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Climate-driven range expansion of a critically endangered top predator in northeast Atlantic waters

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Global climate change is driving rapid distribution shifts in marine ecosystems; these are well established for lower trophic levels, but are harder to quantify for migratory top predators. By analysing a 25-year sightings-based dataset, we found evidence for rapid northwards range expansion of the critically endangered Balearic shearwater *Puffinus mauretanicus* in northeast Atlantic waters. A 0.6°C sea surface temperature increase in the mid-1990s is interpreted as an underlying controlling factor, while simultaneous northward shifts of plankton and prey fish species suggests a strong bottom-up control. Our results have important conservation implications and provide new evidence for climate-driven regime shift in Atlantic ecosystems.

Keywords: climate change; trophic cascade; Atlantic Ocean; Balearic shearwater

1. INTRODUCTION

Global climate change is impacting both marine and terrestrial ecosystems (Reid *et al.* 1998; Thomas & Lennon 1999), with many species currently shifting their range polewards (Parmesan & Yohe 2003). In the northeast Atlantic, rising sea temperature is thought to be the major control behind northwards distribution shift at a variety of trophic levels, from phytoplankton (Reid *et al.* 1998; Beaugrand & Reid 2003; Richardson & Schoeman 2004) through to zooplankton (Beaugrand *et al.* 2002; Beaugrand & Reid 2003) and fish (Stebbing *et al.* 2002; Beare *et al.* 2004*a*,*b*; Genner *et al.* 2004; Perry *et al.* 2005). It has also been predicted that top predators at higher trophic levels will inevitably have to adapt to changing spatial distribution of their prey (Richardson & Schoeman 2004; McMahon & Hays 2006). However, long-term datasets quantifying large-scale climate-induced distribution changes in migratory marine top predators are lacking for the Atlantic region.

In this study, we use a 25-year sightings-based dataset to show that the post-breeding distribution of a critically endangered migratory seabird, the Balearic shearwater *Puffinus mauretanicus*, has rapidly expanded northwards in the last decade. We then discuss the controls on this range expansion, including changes in northeast Atlantic sea surface temperature (SST) and prey fish distribution. The Balearic shearwater has been selected for detailed study as (i) it is a declining species threatened with virtual extinction by 2050 (Oro *et al.* 2004; IUCN 2006), so understanding how external factors such as climate change affect adult survival is an urgent conservation requirement, and (ii) it is a well-recorded and mobile migratory seabird with a preference for coastal waters, and is therefore a useful and accessible ecological indicator of climate change. Previous research has shown that post-breeding concentrations of Balearic shearwaters along the French Biscay coast decreased markedly between 1982–1984 and 1990–2000 (Yésou 2003); our aim is to determine whether this decrease represents a change in distribution or simply reflects overall population decline.

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2. MATERIAL AND METHODS

Land-based sightings data for the Balearic shearwater, covering the period 1980–2003 (the last year for which complete data are available), were obtained from nine countries along the northwest European coastline (north of 48° N; figure 1). In a majority of cases, individual records have been peer-reviewed before acceptance by the relevant national or local ornithological records committee. Annual totals were compiled for each country or region; duplicate records were removed where timings suggest a single bird passed multiple watch-points.

Data used in this study are potentially affected by observer bias to varying degrees, as a result of (i) differences in observer effort, identification skills and optical aids, (ii) greater awareness of Balearic shearwaters due to taxonomic changes, and (iii) variable viewing conditions. Such factors are hard to quantify, and bias reduction is therefore difficult. However, as discussed below, spatial and temporal consistency of results is high, indicating that observer bias has not significantly affected the dataset.

3. RESULTS

The most comprehensive sightings data for the period 1980–2003 are available from the UK and Ireland. In this region, relatively small numbers of Balearic shearwaters were recorded between 1980 and 1990, with annual totals of less than 500 birds per year. Numbers then rapidly increased through the mid-1990s and peaked at 3500 birds in 2001 (figure 2*a*). The largest numbers of birds (approx. 70%) are typically seen from southwest England, with smaller numbers penetrating north to Scotland. There is evidence for progressive northwards range expansion, with annual totals in southern England peaking in 2001, and those from Wales and Scotland peaking in 2003 (figure 2*b*). The change in status in UK waters is supported by long-term sightings data from manned bird observatories, for example, Portland Bird Observatory (figure 2*b*), where Balearic shearwaters have been recognized and recorded since the 1950s (Ash & Rooke 1954).

The rapid and sustained increase in numbers observed in UK waters since the mid-1990s has been repeated across northwest Europe (figure 2*b*), with additional evidence for a progressive northwards shift. Annual totals in northern France (Yésou 2003), England and The Netherlands all peaked between 1996 and 2001, whereas annual totals in countries north of 55° N (e.g. Scotland, Denmark, Sweden,

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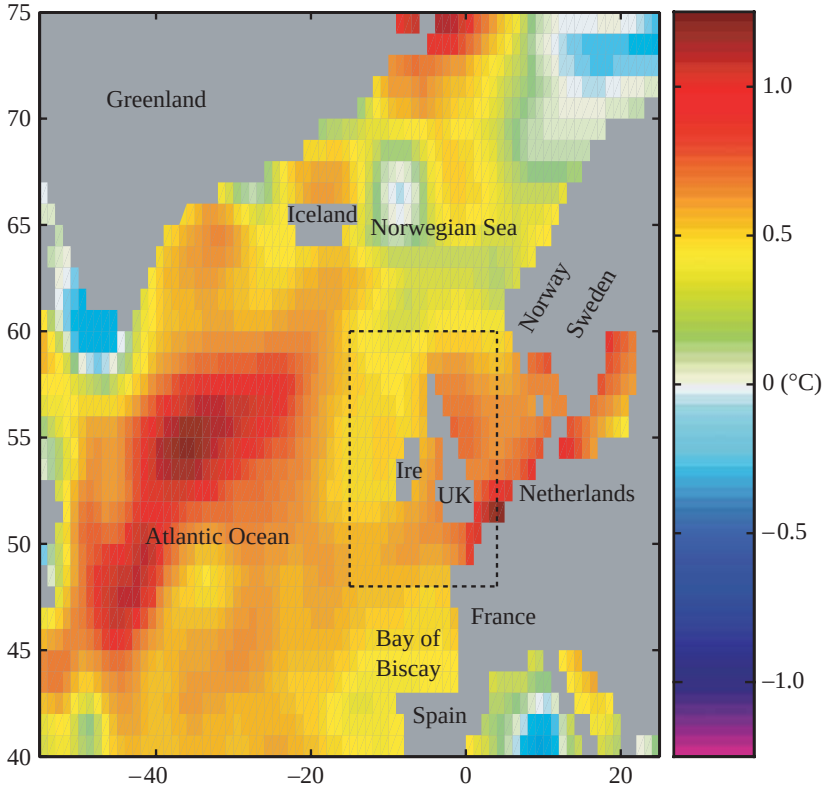

Figure 1. Map of the study area, showing differences in annual mean SST (°C) between the two periods 1995–2005 and 1980–1994. Image resolution limited by climatological grid cell size. Dashed rectangle shows the UK and Ireland region used to calculate SST statistics in this study, where temperatures have risen by approximately 0.6°C since the mid-1990s.

Norway) all peaked in 2003, although the numbers involved in the latter region are relatively small. The temporal (decadal and inter-annual) and spatial (intra- and international) consistency of data from across northwest Europe (figure 2*b*), including those from long-term observatories, provides firm evidence for genuine range expansion and indicates that observer bias has not significantly affected the results.

4. DISCUSSION

Rapid increases in northeast Atlantic SST have been observed in recent decades as part of larger-scale global warming of the ocean surface (Rayner *et al.* 2006). In order to assess potential impacts on Balearic shearwater distribution, we quantified the rise in SST for a region centred on the UK and Ireland (figures 1 and 2*a*) using the ship observation-based NOC1.1 dataset (Josey *et al.* 1999; dataset available at http://www.noc.soton.ac.uk/ooc/CLIMATOLOGY/index.php). Regionally averaged SST has increased throughout the period considered, with an upward shift in the mid-1990s that parallels the rise in Balearic shearwater numbers in UK and Irish waters. The mean SST values for 1980–1994 and 1995–2005 are 11.1 ± 0.1 and 11.7 ± 0.1°C, respectively, i.e. the surface temperature over the latter period was on average approximately 0.6°C warmer than the preceding 15 years (consistent with Rayner *et al.* 2006, their fig. 14*d*). Over the common data period (1980–2003), the correlation coefficient between numbers of Balearic shearwaters and regionally averaged SST is $r = 0.65$; this value is significant at the 95% level (threshold for significance, $r_{Th} = 0.40$, note autocorrelation within the time series may increase this value). Our result thus suggests that Balearic shearwater numbers are linked to SST variability, although it does not establish a direct causal connection.

To gain insights into the mechanisms by which rising SST may be driving the observed change in Balearic shearwater distribution, we must investigate spatial and temporal changes in prey species. The dominant prey of the Balearic shearwater is small pelagic fish, particularly anchovy *Engraulis encrasicholus* and sardine *Sardina pilchardus* (Arcos & Oro 2002; Yésou 2003). Along the French Biscay coast, specifically in areas where Balearic shearwaters used to occur in greatest numbers, these two fish species have decreased dramatically since the mid- to late-1990s (Poulard & Blanchard 2005; ICES 2006); coincident with a local decrease in Balearic shearwater numbers (Yésou 2003) and increased northwards dispersal (figure 2). Further north, fisheries data provide indications for a rapid increase in both anchovy and sardine abundance in UK waters during the mid-1990s (Armstrong *et al.* 1999; Beare *et al.* 2004*b*), while several other fish species with southern biogeographic affinities show an apparent northwards distribution shift in the mid-1990s that is strongly correlated with rising SST (Stebbing *et al.* 2002; Beare *et al.* 2004*a*; Genner *et al.* 2004; Perry *et al.* 2005; Poulard & Blanchard 2005).

There is also increasing evidence for climate-related distribution shifts in the plankton that directly, or indirectly, provide food for prey fish species. Copepod species associated with warm temperate waters have

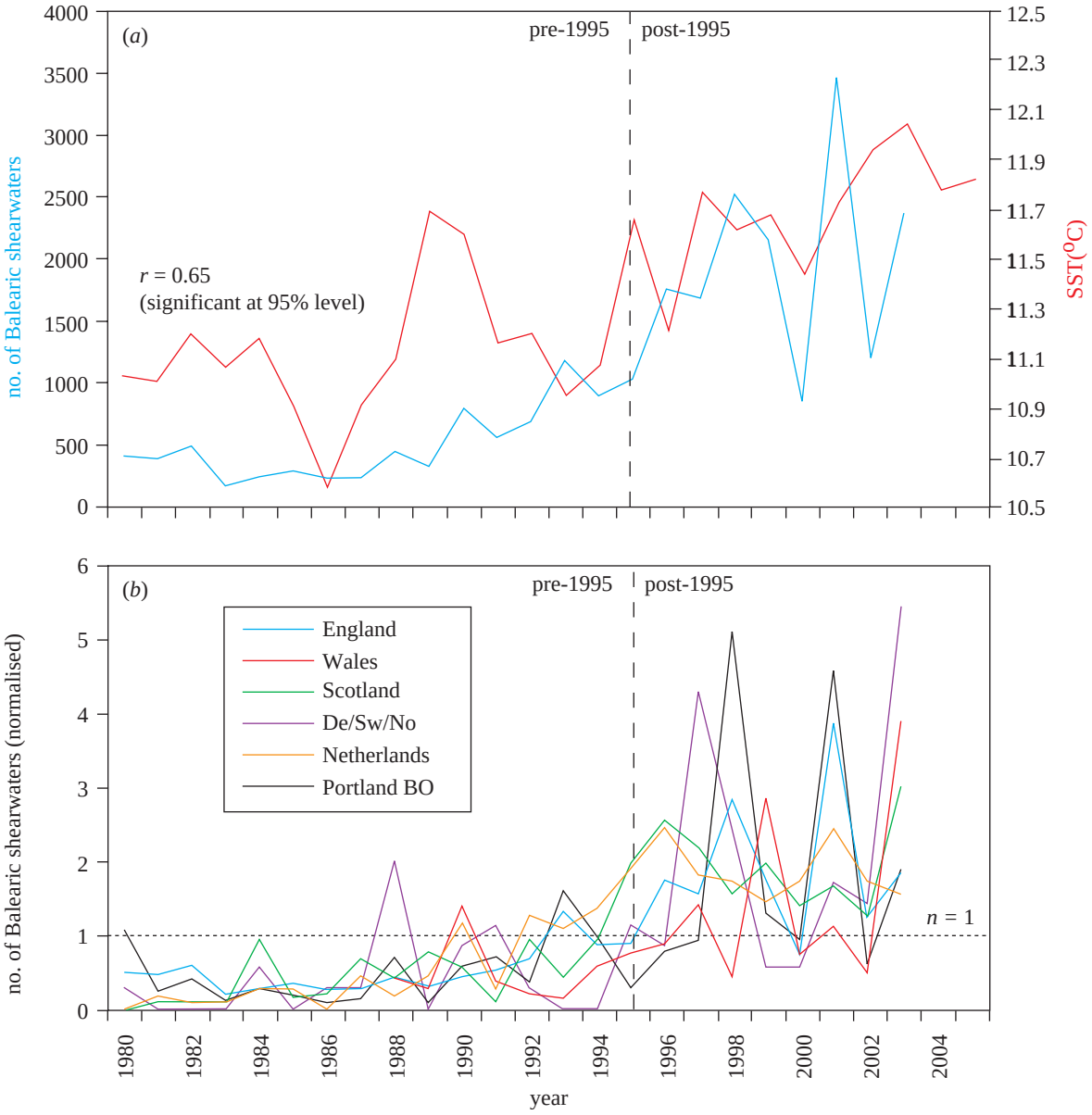

Figure 2. (*a*) Time series for the period 1980–2003 showing annual totals of Balearic shearwaters in UK and Irish waters (blue), and annually averaged SST in the UK and Ireland region shown in figure 1 (red). (*b*) Time series showing numbers of Balearic shearwaters in northwest European waters from 1980 to 2003; note the consistent increase in numbers in the mid-1990s (vertical dashed line). Individual annual totals have been normalized relative to 1980–2003 average values; a value of 1.0 (represented by dotted line) is therefore equal to the long-term average, a value of 0.5 is half the long-term average, and a value of 2.0 is double the long-term average. Values for Denmark (De), Sweden (Sw) and Norway (No) have been combined. Portland BO, Portland Bird Observatory.

moved north by 10° latitude in northeast Atlantic waters since the early to mid-1980s (Beaugrand *et al.* 2002; Beaugrand & Reid 2003), with a simultaneous retreat of subarctic and arctic species. These shifts are strongly correlated with increasing SST. At the very base of the food chain, proxies for local phytoplankton abundance demonstrate a simultaneous stepwise change (Reid *et al.* 1998; Beaugrand & Reid 2003). Increasing SST therefore appears to initiate a cascade effect, with subsequent changes in phytoplankton occurrence affecting their herbivore grazers and ultimately their predators in a bottom-up manner (Richardson & Schoeman 2004; Frederiksen *et al.* 2006). Our work provides the first evidence for this cascade affecting the large-scale distribution of a migratory top predator in Atlantic waters, although Veit *et al.* (1996) have previously documented a similar relationship in the northeast Pacific Ocean.

It is important to identify major potential threats to the survival of endangered species before their influence becomes irreversible, so that effective conservation strategy can be planned and implemented (McMahon & Hays 2006). The breeding population of the Balearic shearwater is undergoing a serious, and potentially terminal, decline (Oro *et al.* 2004), and the breeding distribution remains restricted to the Balearic Islands. However, our results indicate a rapid northwards expansion in post-breeding distribution since the mid-1990s, while a simultaneous decrease in numbers using northern Biscay may point towards a genuine distribution shift (Yésou 2003). We propose that this phenomenon has occurred in

response to climate-driven shifts in prey distribution. Increased dispersal range and/or decreased foraging success at sea may be contributing to the species unusually low adult survival rate (Oro *et al.* 2004). Early indications for northwards range expansion of other scarce migratory seabirds (e.g. Fea's Petrel (*Pterodroma feae*); Steele 2006), suggest that they could also be affected in a similar fashion. Further research should therefore be directed towards predicting future distribution changes in response to predicted SST increases, in combination with ongoing (pan-European) long-term monitoring initiatives.

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