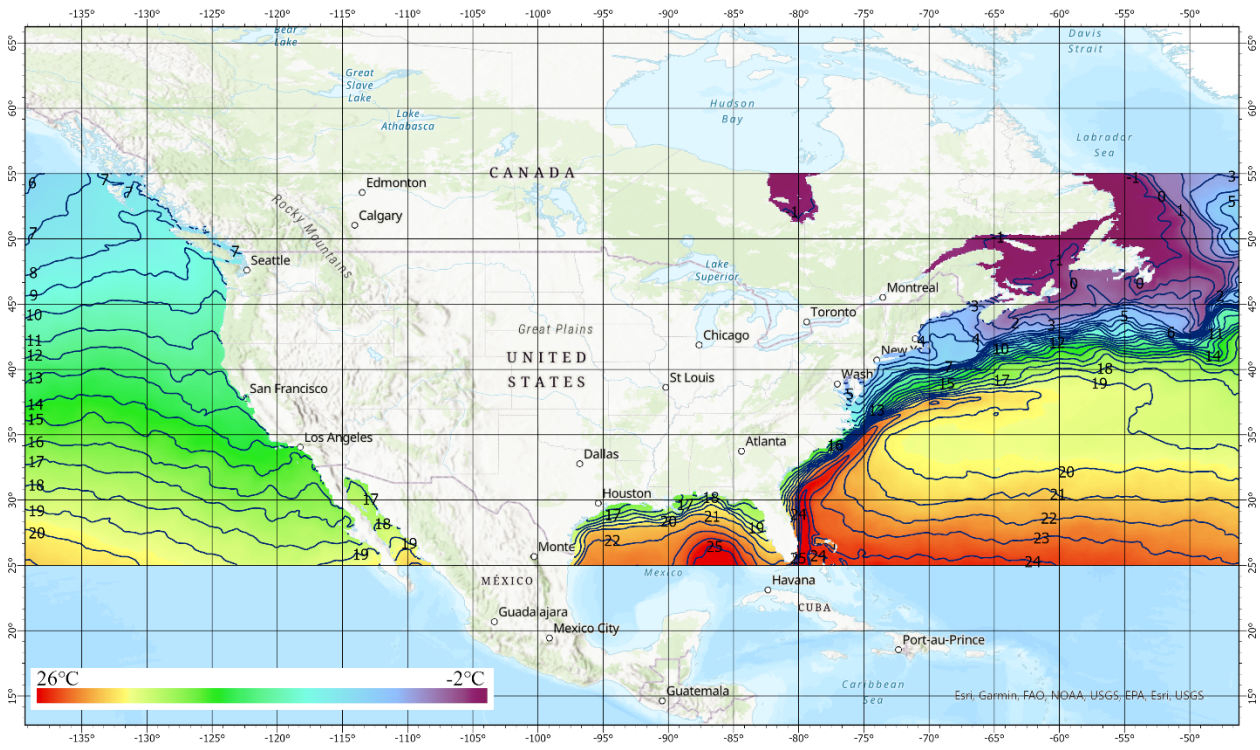


Figure C6. Average decadal winter sea-surface temperatures off the coasts of the United States during the 1990s. Contour lines indicate variation of 1°C.

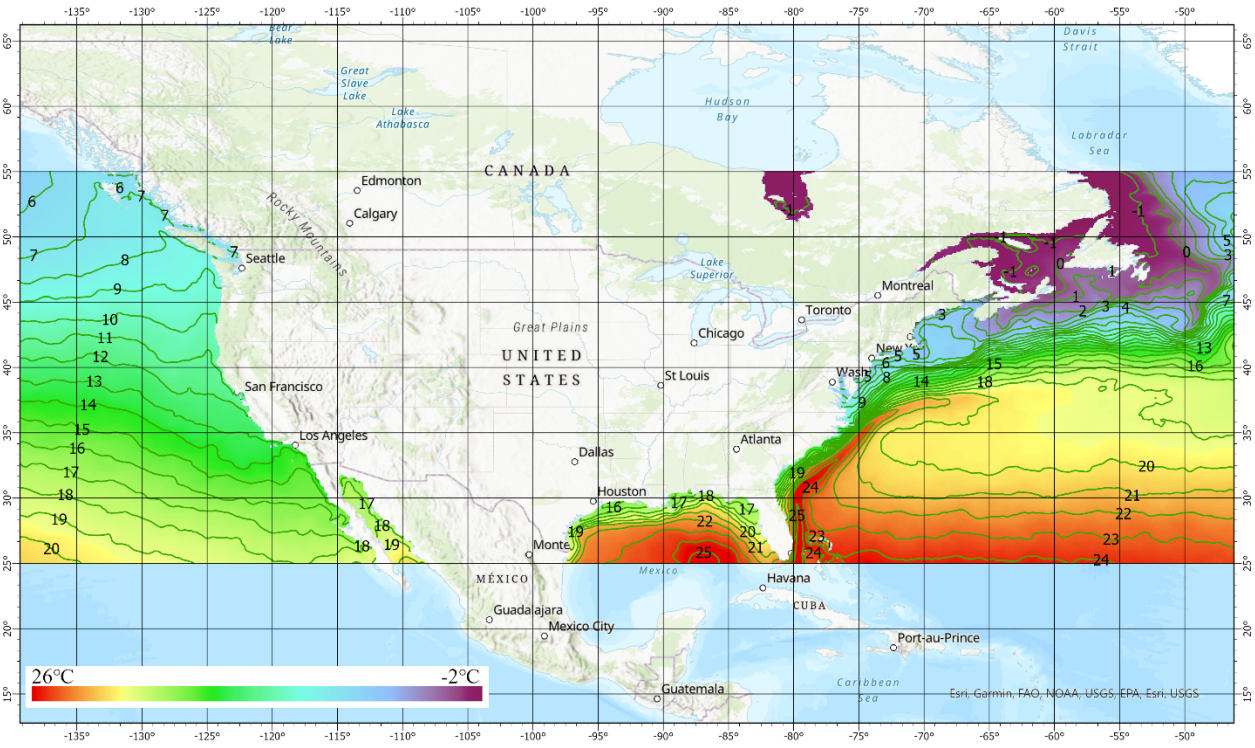


Figure C7. Average decadal winter sea-surface temperatures off the coasts of the United States during the 2000s. Contour lines indicate variation of 1°C.

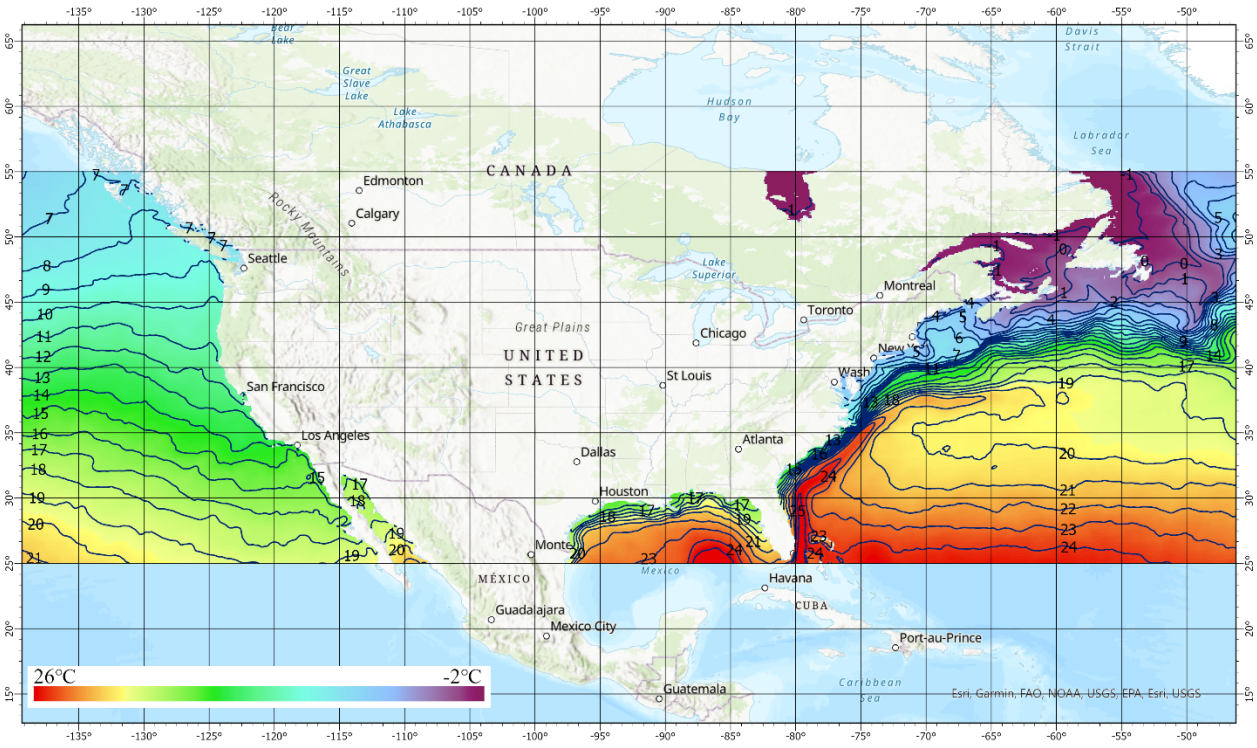


Figure C8. Average decadal winter sea-surface temperatures off the coasts of the United States during the 2010s. Contour lines indicate variation of 1°C.

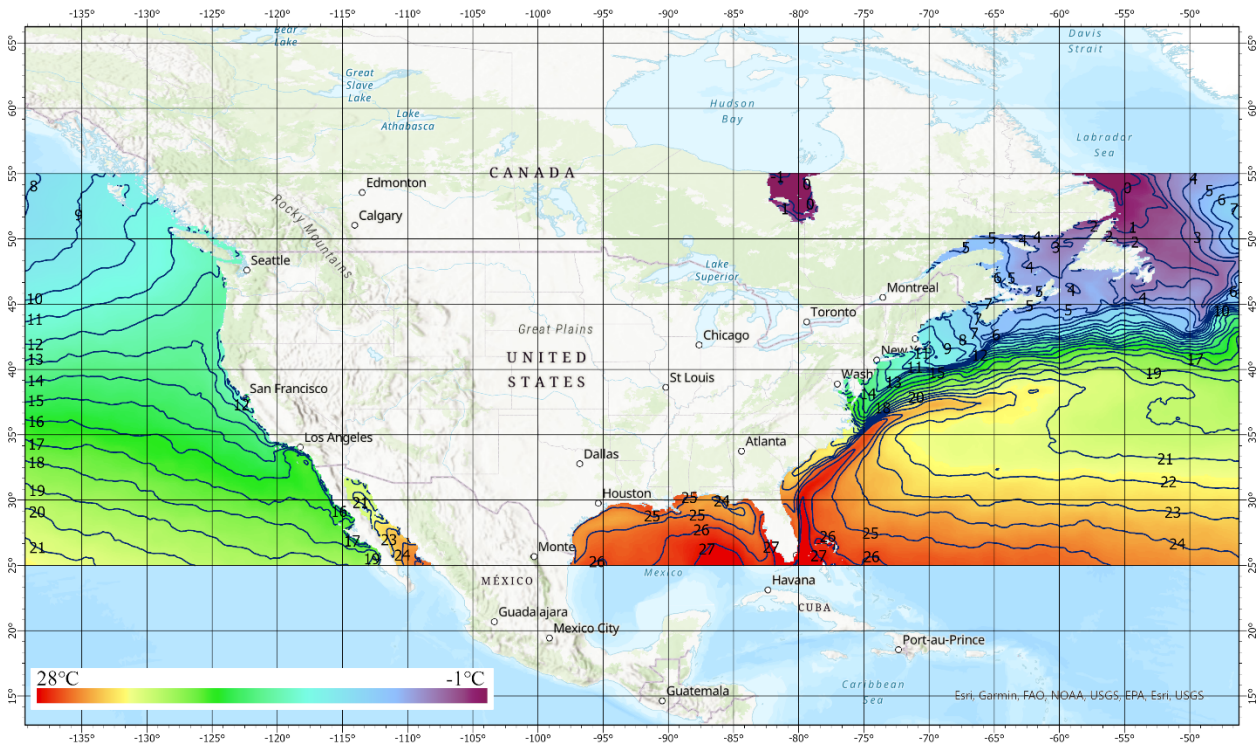


Figure C9. Average spring, decadal sea-surface temperatures off the coasts of the United States during the 1990s. Contour lines indicate variation of 1°C.

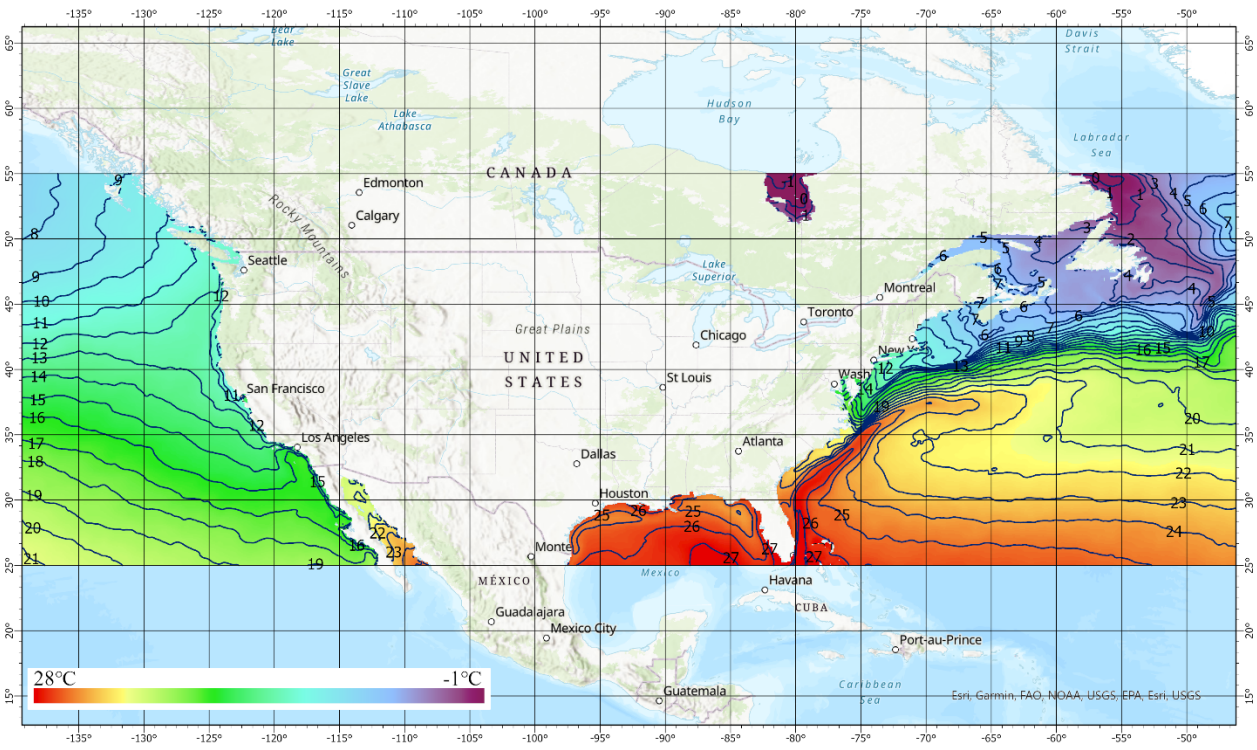


Figure C10. Average spring, decadal sea-surface temperatures off the coasts of the United States during the 2000s. Contour lines indicate variation of 1°C.

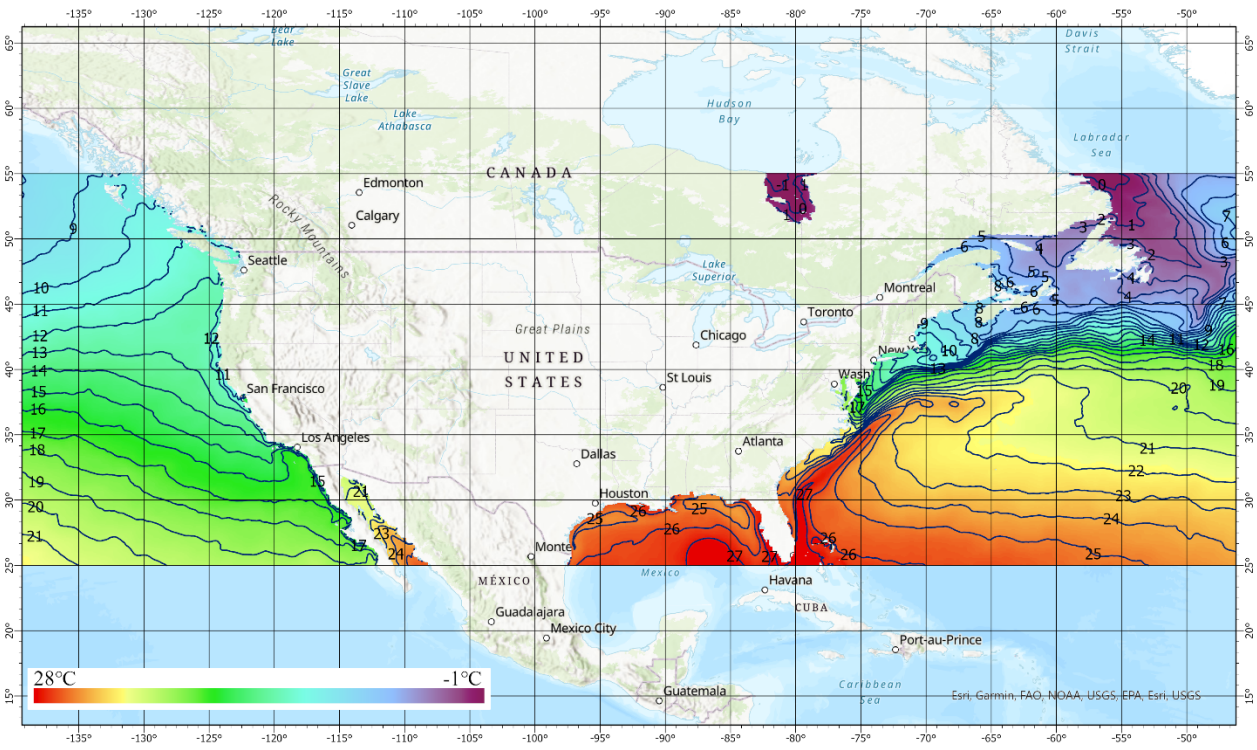


Figure C11. Average spring, decadal sea-surface temperatures off the coasts of the United States during the 2010s. Contour lines indicate variation of 1°C.

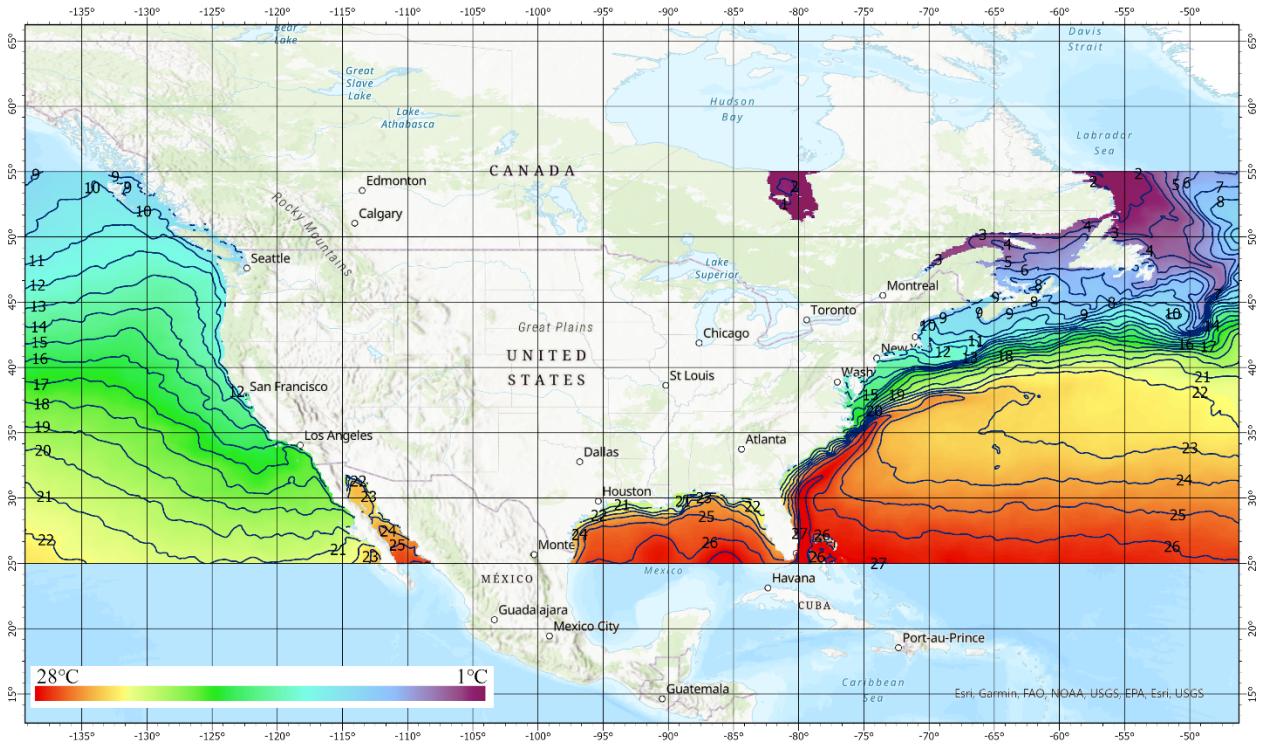


Figure C12. Average autumn, decadal sea-surface temperatures off the coasts of the United States during the 1990s. Contour lines indicate variation of 1°C.

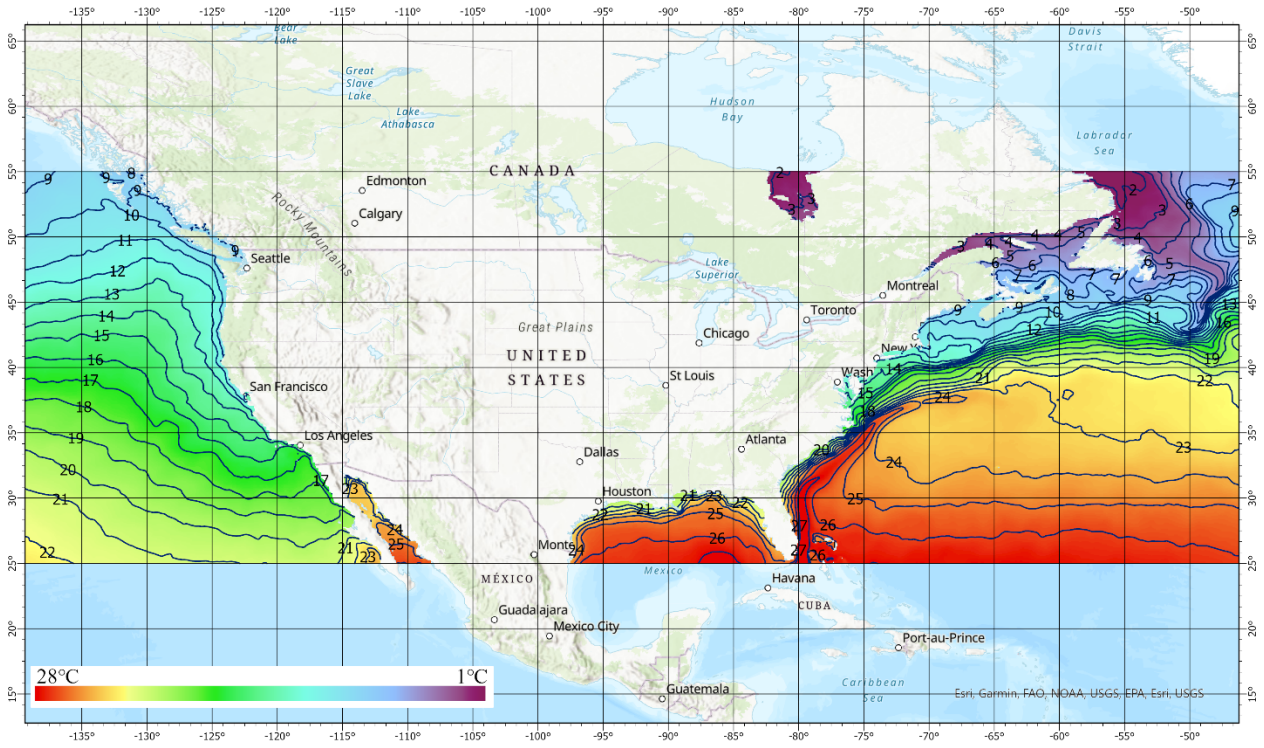


Figure C13. Average autumn, decadal sea-surface temperatures off the coasts of the United States during the 2000s. Contour lines indicate variation of 1°C.

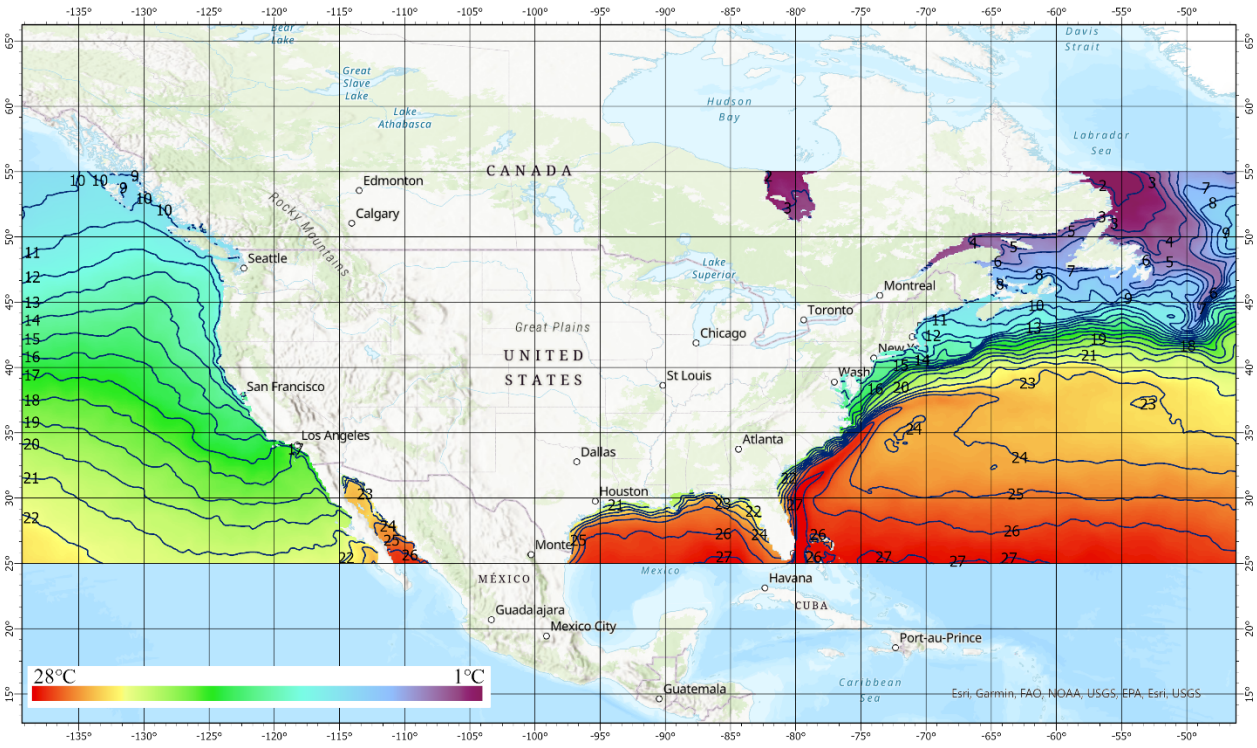


Figure C14. Average autumn, decadal sea-surface temperatures off the coasts of the United States during the 2010s. Contour lines indicate variation of 1°C

Appendix D: Useful Tools for Environmental Education: Spreading Knowledge in Innovative and Engaging Ways

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CHAPTER 9

Useful tools for Environmental Education: Spreading knowledge in innovative and engaging ways

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Abstract

Research outcomes are still often kept within academic circles for a long time, even though they may play a useful role for different purposes and foster relevant positive changes in society. To help solve this issue, we explore fun and innovative ways to spread scientific knowledge to the general public. This chapter showcases four ways to engage society in useful applications of scientific knowledge for the management of ocean and coastal ecosystems and species, with a focus on conservation and people's wellbeing. Our cases are from coastal areas in Brazil and Argentina and include technological applications and websites, as well as community engagement activities and events.

Introduction

With the increasing demand for science-public interactions and the growing role of science in helping to manage real-world problems (*e.g.*, under a transdisciplinary approach), there is a raising need for integrating civil society into science and discussing research findings with a broader audience, particularly with the general public (POHL 2010; BROWNELL *et al.*, 2013). Building skills in science includes delivering disciplinary courses, developing research methods, and building analytical skills, as well as communication skills within the scientific community. However, a key gap for science to effectively reach the public is insuf-

ficient training in communication with a non-scientific audience (NISBET; SCHEUFELE, 2009; KEMP; NURIUS, 2015).

This scenario can create mistrust and misunderstanding between scientists and the lay public due to a lack of scientific literacy. In the case of climate change, for instance, the lack of understanding of scientific findings has directly influenced decision-making in the wrong direction in terms of regulation, policies, and funding (NISBET; SCHEUFELE, 2009). Moving forward, many other scientific discoveries, with the appropriate dissemination, may have the potential to well inform environmental management and, ultimately, our everyday decisions (e.g., eating habits, transportation choices). The consequence of science-public miscommunication, which leads to a lack of socio-economic and ecological progress, reinforces the mistrust in scientists by the lay audience and misunderstanding of the scientific relevance in fostering positive changes in society.

Even though many scientists have shown a great ability to proliferate science to the world through literature (e.g., Stephen Hawking and Carl Sagan), most researchers still do not have a formal opportunity to develop and practice their communication skills (KEMP; NURIUS, 2015). Brownell *et al.* (2013) addressed this problem, providing several examples of infusing communication training into the academic curriculum. They guided graduate and undergraduate students to translate academic work into newspaper articles for the lay public with

the final aim of increasing awareness of non-scientific audiences about neuroimmunology. Communication strategies to disseminate scientific knowledge are especially relevant in the case of environmental sciences and education to help us understand our impact on the planet.

Environmental education is a process with the purpose of promoting knowledge about the functioning of the environment, key environmental changes, as well as our impact on and our dependence upon nature. The process of environmental education involves building awareness, guiding behavior, sharing knowledge, and the ability to understand the links between people and the environment (DIAS, 2004). The use of ludic (*i.e.*, playful, creative, engaging) activities in the education process allows the teaching of science through fun activities that stimulate the interest, attention, and curiosity of participants of different ages (MALUF, 2015). In this context, the goal of this chapter is to discuss different ways of promoting environmental education in informal spaces, using ludic activities as allies in the process of transforming people's perception regarding their impact on and dependence upon nature.

Currently, a substantial number of interactive and user-friendly ways to teach and learn basic science exist. Interactive platforms demonstrated to be useful in raising awareness of environmental threats and encouraging behavioral action, especially when tailored to target groups (NELSON *et al.*, 2020). Some of the tools being used are games, nature

guides, documentaries, and interactive mobile applications (ILLINGWORTH, 2017). In addition, music is a popular method used in elementary and middle schools to teach basic science. Using songs, such as "Meet the elements" by the American rock band "They May Be Giants" -- which comes with an infographic-style music video, or even giving children the opportunity to create their songs on certain scientific topics can foster learning and understanding in a fun and easy way. Another example of science being taught through music can be found at sciencewithtom.com, where a biologist with a master's degree in science communication develops projects and helps create science-themed music and videos covering various scientific topics.

Here we explore examples based on four case studies of creative tools and methods applied as potential means to disseminate science to the public. We first document the four initiatives and analyze their key features in various settings. Secondly, we evaluate the engagement of the general public within these initiatives.

Case studies

Overview of case studies

We analyzed four Latin American cases of environmental education tools targeting a varied audience (i.e., the fishing sector, coastal communities, students and/or the general public).

All cases had the ultimate goal of promoting environmental education on fisheries, social-ecological changes, and ocean ecosystem processes. Tools used include technology (*e.g.*, mobile application and interactive website), participatory activities (*e.g.*, World Café workshop, events), and visual arts (*e.g.*, graphic facilitation). Table 1 summarizes the key characteristics of the analyzed case studies. We selected these cases because they illustrate innovative methods that engage a lay audience in the research process and findings dissemination. We made use of published information about the cases, as well as the in-depth case-specific knowledge of the authors who contributed to these initiatives.

Table 1. Case studies using environmental education tools.

Case study	Location	Audience	Goal	Methods	Outcomes
Case 1 - Mobile app for reducing by catch in shrimp fishing	Brazil (São Paulo state)	Fishermen, environmental and fishery agencies, NGOs, general public	Educate about by-catch species in shrimp fishing	Mobile app	Scientific and general public engagement
Case 2 - World Café and graphic facilitation for environmental change awareness	Brazil (São Paulo state)	Coastal communities	Understanding how social--ecological changes affect community wellbeing	World café and graphic facilitation	Key changes identified; Children's engagement at schools

Case study	Location	Audience	Goal	Methods	Outcomes
Case 3 - TallEx (Experiments of Geophysical Fluids)	Argentina	Students, graduates and teachers	Explaining how natural systems work in the ocean	Website containing extracur-ricula r activities	General public and student engagement
Case 4 - Ludic activities in the environmental education processes	Brazil (Espírito Santo state)	Traditional commu-nities and tourists	Aware-ness of endangered species and ocean issues	Activities in events and schools	Traditional community engagement on envi-ronmental issues

Case study 1: Mobile app for reducing bycatch in shrimp fishing[5]

Shrimp fishing is an important economic activity world-wide generating impressive income in our society. Marine and coastal shrimp are usually caught by shrimp trawler nets, but this invasive method captures large amounts of non-targeted and economically non-relevant species, which are discarded back into the sea. Non-targeted species are known as bycatch, which is composed of fish, crustaceans, mollusks, and starfish, among other benthic and demersal organisms. It is estimated that shrimp trawling bycatch ranges from 5 to 20 kg per kg of caught shrimp, resulting in a significant loss of biodiversity and ecological functioning (DAVIES *et al.*, 2009). However, in addi-

5 This app is available for open access at Play Store (Portuguese version): https://play.google.com/store/apps/details?id=br.com.zeropoint.facom&hl=pt.

tion to their ecological importance, these species have relevant biological activities and chemical compounds, which can be explored by pharmaceutical companies and the food industry (*e.g.*, *Paralonchurus brasiliensis* and *Micropogonias furnieri*, CAMARGO *et al.*, 2021).

To deal with the issue of bycatch, an interactive and innovative mobile app 'Fauna Acompanhante - Pesca de Arrasto' ('Bycatch fauna – Trawling') (Figure 1) was created to help fishermen, environmental and fishery agencies, NGOs, and the general public to understand this hidden biodiversity. This pioneering project in Brazil was created by a group of scientists, graduate and undergraduate students from the São Paulo State University (UNESP), supported by national research foundations. Based on published studies and several samplings conducted by the researchers involved, specimens of the most common bycatch species found in the state of São Paulo State were identified, listed and separated by groups. High-quality images of species were taken and uploaded in the app, when possible, to facilitate species identification by users. Moreover, their common and scientific names and relevant information about their biology, distribution, commercial interest, and status of conservation according to The International Union for Conservation of Nature (IUCN) were also uploaded to the app. The app highlights, for instance, that endangered species of elasmobranchs (e.g., sharks, rays) are usually captured, and that there are still gaps in information for some groups, mainly invertebrates. As a first-generation, modern

tool it may gain attention and gain popularity with the general public. Several people from different areas informally described the app as a useful tool for the identification and information of the species. The app is an example of how to foster local actions to deal with global issues (*e.g.*, bycatch in fisheries) and seems to be a great step to gain knowledge about the environment, as well as foster thoughtful discussions on the impacts of human activities in the ecosystem and how to mitigate them.

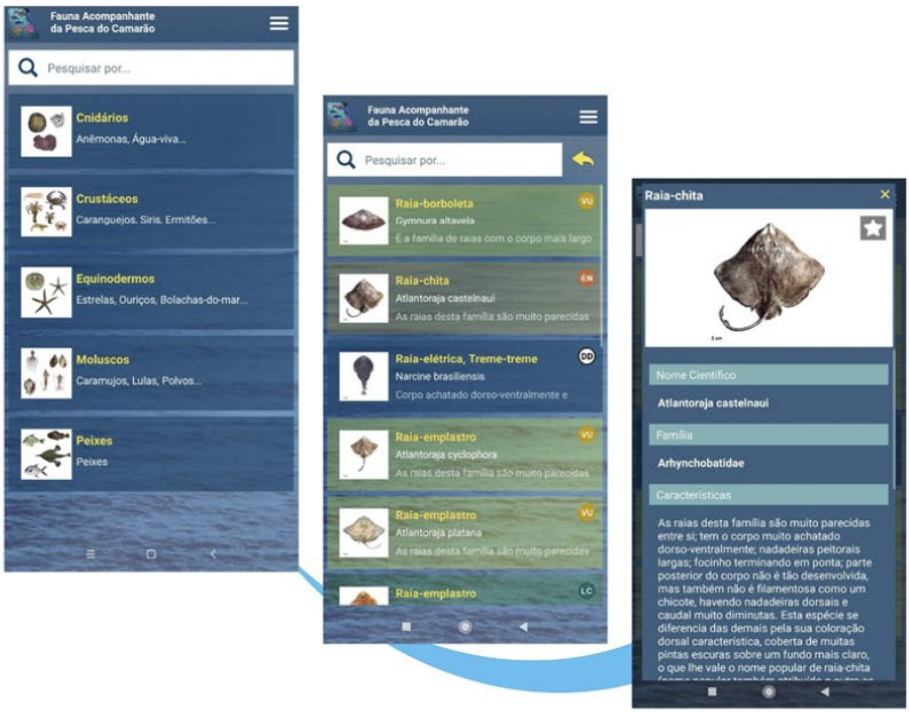


Figure 1: Layout of the Mobile app 'Fauna Acompanhante – Pesca de Arrasto' ('By-catch fauna – Trawling').

Case study 2: World Café and graphic facilitation for environmental change awareness

Researchers from the University of Waterloo (Canada) conducted participatory workshops, including graphic facilitation in three communities on the Southeast coast of Brazil (Almada Beach, Puruba Beach, and Picinguaba Village). The objectives of these workshops were (i) to understand how environmental changes interfere with coastal community well-being, (ii) to generate systematized data based on local knowledge with scientific rigor to inform coastal management, and (iii) to engage traditional coastal communities facing accelerated cultural and environmental changes in coastal management. The workshops were guided by the world café (BROWN; ISAACS, 2005) method and the discussions were visually represented through graphic facilitation. Participants were divided into four groups randomly (Figure 2). A large sheet and colored pens were made available to each group. All participants were invited to freely express themselves through records (*e.g.*, including drawings, scribbles, words) on the sheet arranged at each table. A host in each group was responsible for systematically recording the discussion. In all groups, three questions were discussed simultaneously at each table, and a summary was shared with all participants. As a result, participants agreed on the main changes affecting the community with social and environmental impacts. The main changes included mass tourism

(causing water pollution, disturbance to marine life, and disturbance in the community - e.g., drugs, irregular parking, diseases) and changes to the river flow, causing fear of floods on the one hand, and opportunities for environmental interpretation on the other (DIAS, 2020; DIAS *et al.*, in press). Participants suggested sending the final summarized graphics to the local school and sending a report to decision-makers with a summary of the discussions. The schools used the content to discuss with students the role they can play in coastal conservation and cultural reproduction. For more details, see Dias (2020).



Figure 2. Photograph of the workshop conducted at Puruba Beach community showing participants at different tables and the graphic facilitator in action on the left. Photographed by: Ana Carolina Esteves Dias.

Case study 3: TallEx (Experiments of Geophysical Fluids)

Changes in the ocean and atmosphere are discussed frequently in the scientific community, but scientists cannot discuss these changes with the general public without first explaining how these systems work. TallEx[6] is an academic extracurricular group of students, graduates and teachers of atmospheric and oceanographic sciences at the University of Buenos Aires (Argentina) that assembled easy-to-do laboratory experiments, which explain how geophysical fluids behave in nature (Simionato *et al.*, 2009). The selected experiments aim to describe oceanic and atmospheric fluid movements due to two effects: stratification and rotation, as follows:

- Deep convection in the Ocean: Pure water was placed in a small fish tank that represented a portion of the ocean from the Equator to the Pole. In one corner, blue-colored cold water was added to the tank, and in the opposite corner, warm red-colored water was added. Within the tank, cold water sank below the surface and flowed towards the "red" corner while the warm water floated along the surface towards the "blue" corner. This experiment communicated oceanic convection properties concerning water temperature changes.

6 Available at: http://tallex.at.fcen.uba.ar.

• Internal Waves: Pure water was placed in a fish tank. Several glasses of water were prepared which contained different amounts of salt and different colors. The "water masses" from the glasses were added slowly, from the less salty to the saltiest. This allowed the audience to see not only stratification related to different salt contents but also internal waves generated between the water layers, which are not usually visible from the surface.

The materials used for the experiments are inexpensive and readily available, which ensures the possibility of reproducing the experiments even with small budgets. The TallEx website shows all the experiments, how to make them, and the scientific explanation behind them so teachers can easily reproduce them with their students.

Case study 4: Ludic activities in environmental education processes

Environmental education practices are effective tools for promoting ocean literacy (GHILARDI-LOPES *et al.*, 2019) and for raising awareness about protecting and conserving the environment (Potter 2010). Integrating different methods for environmental education, such as ludic activities, is generally more efficient than traditional expositive teaching (HAYES *et al.*, 2013), especially with activities that stimulate different senses

and processes, such as listening, speaking, reading, touching, observing, and interpreting.

This case study was carried out by Projeto Meros do Brasil, sponsored by Petrobras, which has as its flag species, the goliath grouper (*Epinephelus itajara*), a protected marine and estuarine fish species critically endangered in Brazil. They conducted several ludic activities such as Body Painting, Ecological Bowling, Ecosystem, Sensorial Box, and Interactive Carpet during public events held in the cities of Conceição da Barra, São Mateus, and Vitória, in the state of Espírito Santo, Brazil. The events fostered the participation of local traditional fishing communities, students, and city residents who live near estuaries and mangrove areas where the goliath groupers are common, as well as tourists visiting these areas. The Body Painting activity consisted of painting the goliath grouper, among several other elements that represent the marine and estuarine ecosystems, on children's skin. The Ecological Bowling activity consisted of bowling pins made from plastic pet bottles, containing images representing the most diverse components of the environment where goliath groupers live. The Ecosystem activity consisted of double-sided cards that were hung around the neck of the participants. On one side of the card there was a riddle and on the other side an image that represented the answer to the riddle. During the activity, one of the participants would read the riddle to the group, and to-

gether they would try to find the answer. The Sensorial Box was an inclusive activity that allowed participants to feel nature in the palm of their hands. This activity consisted of a box with an opening where the participants would stick one of their hands in and only by touching the components inside the box tried to guess what they were touching. The game aimed to provide the visually impaired the possibility of participating in the game based on equality with other participants since no one can see what they are touching. The Interactive Carpet (Figure 3) was an inclusive activity consisting of two mats produced with felt, one representing the estuarine environment and the other the marine environment. This activity included several elements of the marine and mangrove ecosystems, natural or unnatural, that were not fixed to the mat, allowing the participants to move the elements around the environments and adapt them according to their perspectives. During the activity, the participants discussed the role and importance of each element for nature, what our role is in its protection, and that we, human beings, are part of nature.

During the development of all activities described above, provocative discussions were fostered, raising awareness of the importance of preserving marine and mangrove ecosystems, preventing illegal vegetation cutting, proper waste disposal, reflecting upon our role concerning nature, preventing illegal fishing, protecting endangered species, understanding

the food chain, sustainability, among other reflections. These environmental education ludic activities were considered facilitators of the teaching process since participants expressed great interest in the subject and the activities. These activities also helped to integrate students with special needs, such as learning or communication difficulties, as well as physical needs, during the reflections. These informal environmental education initiatives show how participatory discussions play an important role in the process of increasing public awareness of environmental issues, creating new patterns of behavior and attitudes of the participants toward nature (MOHAMMED *et al.*, 2006).



Figure 3. Environmental activities developed during events in the cities of Conceição da Barra, São Mateus, and Vitória, in the state of Espírito Santo, Brazil. (A) Body painting, (B) Ecological Bowling, (C) Sensorial Box, and (D) Interactive Carpet.

Environmental education as a transformative societal strategy

The four cases described in this chapter provide examples of creative tools and methods applied in environmental education and science communication to a lay audience, including the general public, students, coastal communities, fishermen, and governmental agencies. These methods innovate by providing

scientific knowledge and understanding of some complex processes and interactions to people with no or scarce requirement for previous knowledge. Overall, these cases provide and co-construct information on coastal ecosystems and species, as well as how the environment benefits and is being affected by humans. Thus, these tools have the potential to foster ecosystem stewardship actions among users/participants.

Three main reasons explain the potential of our cases to foster stewardship actions towards coastal environments in fun and engaging ways. Firstly, three of our cases highlight human-nature connections to the benefits nature provides to people (cases 1, 2 and 4) in a ludic way. Ludic activities can bring many benefits, including public engagement and better experiential learning in which participants are an active part. This is especially relevant as the use of games and fun activities attracts the participants, stimulating curiosity and strengthening social interaction casually. This may help to foster a sense of responsibility over the environment users and participants are in and from which they obtain benefits. Case two, for instance, engages participants in an active discussion on what the key environmental changes are within the community and drives participants to draw connections between these changes and how they affect their well-being. Participants showed a great interest in the graphic facilitation outcome, especially by recognizing their local issues with the content represented in the drawing. The drawing that resulted from graphic facilitation was used as a teaching tool by

local schools, where students could reflect upon environmental changes in their communities and their actions towards marine conservation (see DIAS, 2020).

Moreover, ludic activities are efficient for young learners, who have a high level of motivation when engaging in enjoyable new and different experiences (ENEVER, 2015). Case 4 illustrates the increase in engagement in environmental education through ludic activities (e.g., body painting). While participants were playing, their imagination and enthusiasm were heightened by all the questions and provocations that they were exposed to during the activities. Participants asked many questions, debated environmental issues and reflected upon the reality that surrounds them. Moreover, playful situations make children learn the proposed knowledge in a fun and relaxed way (KOLB; KOLB, 2010), that is, they have an additional and unconscious encouragement that favors their ability to speculate, deduce and interpret the information that is presented to them. This is supported by Krashen's affective filter hypothesis which states that students' emotional states and attitudes are considered a modifiable affective filter in learning (KRASHEN, 1982). According to this hypothesis, when a person feels anxious, threatened, or overwhelmed, he or she ends up blocking the absorption of information, which is necessary for the acquisition of knowledge (KRASHEN, 1982). On the other hand, when the student is relaxed, by playing a simple game, for example, the participant learns more effectively by making connections to real-life concerns, such as social, ecolog-

ical, economic, cultural, and political issues (KRASHEN, 1982). Therefore, ludic activities can make the absorption of information easier and encourage the participants to build a critical opinion about complex environmental issues that will foster a new generation of well-informed citizens.

Secondly, these cases demonstrate the impacts people have on coastal ecosystems and species – which is a basis to foster environmental awareness. In fact, there is an established recognition that technology is a powerful tool to increase environmental awareness. Contemporary technological resources have been considered efficient materials in environmental education initiatives (UZUNBOYLU *et al.*, 2009; CHANG *et al.*, 2011; HILL *et al.*, 2011). Mobile devices, for instance, provide a vast number of interactive possibilities (e.g., audio-visual podcasts, mobile applications) to increase awareness of specific environmental topics and to support formal education via mobile learning (M-Learning) (DODGE, 1995; SHARMA, 2014; LUNA *et al.*, 2018). Our study and the literature show that mobile applications dealing with local environment information (e.g., biodiversity, weather) are fruitful tools to increase the community's sensitivity to their surrounding environment (JENKINS, 2003; SHARMA, 2014). *Brincando com os bichos do mar* (Playing with sea animals), for instance, aims to teach children about marine animals in a playful way in Brazil. SharkCount is another citizen science tool for divers that helps to monitor and provides information about marine fauna in Galápagos. Our case study 1, "Fauna Acompan-

hante – Pesca de Arrasto" – the bycatch app, is also an emerging initiative where focal users are personally close to the topic (*i.e.*, in this case, users are fishers who may produce bycatch). Despite the recognized economic and ecological importance of shrimp trawl fisheries, direct and indirect actors involved in the activity still lack a full understanding of bycatch species and comprehension of alternative ways to minimize the impacts of trawling (HAULE, 2001; EAYRS, 2007). The mobile app helped to foster knowledge surrounding bycatch species among stakeholders.

Finally, our cases demonstrate the relevance of tailoring the activities to the target audience. The target audience is important to take into consideration when designing and constructing an activity such as educational activities for school kids (such as in Case 3), activities for local communities (such as in Case 2 and 4), or adult professionals (such as in Case 1) to increase its impact. In the school environment, hands-on experiments to engage students to discover natural cycles were demonstrated in case 3, a laboratory environment tailored to the context of students and schools. For fishers who use cell phones, a mobile app was easy to use and provided relevant information on the bycatch species, including their commercial value – which might be of interest to them.

A preliminary screening of the target audience allows for the design of a more adequate experience for that particular audience and increases the positive outcomes by personalizing the content of the activities to some extent. An example of an inter-

active educational game with a well-thought design can be found in the study by Barab *et al.* (2005), where they state the following as the main social and educational slogans which founded their activity design:

1. Creative Expression – I Express Myself.
2. Diversity Affirmation – Everyone Matters.
3. Personal Agency – I Have a Voice.
4. Social Responsibility – We Can Make a Difference.
5. Environmental Awareness – Think Globally, Act Locally.
6. Healthy Communities – Live, Love, Grow.
7. Compassionate Wisdom – Be Kind.

These messages could be used in various educational activities as founding principles on which to base the overall experience, adding the customized features adapted to a particular target audience.

Thus, through ludic activities, participants reflect more effectively on how their decisions and actions affect marine ecosystems, as well as the importance of keeping our oceans healthy and sustainable for the future. These case studies are examples of existing efforts to educate the lay audience, raise awareness and stimulate positive behavior towards the environment. We highlight that the chosen methods must be tailored to the target audience in order to adequately convey scientific information. For future studies, the development of preliminary screenings of target audiences to develop more personalized experiences and their subsequent debriefing, as well as an evaluation of the out-

come, could be useful additions to increase the effectiveness and improve these educational activities.

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