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CLIMATE CHANGE AND MIGRATORY SPECIES REPORT PART 1

(Prepared by the UK Government and the CMS Secretariat)

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Climate change and migratory species: a review of impacts, conservation actions, indicators and ecosystem services

Part 1 – Impacts of climate change on migratory species

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The Convention on the Conservation of Migratory Species of Wild Animals (CMS, also known as the Bonn Convention, after the city in which it was signed in 1979) is the global international agreement of the United Nations which addresses the conservation and sustainable use of migratory animals and their habitats. Over the past 40 years, CMS Parties have identified over six hundred species that merit protection under the Convention as they migrate across Range State boundaries and so require co-operative actions between Range States.

The key issue of climate change was first discussed at the fifth meeting of the CMS Conference of the Parties (CoP5) in 1997 and has been addressed at multiple subsequent CoPs.

In support of this work, the Government of the United Kingdom of Great Britain and Northern Ireland (through a contract to the British Trust for Ornithology (BTO) funded by the Department of Environment, Food and Rural Affairs via the Joint Nature Conservation Committee (JNCC)) commissioned a review of the latest evidence on the impacts of climate change on migratory species, with regard also to conservation actions, indicators and ecosystem services.

The results of this review are presented in three parts:

Part 1 – Impacts of climate change on migratory species
Part 2 – Conserving migratory species in the face of climate change
Part 3 – Migratory species and their role in ecosystems.

A Summary for Policy Makers is also available.
Access the full review at jncc.gov.uk/climate-migratory-species-report/

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Climate change and migratory species: a review of impacts, conservation actions, indicators and ecosystem services

Part 1 – Impacts of climate change on migratory species

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Summary

Background

Over the last several decades, anthropogenic emissions (primarily of carbon dioxide (CO_2)) have rapidly increased global temperatures and altered climate patterns. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred, affecting both average conditions and annual variability, in particular the frequency of extreme events. Climate change has already caused substantial damage and increasingly irreversible losses to most species groups in terrestrial, freshwater and marine ecosystems.

Migratory species are vulnerable to a wide range of threats, both climate-related and non-climate-related, as they move between countries and ecosystems on a seasonal basis. This potentially exposes them to the impacts of climate change at multiple locations along their migration route, with possible interactions and divergence in the timing of cues at these locations.

The aim of Part 1 of this review was to critically evaluate the current evidence on the impacts of climate change on migratory species, with regard to the size of those impacts at a population level and the strength of evidence for each. We also use the evidence base to assess migratory species responses and potential adaptations to a changing climate, in order to help identify where international conservation actions are most needed.

To achieve this, we carried out a review of the literature on the impacts of climate change on each class of species within the Convention on the Conservation of Migratory Species of Wild Animals (CMS) Appendix I and Appendix II from 2005 to present, to identify new research that has been undertaken since the previous reviews of climate change impacts on migratory species (Robinson *et al*. 2005; McNamara *et al*. 2010).

The results of this review build on the findings of these previous reviews, highlighting a range of climate change impacts on migratory species, associated adaptations and responses to climate change, and key research gaps. This review finds that the impacts of climate change are becoming increasingly apparent across a range of scales, from species genetics to entire ecosystems. There is now particularly strong evidence of the impacts of climate change on migratory species in aquatic environments, and migratory marine predators across a range of taxa are particularly vulnerable to the negative impacts of warming. Current evidence suggests the effects of warming will be greatest at mid- and high latitudes, whilst changes in precipitation will have the greatest impact at low latitudes. Increases in the severity of extreme events, particularly storms, are having large, but localised, negative consequences on some migratory species groups.

Overall, there is widespread evidence of changes in the distribution and phenology of migratory species. In particular, poleward range shifts and earlier migration and breeding are already occurring in temperature-driven medium and high latitudes, and more mixed directional shifts are apparent in the tropics, depending on changes in rainfall.

The results of this review suggest that evidence on the impacts of climate change is lacking for several species groups, particularly bats, fish, South American grassland birds, and sharks and rays, as well as regionally for species residing in the tropics and Global South.

Seabirds

Seabirds are a taxonomically diverse group of species that are linked by their use, to a greater or lesser extent, of marine habitats. Most are long-lived, breed colonially and spend long periods away from land. Increases in sea surface temperature generally induce reductions in food availability which are having widespread negative effects on survival, breeding success and population abundance. Linked to this, reductions in sea ice extent are reducing the area of suitable habitat for polar-dwelling species, and these may be replaced by more temperate species. The breeding habitat of those utilising low-lying coastal areas is threatened by both sea level rise and a predicted increase in the frequency and severity of storms. There are already observed changes in species distribution, the timing of breeding (creating the potential for temporal mismatches between peak food requirement and prey availability) and, possibly, migration routes. Furthermore, extreme events (such as intense storms) are having large impacts on individual colonies, which may be particularly problematic for those with restricted distributions.

Waterbirds

Waterbirds fall into three main groups: waterfowl (ducks, geese and swans), wading birds (herons and allies) and shorebirds, all of which rely on freshwater and/or coastal wetlands at some point in their life-cycle. The effects of increased temperatures, at least for temperate species, have been broadly positive, although summer drought and the drying of wetland habitats, especially at lower latitudes, will reduce the area of suitable habitat available and prey availability, with consequent negative population effects. Coastal habitats, on which many of these species rely, are particularly vulnerable to sea level rise, both through a reduction in area (especially where 'hard' sea defences, such as sea walls, are employed) and a predicted increase in the frequency and severity of storms. We are already seeing large-scale distributional shifts (in both breeding and non-breeding distributions) in many temperate species which are projected to continue into the future, although the mechanisms by which this happens appear to vary between groups, affecting the speed at which species can adapt.

Raptors

Historically, raptors have been persecuted in many parts of the world, and many populations have suffered from the effects of toxic chemicals (pesticides, antibiotics) that have entered the environment, although some populations are now recovering. Major habitat change has also reduced many populations, for example in steppe habitats of Central Asia. These long-term threats may mask species' responses to climate change. Evidence (based largely on changes in productivity and survival in response to annual variation in conditions) suggests that raptors are affected to a greater extent by changes in precipitation than temperature. Such impacts can be either negative, by limiting foraging potential, or positive, by enhancing prey abundance through a cascade in the food chain.

Afro-Palearctic passerines

Numerically, passerine birds that migrate between Eurasia and Africa in their billions each year are one of the biggest groups to be affected by changing climates. Such impacts are well documented, in terms of both changes in range and migration routes/timing, particularly in response to widespread increases in temperature. The population consequences of these impacts, though, are less well characterised, being confounded by simultaneous widespread changes in habitat area and suitability. The potential impacts of mismatches between the timing of breeding and peak prey abundance are perhaps less severe than first thought, but depend on the capacity of species to adapt their migration schedules, which varies. Populations of many species fluctuate with respect to rainfall on the non-breeding grounds which affects overwinter survival and hence annual population change. Changes to the timing and quantity of rainfall along these species' migratory routes could have large population-level impacts but research into this is limited.

South American grassland birds

The effects of climate change on South American migratory grassland birds have not yet received much focus in the literature, though it is recognised as an important subject to address moving forwards. It is likely that changes in precipitation patterns will impact food availability and habitat structure, and that species will become vulnerable to heat stress, particularly during extreme events. As grasslands are often used as agricultural and grazing habitats, which independently puts pressure on the habitat available for the bird population, the responses of farming to climate change will further influence how birds and agriculture interact in these regions.

Terrestrial mammals

Terrestrial mammals covers a diverse group of species, including primates, bears, elephants, carnivores and ungulates. Migration is generally seasonally-driven by food availability, often linked to rainfall patterns. Declines in rainfall across some areas, for example over much of the Sahel region and northern Africa, will lower primary productivity. This reduces food availability for herbivores, thus also reducing the food available for carnivores, indicating the interlinked nature of climate-induced changes. Population trends vary between species and regions, but declines are most common, and for many species habitat loss due to human activities is the biggest threat, which may be compounded by human responses to climate warming.

There is evidence that migratory terrestrial mammals have some capacity to adapt to current and future climate change through behavioural changes, changes in migratory patterns and polewards range changes. However, such adaptation may be short term and adaptability will be limited where movement is prevented by human infrastructure, such as fences and roads, and suitable habitat in more favourable climates is not available. Interventions to create and maintain protected habitats and corridors will be vital for the survival of many migratory terrestrial mammals.

Bats

Research on how bats are being affected by climate change is limited compared to other taxa and generally insufficient to comprehensively determine the impacts. Research that has examined the consequences of climate change for migratory bats has highlighted a range of impacts, resulting particularly from changes in temperature, precipitation and extreme weather events, all of which can alter population size. Extreme weather events, particularly heat waves in the tropics, negatively impact survival and breeding success, with multiple mass die-off events being reported, particularly in flying foxes.

In response to the changing climate, range expansions/shifts have been observed in some species and are projected through predictive modelling for many more, with some evidence of phenological shifts which respond more to wind and precipitation than temperature.

Marine mammals

The impact of climate change on marine mammals is particularly complex as there are likely to be long-term fundamental changes to ocean currents and circulation. There has been much work on marine ecosystems in recent years, but their capacity to adapt is poorly understood, making future population-level impacts very difficult to predict. The most important impact of climate change for most marine mammal species is likely to be on food availability, which in most cases will reduce. Temperature increases, loss of sea ice, increasing ocean acidification and increases in oceanic weather systems events such as the El Niño/La Niña climate system are generally predicted to reduce food availability, particularly krill abundance. Other climate change impacts include the increased risk of disease and toxic algal blooms, responsible for an increase in mass mortality events, an increase in the frequency of coastal storms, and sea level rise.

Changes in food availability will lead to changes in the range, phenology and abundance of marine mammals. Arctic species such as the Polar Bear, Narwhal and Beluga Whales may be particularly vulnerable as their habitat is lost and they face increasing competition from other species moving polewards. Most studies predict declines in baleen whales, although this is not consistently predicted. In particular, marine mammal declines are predicted in mid- and low latitudes, though there may be increases in some areas. Other particularly vulnerable species include freshwater and coastal species.

Reptiles

Marine turtles and Saltwater Crocodiles are particularly threatened by the loss of nesting habitat due to sea level rise and increasing storm frequency and intensity. Coastal development on alternative beaches, particularly at the poleward edges of their shifting ranges, is a key threat to their ability to adapt to sea level rises and temperature increases. The human response to storm surges and sea level rise will also determine whether beach profiles shift inland naturally, likely maintaining suitable nesting habitat, or are lost. Temperature increases have had a significant impact on turtle and crocodile sex ratios, although currently this is likely to be beneficial to population trends.

Bony fish

Most migratory fish species have undergone extreme population declines over the past 50 years. The main drivers of these declines are habitat loss, disruption of migration through damming, and overfishing, but climate change is increasingly becoming a major threat. The impacts of climate change on migratory fish are complex and under-researched but are likely to be detrimental to most species. Increasing temperatures, reduced river flow and, in some areas, reduced rainfall will lead to spawning habitat loss and may also impact survival rates and lead to extinctions. Poleward range shifts may be possible for some species, but many are strongly tied to natal spawning grounds, which will reduce their ability to shift ranges. Human interventions such as translocation, artificial stocking, habitat restoration and the removal of dams, or installation of bypasses may be necessary for many species to survive increasingly warm temperatures.

Sharks and rays

Since 1970, the global abundance of oceanic sharks and rays has declined by 71%, largely due to overfishing, bycatch and coastal habitat loss, mainly from fishing activities such as trawling. The impacts of climate change on sharks and rays are complex, due to various physiological, behavioural and ecological changes. For most species, research on the impacts of climate change is scarce, but in general, sharks and rays are thought to be vulnerable to climate change due to low reproduction rates. Species that are dependent on coastal and inshore nursery habitats or coral reef habitats are likely to be at the highest risk from climate change. Increases in sea surface temperatures are changing food availability, and also metabolic rates. Increased ocean acidification reduces the growth of zooplankton, on which some species feed, and reduces olfactory function in sharks and rays, reducing their ability to hunt. Poleward range shifts are already moderately well documented and changes in migration phenology are predicted, although there is little research to examine this. Increases in temperature and sea level are likely to reduce the amount of suitable habitat available, while an increased frequency and severity of storms particularly affects species with inshore nurseries.

Insects

There are many migratory species of insects, but only one species is listed on the CMS Appendices, the Monarch Butterfly. It occurs in North and Central America and has been a major focus of research, with increases in temperature and the frequency of extreme events having an impact on local population sizes. However, with a multi-generational migratory cycle, long-term impacts of climate change are hard to discern.

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1 Introduction

1.1 Impacts of climate change on biodiversity

Biodiversity is declining globally at unprecedented rates, and climate change is one of the major drivers of this due to a wide range of changes in the physical environment (IPBES 2019). There are well-documented increases in global temperatures, but also increases in the frequency of extreme weather events, global sea levels and ocean acidification, and decreases in snow/ice cover. While there is global action to limit greenhouse gas emissions that drive these changes, they are projected to increase for at least the remainder of the century, even if emissions are reduced (IPCC 2022). There is already compelling evidence that animals and plants have been affected by climate change over the last few decades, with impacts on their genetic evolution, physiology, morphology, behaviour, phenology, abundance and distribution, cascading to alter communities and ecosystems (Scheffers *et al.* 2016). Many of the impacts on species' populations and communities result from mechanisms operating through altered species interactions (Ockendon *et al.* 2014). The impacts of climate change vary globally, with impacts mediated through changes in precipitation more important in the tropics than at higher latitudes, where temperature is the main driver of change (Pearce-Higgins *et al.* 2015b).

Animal migration is broadly defined as the persistent, directional movement of an individual or group of individuals from one destination to another; it is important to note that this is rarely 'point-to-point', but is often followed by substantial post-migratory movement, which may itself be climate-driven through variations in resource availability (Teitelbaum *et al.* 2023). The CMS regards a species (or population) as migratory where a significant proportion of its members cyclically and predictably cross one or more national jurisdictional boundary(ies), which includes species where individuals make shorter, but regular, movements within their overall range.

Each year, billions of individual animals undertake seasonal movements that, in aggregate, span the globe (Bauer & Hoye 2014). Migratory species are subject to a wide range of environmental influences due to the large distances they travel, and they rely on a wide range of natural resources along their migration routes, making them particularly likely to be affected by climate change at some point in their life-cycles (Learmonth *et al.* 2006; Robinson *et al.* 2009; Winkler *et al.* 2014). Migrants require not only suitable habitats at each end of their migration route but also suitable conditions and habitats en route. Wind speed and direction, or ocean currents, may be important for the successful completion of a migratory journey, and the presence of high-quality stopover sites for resting or foraging is also of key importance. Throughout their migrations, animals must gather information, integrate environmental and internal state data, and make decisions about the timing and orientation of migratory movements, which can be increasingly difficult in rapidly changing environments. This raises the possibility of major mismatches between behaviour and environmental conditions, especially when cues in one area may be increasingly decoupled from changes in other areas. The complexities of uncertain migratory connectivity, and the difficulty in undertaking assessments of population processes throughout the full life-cycle of migratory species, make understanding the impacts of climate change and assessing climate change vulnerability in migratory species particularly challenging (Small-Lorenz *et al.* 2013).

Previously identified threats from climate change include loss of habitat, from both increased temperatures melting sea ice and permafrost, and lower rainfall reducing wetland areas; increased frequency of extreme weather events, both localised (storms) and regional (e.g. through the El Niño Southern Oscillation); sea level rise; increased acidification of oceans; and changes in ocean circulation patterns. More pervasive, and harder to predict, are wide-scale changes in ecosystem functioning, particularly changes in the spatial and temporal distribution of prey, but also the composition of biological communities. Direct effects include changing hatchling sex ratios in those species with temperature-based sex determination (e.g. turtles) and phenological shifts in the timing of life-cycle events (including migration itself). Existing anthropogenic threats, such as human take (deliberate or bycatch), the existence of physical barriers (sea walls, river dams or fences) and habitat loss, will exacerbate the challenges faced by migratory species under changing climate regimes. Some of these will exacerbate climate change impacts, for example increased water abstraction in areas with reduced rainfall, or expanding renewable energy developments in important habitats. These will further reduce species' resilience to cope with, and ability to adapt to, climate change (Robinson *et al.* 2005; McNamara *et al.* 2010).

The impacts of climate change on migratory species may usefully be classified into two general categories. Firstly, climate change may affect the species' biology directly, through changes to the abiotic environment. This may affect either the species' physiology (e.g. increased heat stress or changes in wind patterns affecting migratory journeys), or its habitat (e.g. drying out of aquatic habitats or rising sea levels encroaching on coastal habitats). Secondly, overlain on these, are less direct biotic impacts resulting from altered species interactions, such as changes in the spatial or temporal distribution of prey or competitors. The impact of many of these indirect effects is difficult to predict. There is a further dimension to the indirect effects, which derives from how society responds to climate change. Such adaptations are likely to be multifaceted, encompassing a wide range of objectives, from mitigating emissions to maintaining food security, which, in turn, may have major impacts on biodiversity (Morecroft *et al.* 2019). Such complexities mean converting scientific knowledge into policy and conservation action has thus far been slow, even where such knowledge is relatively good (Trathan *et al.* 2020).

1.2 Conservation of migratory species and climate change

In a global context, the conservation of migratory species is led by the Convention on the Conservation of Migratory Species of Wild Animals (1979) (CMS, also known as the Bonn Convention), which provides a global platform for the conservation and sustainable use of migratory animals and their habitats. Over the past 40 years, CMS Parties have identified several hundred species that merit protection under the Convention as they migrate across Range State boundaries, including many birds, land mammals and bats, as well as a range of marine vertebrates, and one invertebrate. The Convention has two appendices: Appendix I lists migratory species that have been assessed as being in danger of extinction throughout all or a significant portion of their range, whilst Appendix II lists migratory species that have an unfavourable conservation status and that require international agreements for their conservation and management. Species that have a conservation status which would significantly benefit from an international agreement can also be included in Appendix II. The Convention works alongside a number of daughter instruments targeted at particular groups (e.g. the Agreement on the Conservation of African-Eurasian Migratory Waterbirds or the Memorandum of Understanding concerning Conservation Measures for Marine Turtles of the Atlantic Coast of Africa) and species (e.g. the Memorandum of Understanding concerning Conservation, Restoration and Sustainable Use of the Saiga Antelope). Depending on the way they were negotiated and are formulated, Agreements and Memoranda of Understanding may be legally or non-legally binding.

The topic of climate change was introduced to the CMS in 1997 (Conference of the Parties (CoP) Recommendation 5.5) and has been the topic of subsequent CoPs, most recently as Resolution 12.21. This calls on Range States to address the effects of climate change, despite the remaining uncertainty surrounding the full scale of its impacts on migratory species, and to assess what steps are necessary to help migratory species cope with climate change. There is a need, then, to critically review the evidence of the impact of climate change on migratory species, with regard to the size of those impacts at a population level, as well as to the strength of evidence, in order that (1) international conservation actions may be prioritised and (2) knowledge gaps identified.

In Part 1 of this review, we aim to review the evidence of the impact of climate change on migratory species, focusing primarily on those species listed in Appendices I and II of the CMS, but drawing on studies of non-listed and non-migratory species where relevant. We also assess the evidence for adaptations and responses to changing climatic conditions, and use the strength and degree of agreement in the evidence base to assign confidence levels to our findings.

2 Methods

2.1 Search methodology

To identify relevant references on the impacts of climate change on migratory species, we undertook a rapid review of the primary literature as set out below, as well as using existing reviews. We carried out a review of the literature on the impacts of climate change on each class of species (birds, mammals, reptiles, bony fish, sharks and rays, and insects) within Appendices I and II of the CMS from 2005 to present, to identify new research since the review of climate change impacts on migratory species by Robinson *et al.* (2005). We divided large classes (e.g. Aves) into smaller subgroups, generally based on their taxonomy at ordinal level, but aggregating smaller groups where they had similar ecological characteristics and so were likely to respond similarly to climate changes. For each group, we carried out a search in Web of Science and, in view of timescales, reviewed at least the first 50 papers for each search listed below, unless there were fewer than 50 available. We then carried out the same search in Google Scholar for larger groups, identifying any relevant papers that did not appear in the Web of Science search from the first 30 papers. We assessed the remaining papers from the Web of Science search (based on the title alone) to identify any additional key papers examining climate change impacts on the group.

The standard search we carried out was:

(Population* OR Demograph* OR Reproduct* OR Decline* OR Abundance OR Breeding OR Survival OR Mortality OR Fecundity OR Density) AND (Climate* OR Global warming OR Sea level rise OR Global environmental change) AND (migrat*) AND [group name(s)]

The group names we included were as follows:

Aves: (duck OR goose OR swan), (albatross OR petrel OR shearwater OR procellariiformes), (accipiter OR eagle OR aviceda OR buzzard OR falco OR kite OR circus OR osprey), (owl), (“microcarbo pygmaeus” OR “phalacrocorax nigrogularis” OR “fregata andrewsi”), (diver OR loon), (flamingo) AND (lesser OR greater), (“podiceps auritus” OR “podiceps grisegena”), (gull OR tern), (egret OR heron OR bittern OR ibis OR pelican), (sporophila OR seedeater OR tyrant OR bobolink), (warbler), (“Afro-palearctic migrant”), (muscicapidae OR sylviidae OR turdidae OR motacillidae), (bustard), (“spheniscus demersus” OR “spheniscus humboldti”), (corncrake OR crake OR crane OR flufftail), (stork), (vulture OR condor), (wader OR shorebird), (wader OR shorebird OR Charadriidae OR Scolopacidae OR Laridae OR Haematopodidae OR Burhinidae OR Ibidorhynchidae OR Recurvirostridae OR Pluvianellidae OR Dromadidae OR Glareolidae OR Laridae OR Alcidae).

Mammalia: Terrestrial mammals: (ungulate OR gazelle OR antelope), (gorilla OR chimpanzee), ("Ursus arctos isabellinus"), (Elephant) NOT (Seal), ("Lycaon pictus" OR "Acinonyx jubatus" OR "Panthera onca" OR "Panthera pardus" OR "Panthera leo" OR "Uncia uncia"); Bats: (bats); Marine mammals: (marine) AND (mammal OR cetacea* OR carnivor* OR seal OR lion OR manatee OR dugong), (Lontra), ("Ursus maritimus").

Reptilia: (marine) AND (turtle); "Crocodylus porosus"; "Gavialis gangeticus"; "Podocnemis expansa".

Actinopterygii: (sturgeon OR actinopterygii OR shovelnose).

Chondrichthyes: (shark OR ray OR chondrichthyes OR sawfish).

Insecta: ("Danaus plexippus").

We also drew on more recent reviews including Robinson *et al.* (2009, and associated papers), Pearce-Higgins and Green (2014), Ockendon *et al.* (2014) and Pearce-Higgins *et al.* (2015b) to identify additional references, and more general patterns and responses of migratory species to climate change.

Accounts for each group follow a standard format. First, we provide a brief overview of the migratory patterns and conservation status, before going on to discuss reported climate change impacts and then documented adaptations and responses to changing climatic conditions. Each subsection deals with a specific aspect and begins with a summary statement (*in italics*) of the key patterns and an indication of our level of confidence in this (**in bold**). We then provide details from the primary literature and reviews identified that support these statements. In general, we chose to present the topics for which there is better evidence first within each group.

2.2 Confidence levels

We used a combination of the amount of published evidence and the degree of agreement in that evidence, along with our experience in these areas, to provide a three-level assessment of confidence associated with individual statements. This was notwithstanding the recognition that reviews of the scientific literature can only assess topics that have been published, and therefore any rapid search (such as we were able to undertake) will necessarily be incomplete, missing studies that have yet to make it into the mainstream literature.

Statements supported by many peer-reviewed papers (c. five or more) with a high degree of consistency were regarded as being associated with **high confidence**. Statements supported by a small number of papers, or with more than one or two contradictory studies, were given a **medium confidence**. Statements supported by only one or two studies, with high uncertainty expressed in the studies, or with a very mixed evidence base, were regarded with a **low confidence**.

3 Aves: Seabirds

3.1 Overview of migration patterns and distributions

Seabirds are defined by their extensive use of marine habitats and cover a range of taxonomic groups, including the Procellariiformes (albatrosses, petrels and shearwaters), Sphenisciformes (penguins) and some members of the Charadriiformes (gulls and auks). Most seabird species are long-lived, maturing late and exhibiting low fecundity (the largest lay a single egg and may not breed every year). As a result, their breeding populations are most sensitive to changes in survival (Sæther & Bakke 2000). All are migratory to some extent. They typically breed colonially in (often remote) coastal locations or islands before migrating out to sea for the non-breeding months. Despite advances in tracking technology, which has provided some insight into their movements in the last couple of decades, there is still much we do not know about their movements and migration, especially before they reach breeding age (Strøm *et al.* 2021).

Albatrosses (all species) and petrels (14 species) form the core of the seabird species listed by the CMS and are the subject of a specific multilateral Agreement (Agreement on the Conservation of Albatrosses and Petrels, or ACAP) (Cooper *et al.* 2006). Three key threats that seabirds are facing are the presence of invasive species, especially those that predate nests, in breeding colonies; bycatch from fisheries; and climate change (Lascelles *et al.* 2014; Dias *et al.* 2019). As a result of long-term studies, there are good demographic models of some Antarctic seabird populations, enabling some confidence in projected climate change impacts (e.g. Barbraud *et al.* 2011; Trathan *et al.* 2020).

3.2 Climate change impacts

3.2.1 Sea surface temperature

Many seabird species show generally negative associations with sea surface temperature with well-demonstrated effects on survival, breeding success and population abundance **(high confidence)**.

Temperate shallow, coastal seas are characterised by a spring flush of diatoms that drives a cascade of increasing zooplankton and small fish biomass. In such systems, seabird productivity is often negatively associated with sea surface temperature, due to the negative impacts of warming on food availability. Climate change is acting to ‘speed up’ such ecological processes and change their timing (Johnston *et al.* 2022). For example, warmer temperatures can lead to changes in the timing and abundance of plankton blooms, reducing food availability for small fish (Scott *et al.* 2006; Burthe *et al.* 2012). Cold-water copepods are replaced with warm-water species that emerge later in the year, reducing the flush of plankton for fish (Beaugrand *et al.* 2002, 2003).

The net result is a reduction in the size and abundance of juvenile fish, such as sandeels, around seabird colonies, and the abundance and size of 1-class fish (those of a size that indicates they hatched in the previous year) that are also important for many seabird species. This has been well demonstrated around the North Sea (e.g. Wanless *et al.* 2004; Frederiksen *et al.* 2004, 2006), Baltic Sea (Österblom *et al.* 2006) and the east Pacific (Gjerdrum *et al.* 2003; Hedd *et al.* 2006).

Away from shallow coastal seas, different processes may operate. Although seabird populations in more open waters may be less sensitive to temperature-mediated trophic cascades (Johnston *et al.* 2022), variations in temperature and the strength of different oceanic currents may still have strong impacts on the abundance of fish prey close to breeding colonies, and therefore on their breeding success (Davoren & Montevecchi 2003; Diamond & Devlin 2003; Durant *et al.* 2003, 2005).

In response to these pressures, adults can show considerable flexibility in their foraging behaviour to try and minimise impacts on their populations. For example, Southern Rockhopper Penguins (Pütz *et al.* 2018) and Little Auks (Jakubas *et al.* 2020) increased the distance and time of their foraging trips in years when increased temperature drove declines in food resources.

In Little Penguins, the land-based climate during the moult period has the greatest effect on adult survival (Ganendran *et al.* 2016), while higher sea surface temperatures decrease breeding success (Johnson & Colombelli-Négrel 2021). Additionally, reductions in prey abundance and foraging range during periods of prolonged drought in El Niño years have caused reduced breeding success (Preston *et al.* 2010; Kowalczyk *et al.* 2015).

Extreme temperatures can reduce breeding success by causing nest desertion, as seen in Adélie and African Penguins (Chapman *et al.* 2011; Traisnel & Pichegru 2018).

Increasing sea surface temperature negatively affects survival in Bulwer's Petrel, which is predicted to decrease under all projected climate change scenarios (Cruz-Flores *et al.* 2022). This study also found stronger impacts on populations in tropical regions compared to those in subtropical or temperate regions.

3.2.2 Sea ice extent

Reductions in sea ice extent reduce the area of high-quality foraging habitats for seabirds **(high confidence)**.

Species that rely on prey whose distribution is tied to sea ice show reduced breeding success in warmer years. For example, the productivity of southern populations of Brünnich's Guillemots is reduced through the impact of warming on Arctic Cod abundance (Gaston *et al.* 2005). Cold years also favour planktivorous Crested and Parakeet Auklets (Kitaysky & Golubova 2000).

In the Southern Ocean, the extent of sea ice is positively related to the productivity and survival of many seabird species as krill are closely tied to sea ice extent, including in Adélie and Emperor Penguins (Jenouvrier *et al.* 2005, 2006; Ducklow *et al.* 2007), Southern Fulmars (Jenouvrier *et al.* 2003) and Snow Petrels (Barbraud & Weimerskirch 2001), with large-scale breeding failures recorded (Fretwell *et al.* 2023). The productivity of the Light-mantled Sooty Albatross (Inchausti *et al.* 2003) and Snow Petrels (Barbraud & Weimerskirch 2001) which feed in the Antarctic is negatively correlated with warming. Lower sea ice concentrations during summer in Antarctica increased the foraging efficiency of Adélie Penguins, though extreme events can disrupt the response (Lescroël *et al.* 2014).

Increases in mortality in Emperor Penguins were observed in relation to reductions in sea ice extent; this effect was more pronounced in males than females reflecting differences between the sexes in foraging areas. Increases in breeding success associated with shorter distances between the breeding colony and open water in warmer years did not offset the negative impact of warming on survival, so overall the population has declined (Barbraud & Weimerskirch 2001) and is likely to continue to do so (Trathan *et al.* 2020).

3.2.3 Timing of spring peaks in prey abundance

Seabirds may be vulnerable to mismatch with the timing of spring peaks in prey abundance, as a result of the timing of those peaks being strongly temperature-dependent. Temperature-related reductions in prey abundance can also limit the ability of seabirds to shift their timing of breeding **(medium confidence)**.

On average, the timing of breeding of seabird species around the world has not shifted in response to warming or through time, potentially making them vulnerable to changes in the timing of oceanographic processes (Keogan *et al.* 2018). Where the cues which influence the timing of breeding and the timing of peak resource availability differ, then mismatch can occur. This can happen when the flow of coastal currents influences the timing and availability of small fish, but the timing of bird breeding is related to temperature, or when temperature-related reductions in prey populations delay the timing of seabird breeding despite advances in the timing of peak prey availability (Pearce-Higgins & Green 2014). These impacts can be compounded by negative impacts of climate change on prey abundance, but there is a general lack of studies investigating the impacts that climate-mediated trophic asynchrony may pose to populations worldwide (Samplonius *et al.* 2021).

3.2.4 Changes in oceanic currents

Large-scale changes in oceanic currents can greatly alter food availability, especially for central-place foragers like seabirds that have to return to a specific location, the breeding colony **(high confidence)**.

There are marked effects on seabird populations concerning variation in the strength and direction of the El Niño Southern Oscillation (ENSO). El Niño years (negative values of the Southern Oscillation Index) are associated with warmer temperatures and reduced productivity in tropical seabird species, due to reductions in the extent of cold water upwellings, reducing nutrient circulation, plankton production and fish productivity. This has been shown to impact Galápagos Penguin (Boersma 1998) and Blue-footed Booby (Oro *et al.* 2010; Ancona *et al.* 2012) in the Pacific, and Roseate Tern productivity in the Indian Ocean (Ramos *et al.* 2006; Monticelli *et al.* 2007).

Elsewhere, high sea surface temperature (associated with reduced food availability) during breeding and positive episodes of the Southern Oscillation (La Niña) during the non-breeding season have a negative impact on survival in Cory's Shearwater. These population-level effects of climate were greater than that of longline fisheries (Ramos *et al.* 2012).

The intensity of winds in the Southern Ocean are increasing and thus altering the depth of layers within the ocean; this can impact prey availability and foraging behaviour/efficiency as seen in Little Penguins (Ropert-Coudert *et al.* 2009; Saraux *et al.* 2016).

3.2.5 Frequency of stormy weather

Increased frequency of stormy weather can impact the survival and breeding success of some species, depending on the timing, with potential consequences for population size **(high confidence)**.

Phalacrocoracidae species, such as Shag, have poor weather-proofing and hence can suffer high mortality following stormy or wet conditions (Harris *et al.* 1994; Frederiksen *et al.* 2008).

Arctic-breeding species are vulnerable to extreme weather events, and it is speculated that climate change may increase the frequency of these, as well as expand the range of stressors that might induce mass mortality in breeding seabirds (Mallory *et al.* 2009).

When storms occur during the breeding season, they can result in the loss of low-lying coastal nests in species such as gulls and terns (e.g. Weston & Fraser 2020), or of low-lying exposed cliff nests in others (Newell *et al.* 2015). Similarly, outside of the breeding season, severe storms can cause mass mortality events, known as 'wrecks' (Camphuysen *et al.* 1999).

Increased intensity of the ENSO has enhanced local storm activity, increasing mortality in Manx Shearwaters. Mortality in Atlantic Yellow-nosed Albatrosses and Magellanic Penguins also increased with storm activity, regardless of the ENSO (Tavares *et al.* 2020). Climate change may also increase the turbidity of the water, which can reduce foraging efficiency in seabirds e.g. Manx Shearwater (Darby *et al.* 2022).

3.2.6 Rising sea levels

Many seabirds are cliff-nesters, but for those nesting in low-lying areas, such as albatrosses, penguins and terns, rising sea levels threaten to inundate nest sites **(low confidence)**.

Many seabirds are cliff-nesters, but there are a range of species such as albatrosses and penguins that nest in low-lying areas. Rising sea levels threaten to inundate nest sites of these species, especially where there are natural or anthropogenic barriers to movement inland (Trathan *et al.* 2015). For example, two migratory albatrosses (Laysan and Black-footed Albatross) nesting in the Hawaiian Islands are predicted to lose 60% of their nesting habitat with a 2 m sea level rise (Reynolds *et al.* 2015).

3.3 Adaptations and responses

3.3.1 Timing of migration and breeding

The timing of migration or breeding can be sensitive to temperature and large-scale atmospheric systems, though responses vary within and between species **(medium confidence)**.

Advances in arrival dates and breeding are documented in a range of species, for example Ring-billed Gull, Pacific Loon and Glaucous Gull, and correlate with temperature increases (Giroux *et al.* 2016; Solovyeva *et al.* 2022); however, this is not true for all species (Solovyeva *et al.* 2022).

In Common Terns, the changes in arrival timing relative to North Atlantic and Southern Oscillation indices differ between age-classes and have shown no long-term trends in recent decades (Szostek *et al.* 2015). The timing of arrival at a European stopover site differs for Great and Sooty Shearwaters, but for both species coincides with favourable flying conditions (Louzao *et al.* 2015).

Local conditions appear to be the main driver of breeding phenology for many seabird species (Keogan *et al.* 2022), particularly temperature, although negative impacts of warming on resource availability can also delay breeding (reviewed by Pearce-Higgins & Green 2014). Resident seabird species appear better able to adjust the timing of breeding in response to climatic variation than migratory, as seen among species breeding on the Houtman Abrolhos Islands in the eastern Indian Ocean (Surman *et al.* 2012).

3.3.2 Distribution

The response of seabird distribution ranges to climate change varies among species; shifts or expansions that have been observed are most often polewards **(high confidence)**.

Modelling suggests that increases in sea surface temperature have driven the poleward range expansions in Balearic Shearwater likely associated with similar shifts in prey (Wynn *et al.* 2007), while there have been southward range expansions in Gentoo and Adélie Penguins, tracking the retraction of sea ice (Lynch *et al.* 2012; La Rue *et al.* 2013).

Not all species appear to be responding to changing climate conditions through a change in their distribution; for example, the migration habits of Herring Gulls that breed in Newfoundland seem to be well established and no northward shift has been observed (Robertson 2016).

In some species, distribution shifts have been attributed to changes in productivity; for example, warmer temperatures are increasing productivity in Brünnich's Guillemots at the poleward range-margins due to reductions in sea ice, but causing reductions in the southern range-margins (Gaston *et al.* 2005). In other species, similar patterns are seen in survival, for example, survival in eastern Atlantic populations of Atlantic Puffin is positively related to temperature in the north of its range, but negatively in the south (Grosbois *et al.* 2009).

Seabirds are amongst the species that are most vulnerable to climate change in the UK, where many are towards their southern range margin. Temperature-related reductions in abundance are widely anticipated, and are symptomatic of anticipated poleward shifts of these species (Johnston *et al.* 2013; Pearce-Higgins 2021).

3.3.3 Migration routes

Some species may have adaptive responses to variations in climate that allow them to alter migratory routes or destinations **(low confidence)**.

In Cory's Shearwater, whilst some individuals show high site fidelity, others are capable of shifting their winter locations between years which is expected to be advantageous under changing and fluctuating environmental conditions (Dias *et al.* 2011).

4 Aves: Waterbirds

4.1 Overview of migration patterns and distributions

Waterbirds are one of the most studied groups when it comes to understanding the impacts of climate change. They are globally distributed and fall into three main taxonomic orders - Anseriformes (also known as waterfowl – ducks, geese and swans), Pelecaniformes (herons, ibises and pelicans, often referred to as 'wading birds') and Charadriiformes (gulls, terns and shorebirds/waders, hereafter termed shorebirds to avoid confusion with other wading birds) - along with a small number of representatives from other groups. Almost all species inhabit freshwater and/or coastal wetlands at some point in their life-cycle, either breeding or non-breeding, and utilise a wide range of migratory strategies. Indeed, many of the shorebird species are among the world's longest distance migrating species and as such have been considered 'sentinels' of global change (Piersma & Lindström 2004).

Most waterbirds, at least of those breeding in the northern hemisphere, migrate along one of eight 'flyways', defined by the Ramsar Convention on Wetlands as "composed of many overlapping migration systems of individual waterbird populations and species, each of which has different habitat preferences and migration strategies". Three of these flyways are in the Americas (along the Pacific coast, inland along the Mississippi catchment to Central and South America, and along the Atlantic coast), three connecting Eurasia with Africa (along the East Atlantic, western Asia to northern Africa, and Central Asia to southern Africa), and, further east, the Central Asian and East Asian-Australasian flyways (Davidson & Stroud 2016).

Temperate wetland and boreal, upland habitats are among those most altered by climate change and, as a result, waterbirds are among the species most threatened by climate change and for which climate change impacts (both negative and positive) have been well documented.

4.2 Climate change impacts

4.2.1 Increased temperatures

The effect of increased temperatures on breeding success and survival varies between species, but generally has a short-term neutral or positive effect, at least for species breeding at higher latitudes **(high confidence)***, although extreme temperatures (both hot and cold) are detrimental* **(medium confidence)**.

Temperature and the timing of snowmelt did not affect breeding success for 12 out of 17 studied species of Arctic-breeding shorebirds (Weiser *et al.* 2018a); however, for those affected, earlier snowmelt/warmer temperatures generally increased clutch size. Taken together this suggests that, in the short term, climate change will neutrally/positively affect breeding in Arctic-breeding shorebirds. Adult survival of six shorebirds was not explained by the timing of snowmelt or temperature at the breeding grounds, suggesting these species seem robust to conditions at the Arctic sites and conditions at stopover and wintering sites are more likely driving changes in survival (Weiser *et al.* 2018b).

Duck species' breeding success was found to be higher in warmer and drier springs in the American prairies (Drever *et al.* 2004; Drever & Clark 2007).

Svalbard Barnacle Geese have shown increased egg production and hatching success with advancing snowmelt and increasing summer temperatures, although these conditions have also correlated with an increase in the abundance of Arctic Foxes and a consequent overall decrease in fledging success (Layton-Matthews *et al.* 2020). Increased temperatures in their UK wintering grounds are also associated with an increase in annual survival rates.

During the breeding season, temperature positively affected breeding success in Slavonian Grebes from estimates made across Scotland (Ewing *et al.* 2013), although this was not the case within a single population that was the focus of another study (Brooks *et al.* 2012), and climate change does not seem to be directly driving the declining population trends (Ewing *et al.* 2013). On the other hand, the condition, and hence first-year survival, of Lesser Snow Goose goslings is lower in warmer than average years (Aubry *et al.* 2013).

Red Knot offspring are smaller with shorter bills at warmer breeding grounds, which negatively impacts foraging success at wintering grounds (van Gils *et al.* 2016) (see also the case study on page 73 for a review of the impact of temperature increases and other threats on the Red Knot).

Temperature has been shown to have a positive effect on growth rate in some populations of Arctic and sub-Arctic breeding shorebirds; this was strongest in the populations that generally breed in the coolest locations and there is evidence that timing of breeding relative to the peak in arthropod abundance influences growth rate (Lameris *et al.* 2022).

Fluctuations in abundance and variation in adult survival rates of a range of wetland bird species are positively correlated with winter temperature, including shorebirds (Yalden & Pearce-Higgins 1997; Cook *et al.* 2021), herons (Pearce-Higgins 2017), and waterfowl (Gunnarsson *et al.* 2012), leading to overall positive relationships between abundance and winter temperature (Johnston *et al.* 2013).

Extreme cold weather is, unsurprisingly, detrimental to wading bird populations, with increased mortality having been demonstrated in Greater Flamingos (Deville *et al.* 2014), Bitterns (Cormont *et al.* 2014) and coastal winter species like the Redshank in the UK (Clark 2009). It is worth noting that such extreme events can precipitate a decline from which the population cannot recover; for example, UK breeding populations of Northern Lapwing decreased as the result of a series of cold winters, and have not recovered due to insufficient reproductive capacity, despite the proximate cause of the decline no longer being present (Robinson *et al.* 2014).

Finally, the effects of increased temperature can be indirect. For example, warmer temperatures in Arctic Canada have meant an increase in the amount of woody vegetation (as a result of faster temperature-mediated growth), reducing the area of suitable breeding habitat for Whimbrels (Ballantyne & Nol 2015). However, in Iceland, warmer temperatures are increasing the area of suitable habitat for several species, such as the Black-tailed Godwit (Gunnarsson *et al.* 2006).

4.2.2 Altered patterns of precipitation

Increased precipitation can have a positive effect on breeding success, and drought a negative impact, at least on temperate breeding waterbirds. Where precipitation is projected to fall, especially in the summer months, overall effects are likely to be negative **(high confidence)**.

Breeding success was halved in dry years compared to wet for Purple Herons in Portugal due to higher rates of predation (Carneiro *et al.* 2016).

In the longer term, hotter, drier summers can have negative impacts on shorebirds (e.g. Pearce-Higgins *et al.* 2010) and species associated with wetland habitats, either through impacting habitat availability, or indirectly through impacts on prey abundance, particularly invertebrates (Carroll *et al.* 2015b; Pearce-Higgins & Morris 2022).

Breeding success was highly influenced by rainfall for White Storks in Spain, with much higher success in wetter years (Cuadrado *et al.* 2016). Survival (Nevoux *et al.* 2008) and population size (Sæther *et al.* 2006) are positively affected by the level of rainfall in the Sahel. However, as there has been more precipitation in recent decades, the strength of this environmental effect has faded.

Egg production was positively influenced by precipitation at a Norwegian stopover site during spring migration for Barnacle Geese in Svalbard (Layton-Matthews *et al.* 2020). Similarly, warmer and wetter conditions during spring and autumn migration increase survival in Greenland Barnacle Geese (Doyle *et al.* 2020).

The survival and changes in abundance of migratory waterbirds that winter in the Sahel are positively correlated with the extent of wet season rainfall (May – October), which recharges wetland habitats during the subsequent winter, likely impacting food resource availability (Zwarts *et al.* 2012). Similarly, migratory herons benefit from wetter conditions on the African wintering grounds (e.g Marion *et al.* 2006; Sæther *et al.* 2006; Nevoux *et al.* 2008; Fasola *et al.* 2010).

For Dalmatian and Great White Pelicans in the Black Sea/Mediterranean flyway, water level fluctuations in inland wetlands are a widespread problem (Catsadorakis *et al.* 2015), and in later breeding species (e.g. White-headed Duck), the earlier drying of wetlands can have negative effects (Özgencil & Uslu 2021).

An increase in precipitation during autumn migration, and on the breeding grounds whilst breeding, reduced recruitment in Whooping Cranes. Similarly, fewer days below freezing during the winter months on the breeding grounds also reduced recruitment, thought to be the result of a positive relationship between winter days below freezing and pond depth during the following summer (Butler *et al.* 2017).

4.2.3 Sea level rise

Sea level rise is predicted to cause habitat loss, particularly at stopover sites along the migratory routes and wintering grounds **(high confidence)**.

The extent of habitat loss varies between species but has been predicted for a wide range of wading birds (Mustin *et al.* 2007; Aiello-Lammens *et al.* 2011; Convertino *et al.* 2011; Iwamura *et al.* 2013; Galbraith *et al.* 2014; Iwamura *et al.* 2014; Ma *et al.* 2014) and migratory waterfowl (Clausen & Clausen 2014; Wikramanayake *et al.* 2020; Livolsi *et al.* 2021; Moon *et al.* 2021). As an example, earlier arriving Semipalmated Sandpipers at a migration stopover site in Nova Scotia experienced higher tides which resulted in higher energy expenditure and a longer stopover duration. The authors suggest that sea level rise is therefore likely to increase the energetic costs of stopovers as extreme tidal amplitudes increase in frequency (Mann *et al.* 2017). Loss of habitat in individual estuaries can have disproportional population impacts through reductions in network connectivity, since such sites tend to form key stopover areas for long-distance migratory shorebirds. For example, in the East Asian-Australian Flyway, a 23-40% loss of habitat as a result of inundation can reduce bird population flows by over 70% (Iwamura *et al.* 2013).

Anthropogenic barriers to landward expansions of coastal habitats, such as sea walls, exacerbate the effects of sea level rise on available habitat (Ma *et al.* 2014; Moon *et al.* 2021).

4.3 Adaptations and responses

4.3.1 Distribution and range shifts

Poleward and elevational range shifts have been observed and are predicted to intensify throughout a wide range of wetland and coastal bird species **(high confidence)**.

As water is crucial for providing food and protection from predation for dabbling and diving ducks, temperature is a key driver of their winter distribution (Schummer *et al.* 2010). Wintering European waterbird abundances and distributions are already shifting in response to warming (Johnston *et al.* 2013), with particular shifts northwards and eastwards towards the breeding grounds (Maclean *et al.* 2008; Lehikoinen *et al.* 2013; Pavón-Jordán *et al.* 2020).

Similarly, long-term shifts in European wintering duck populations have mostly been in northward and eastward directions or into regions previously considered too cold (Musil *et al.* 2011; Ekroos *et al.* 2012; Guillemain *et al.* 2013). Waterfowl with distributions that already occupy the northern edge of the continent are expected to experience range contractions (Guillemain *et al.* 2013).

Climate change appears to be affecting several endangered wading bird species, which will need to be accounted for when formulating conservation management plans targeted at currently small populations. Black-necked Cranes on the Qinghai-Tibetan plateau are expected to experience an expanding range, of varying degrees depending on the climate scenario, with movements particularly to the northwest and higher elevation (Li *et al.* 2022). Similarly, the distribution of the Red-crowned Crane is predicted to shift poleward, moving away from almost all of its current breeding range in the next century; this shift will mean the country containing the greatest proportion of the population will change from China to Russia (Liu *et al.* 2020). The wintering range of the Black-faced Spoonbill is predicted to increase in area in addition to shifting polewards (Hu *et al.* 2010).

Climate change is projected to reduce the suitability of 58% of critical sites for waterbirds within Africa-Eurasia, with those in Africa and the Middle East, where protection is least effective, most threatened (Breiner *et al.* 2021). The most vulnerable species are dispersive species within the Afro-tropical realm and Arctic breeding shorebirds (Nagy *et al.* 2021). Projected improvements in passage and wintering conditions are likely to support the northwards and eastwards expansion of non-breeding ranges across Eurasia, particularly into Eastern Europe, Scandinavia, Russia and Kazakhstan (Breiner *et al.* 2021; Nagy *et al.* 2021).

4.3.2 Changes in migratory route

Waterbird species vary in their capacity to alter migratory routes. Shorebirds seem highly site faithful, with changes only coming about as young birds learn new routes, whilst adult birds of other waterbird species appear able to occupy new wintering areas **(low confidence)**.

The establishment of new wintering sites with more favourable conditions and closer to the breeding grounds has occurred in Whooping Cranes, a behavioural change enabled by older birds, highlighting the importance of age structure within populations for allowing adaptive responses to change (Teitelbaum *et al.* 2016). In Pink-footed Geese, colonisation of new breeding grounds in response to warming temperatures was enabled by cultural transmission within and between species (Madsen *et al.* 2023). Lesser Snow Geese also change their breeding grounds in response to declining resources in their traditional breeding grounds, and body condition and juvenile survival are higher in newly colonised areas (Aubry *et al.* 2013). In contrast, for Icelandic Black-tailed Godwits, adults remain highly site faithful and new areas (which have tended to be closer to the breeding grounds) have been settled by young birds (Gunnarsson *et al.* 2005).

4.3.3 Timing of migration and breeding

The timing of migration and breeding is most often advancing in response to warmer temperatures, with generally positive impacts on breeding success **(high confidence)**.

Changes in the timing of arrival tend to be much better documented than the timing of departure, although it should be noted that such work often concentrates on the arrival of the earliest individuals rather than the median across the population, which may show different patterns, for example being confounded by population trend (Miller-Rushing *et al.* 2008). Later departure (Stirnemann *et al.* 2012; Orellana-Macías *et al.* 2020) and earlier arrival (Vähätalo *et al.* 2004) at the breeding grounds have been documented for European waterfowl in response to the decreasing harshness of winter. Similarly, White Storks arrive earlier in western Poland when March is warmer (Tobolka *et al.* 2015).

In a study of Danish breeding shorebird species, there were phenological responses to the North Atlantic Oscillation (NAO), temperature and precipitation, and the authors conclude that spring arrival can respond to climate in short-, medium- and long-distance migrants, but not all long-distance species are advancing the start of their respective breeding seasons (Meltofte *et al.* 2018).

The initiation of breeding in six Nearctic wading bird species was correlated with the timing of snowmelt, and the time of snowmelt affected the extent of phenological mismatch between the breeding birds and their invertebrate prey, suggesting wading birds may be vulnerable to negative consequences of mismatch under climate change (Kwon *et al.* 2019).

The timing of spring migration is not related to the climatic conditions at the breeding grounds for American White Pelican (King *et al.* 2017). Great White Pelicans have not advanced their average timing of breeding, but have advanced the endpoint, thereby reducing the duration of their breeding season (Doxa *et al.* 2012).

5 Aves: Raptors

5.1 Overview of migration patterns and distributions

Taxonomically, raptors fall into three orders: Cathartiformes (New World vultures); Accipitriformes (hawks, eagles and Old World vultures); and Falconiformes (falcons). All species in these orders are listed on the Appendices of the CMS (with the exception of the anomalous Secretary Bird). Many are considered as part of the Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia, which also includes 12 species of migratory owl. Raptors range from relatively sedentary to highly migratory. The larger species (vultures, eagles, some hawks) in particular use thermal updrafts to assist their migration, and migration routes can become quite narrow as a result, especially where sea crossings are involved (for example, most raptors cross the Mediterranean at either its eastern (Bosporus) or western (Gibraltar) extremity, resulting in large concentrations of birds).

Raptors face a wide range of threats, including agricultural practices (e.g. Sánchez Zapata *et al.* 2003), hunting and the prevalence of toxic chemicals, but climate change has largely not been seen as a widespread conservation issue to date (McClure *et al.* 2018), with the most widely documented effects being on distribution and timing of migration (Martínez-Ruiz *et al.* 2023). Although some have undergone large-scale population recoveries in recent years, a substantial number are threatened with extinction.

5.2 Climate change impacts

5.2.1 Altered patterns of precipitation

Changes in precipitation can affect breeding success, although the direction of the effect varies depending on the general climate and habitat the birds breed in. Rainfall tends to have a positive effect on tropical breeding raptor populations through impacts on prey abundance **(medium confidence)***, whilst at higher latitudes, more negative responses to precipitation are likely due to chilling and reduced foraging opportunities* **(medium confidence)**.

A wide range of species show negative impacts from heavy rain when the semi-precocial chicks are young, although these effects are particularly apparent at northern latitudes (Pearce-Higgins & Green 2014). There is a combined impact of chilling of chicks and reduced foraging opportunities in wet weather that, alongside heavy rainfall, has a negative impact on raptor breeding success in the tropics – for example, monsoon conditions (Senapathi *et al.* 2011).

In contrast, breeding in Wedge-tailed Eagles in Australia is positively affected by rainfall in arid habitats, whilst rainfall has no effect in mesic regions. The productivity of nests is also substantially lower in the arid zone which may put the population at risk with the increasing frequency of extreme weather events (Cherriman *et al.* 2022).

Rainfall tends to have positive effects on tropical breeding raptor populations, although these are primarily associated with lagged impacts during the following year rather than direct impacts (Pearce-Higgins & Green 2014). Rainfall has a positive impact on vegetation growth and the abundance of prey species, as shown for larger raptors in the Kalahari (Krüger *et al.* 2002), the Aplomado Falcon in Mexico (Macias-Duarte *et al.* 2004) and kestrels in the Mediterranean (e.g. Fargallo *et al.* 2009). In such dryland systems, El Niño heavy rainfall events can stimulate rapid vegetation growth and rodent population increases, leading to a flush of food for owls and raptors, which then contributes to a decline in rodent populations alongside a return to dry conditions (Lima *et al.* 2001).

Higher rainfall in the Sahel (the wintering grounds), particularly when paired with high breeding success, had a positive effect on adult survival in Montagu's Harrier, which is expected to imply higher prey availability over winter (Millon *et al.* 2019). Similarly, there was a positive correlation between adult survival and rainfall in the Sahel for Eurasian Scops Owls that breed in France (Barbraud *et al.* 2022).

5.2.2 Increased temperatures

The effects of temperature change appear relatively weak, with no strong impact of temperature upon breeding success **(low confidence)**.

Increased spring temperatures are associated with an increase in breeding success in Switzerland's Red Kite population (Nägeli *et al.* 2021).

Higher temperatures were associated with decreased hunting frequency but were not found to affect hunting success in Snowy Owls. The authors suggest this may imply they are better able to meet their metabolic demands with warmer temperatures; snow depth did not affect hunting frequency or success (Winter & Shields 2021).

Lower adult survival was associated with cooler and drier years for Little Owls in the Netherlands (Le Gouar *et al.* 2011).

Survival for Peregrine Falcons breeding in Alaska was higher in years with earlier snowmelt, milder winters and warmer breeding seasons (Bruggeman *et al.* 2015).

5.3 Adaptations and responses

5.3.1 Timing of migration and breeding

The timing of migration and onset of breeding responds to temperature and precipitation, though responses vary among species **(medium confidence)**.

Arctic Peregrine Falcons arrive back in Alaska faster in years with earlier snowmelt/milder winters (Bruggeman *et al.* 2015).

Golden Eagles in north-eastern North America have been found to delay spring migration and advance autumn migration in response to warmer temperatures, reducing the duration of time spent on the breeding grounds and contrasting with the most common results regarding shifts in the timing of migration (Maynard *et al.* 2022).

The timing of autumn migration is being delayed as temperatures increase, leading to the potential for longer breeding seasons, in both Europe (Jaffré *et al.* 2013) and North America (Buskirk 2012).

5.3.2 Distribution and range shifts

Changes in temperature and precipitation are expected to influence species distribution ranges, with some current evidence of range losses **(medium confidence)**.

Increasing summer temperatures and precipitation are thought to drive the absence of Red Kites in regions of Spain (Seoane *et al.* 2003), though climatic parameters only weakly affect their distribution in Germany at the core of their range. The effects of shifting climatic conditions across Europe on reproduction may influence population declines at the south of their range (Mattsson *et al.* 2022).

It is predicted that there will be substantial range contractions on both the breeding and wintering grounds for the Oriental Honey Buzzard, which will increase the distance required for migration under all climate change scenarios (Condro *et al.* 2022).

For vulture species in the Gangetic-Thar-Deccan region of India, environmental factors such as land use and direct anthropogenic impacts are estimated to have the greatest influence on current distribution, but climatic variables such as temperature and precipitation are predicted to be the greatest determinant as climate change progresses (Jha & Jha 2021).

6 Aves: Afro-Palearctic migratory passerines

6.1 Overview of migration patterns and distributions

Every year, in the order of 2 billion birds migrate between Europe and Africa in a huge transfer of ecosystem resources (Hahn *et al.* 2009). About three-quarters of these individuals are from 16 species and 95% are passerines, particularly from the Muscicapidae/Sylviidae group of families, with eight individual families listed in their entirety on the Appendices of the CMS (Cisticolidae, Acrocephalidae, Locustellidae, Phylloscopidae, Sylviidae, Turdidae, Muscicapidae and Motacillidae). These species exhibit a range of migratory schedules, both between and within species, with some individuals being relatively sedentary, while others migrate long distances. Leapfrog migration is common, with northern breeding populations migrating to more southerly locations for the boreal winter than southern breeding populations.

Threats to these species come mainly from habitat loss and alteration and, despite widespread population responses to climate change (Pearce-Higgins & Crick 2019), just 15 out of 103 studies have found demographic parameters to be directly affected by climatic variables, suggesting limited evidence for the impact of climate change compared to that of anthropogenic habitat/land use changes (Vickery *et al.* 2014, 2023). Climate change appears a more important driver of change on the breeding grounds of short-distance migrants, but land cover change more so on the wintering grounds for long-distance migrants (Howard *et al.* 2020).

6.2 Climate change impacts

6.2.1 Alteration in patterns of precipitation

Annual variation in the survival and abundance of long-distance migratory passerines, especially those that spend the boreal winter in African drylands (such as the Sahel), tends to be most strongly linked (positively) to variation in rainfall there **(high confidence)**.

Long-term changes in the abundance of migrants that winter in the Sahel match long-term rainfall trends, whilst annual fluctuations also correlate with rainfall levels (Newson *et al.* 2009; Pearce-Higgins & Green 2014). This is driven by rainfall during the wet season (May – October) influencing the carrying capacity of the region during the subsequent winter (Baillie & Peach 1992), either by determining the extent and duration of wetland habitats for wetland associated species such as Sedge Warblers and Sand Martins (Zwarts *et al.* 2012), or by stimulating vegetation growth, increasing the abundance of fruit and invertebrate prey (Schaub *et al.* 2005). There is some evidence that these conditions can carry over to impact the timing of breeding (and in some species, clutch size), although the magnitude of these effects is relatively small (Ockendon *et al.* 2014).

The overwinter survival rates of Nearctic migrants fluctuate in response to rainfall in the Caribbean (Sillett *et al.* 2000; Mazerolle *et al.* 2005), although the evidence for such effects is from fewer species than for Afro-Palearctic migrants. There is also evidence for carry-over effects of overwintering conditions in the tropics impacting on the timing of arrival back to the breeding grounds (Studds & Mara 2005), and subsequent return rates of female American Redstarts (Studds & Mara 2007).

Heavy rainfall during critical periods may negatively impact migrant survival rates, as shown for Barn Swallows (Møller 1989) and Alpine Swifts (Robinson *et al.* 2020). Such effects may be most likely to occur close to or during migration periods (Stokke *et al.* 2005). Weather conditions on migration may also carry over to impact the timing of breeding (Finch *et al.* 2014).

6.2.2 Increases in temperature

Increased temperatures generally promote an abundance of insect prey, which are the primary source of food in the breeding season (less so in the boreal, winter months), and often results in higher breeding success if temperatures are not too extreme **(medium confidence)**.

Food availability on the breeding grounds is a key driver of breeding success, and is often linked to temperature through its effect on insect development. This means that the abundance of invertebrate prey can strongly impact the breeding success of migratory passerines. Given the strong links between the weather and invertebrate populations, climate change has the potential to impact migratory bird productivity through impacts on their invertebrate prey (Pearce-Higgins & Morris 2022). For example, the abundance of aerial insects is positively correlated with the survival of Barn Swallow chicks (Martay *et al.* 2023), and the productivity of Black-throated Blue Warblers is linked to the effects of weather on caterpillar abundance (Sillett *et al.* 2000). Long-term declines in the abundance of key invertebrate groups, such as moths, partly driven by climate change (Fox 2013; Martay *et al.* 2017), may therefore have contributed to declining long-distance migrant populations across Europe.

High temperatures have also been directly linked to negative impacts on birds. High temperatures reduce Barn Swallow chick growth (Facey *et al.* 2020), while the risk of overheating reduced chick provisioning rates at high temperatures for an American migratory passerine, the Tree Swallow (Tapper *et al.* 2020). High temperatures are linked to increased mortality in Great Reed Warblers, though their reproduction has been benefiting from improved rearing conditions (Schaefer *et al.* 2006).

6.2.3 Timing of spring peaks in prey abundance

Increased temperatures in the spring can lead to earlier insect emergence, and hence asynchrony with the timing of breeding **(low confidence)**.

The spring caterpillar peak in temperate deciduous woodlands provides a pronounced pulse of food availability in spring, utilised by a range of passerines, both migratory and resident, whilst rearing offspring. Some evidence suggests that asynchronous timing of spring arrival or breeding in birds relative to this caterpillar peak is detrimental to breeding success (Both *et al.* 2006) and asynchrony increases with temperature (Burgess *et al.* 2018; Franks *et al.* 2018). However, while there is a substantial amount of evidence for temporal asynchrony in the timing of breeding with respect to the prey base, evidence for population impacts is generally lacking and even in the two best studied species, one of which is the migratory Pied Flycatcher, only some populations seem affected (Franks *et al.* 2018; Samplonius *et al.* 2021; Nater *et al.* 2023). The ability to adapt to such changes may also depend on the cues that trigger migration – if these are uncorrelated with conditions in the breeding range, departure times may not change, reducing the flexibility of populations to respond (Davies *et al.* 2023).

6.3 Adaptations and responses

6.3.1 Timing of migration and breeding

Temperature, in particular, positively influences the timing of breeding and spring arrival, although these effects can be modified by more local weather conditions en route **(high confidence)**.

Earlier arrival, and breeding, of migratory passerines in Europe is one of the most well documented impacts of climate change (Pearce-Higgins & Green 2014; Haest *et al.* 2020), although not all species are doing so (Davies *et al.* 2023).

As migratory birds often breed later than their resident competitors, they are thought to be at higher risk of the detrimental effects of being mistimed. However, robust evidence of widespread demographic effects is lacking, despite vast amounts of research among a small number of resident (Great Tit) and migratory (Pied Flycatcher) species (Samplonius *et al.* 2021).

6.3.2 Distribution and range shifts

Migratory passerines are shifting, or expected to shift, poleward in both their breeding and wintering grounds, though the Sahara presents a barrier for those north of the Equator in their African wintering grounds **(medium confidence)**.

In northern Europe, the range edges of resident bird species have shifted further north than the range edges of long-distance migrants (Hällfors *et al.* 2023). Species with narrow climatic niches have shifted their ranges more than those with wide climatic niches (Hällfors *et al.* 2023). For some migratory habitat specialists, northward range shifts are facilitated by northwards habitat expansions. For example, Reed Warblers, which breed primarily in reedbeds, and whose productivity is related to the rate of growth of reeds (which is often constrained by lower than optimum temperatures), are expanding their range northwards as temperatures increase (Eglington *et al.* 2015). More generally, climate suitability alone is a relatively poor predictor of observed range shifts; land use and the availability of source populations also need to be accounted for (Howard *et al.* 2020, 2023).

It has been predicted that 37 of the 64 long-distance Afro-Palearctic migratory passerines studied will experience a winter range reduction by 2100; those wintering in the southern hemisphere will shift poleward, while those wintering north of the Equator will shift east due to being limited to the north by the Sahara (Barbet-Massin *et al.* 2009).

Documented changes in migratory routes are scarce, though are likely, initially at least, to involve only part of the population (as has been seen in shorebirds and waterfowl), which may be difficult to detect. However, new range areas can be established as (boreal winter) temperatures have increased (Dufour *et al.* 2021).

7 Aves: South American grassland birds

7.1 Overview of migration patterns and distributions

There are 288 grassland bird species in South America as a whole, 16% of which are migratory, including those that migrate to North America (Chesser 1994; Vickery *et al.* 1999). However, the proportion of migratory species (30%) within the temperate grasslands of south-eastern South America is higher (Azpiroz *et al.* 2012; Jahn *et al.* 2017). Of these species which migrate within South America, six are classified as ‘Globally Threatened’ and a further six as ‘Near Threatened’. A range of migration strategies are observed, with species migrating either between temperate and tropical ecosystems or solely within tropical ecosystems, and some movements are more nomadic, tracking the availability of grass seeds (e.g. Pearce-Higgins 1996). Research on these species directly is limited, so we refer to species in other ecosystems to make inferences.

7.2 Climate change impacts

7.2.1 Alteration in patterns of precipitation

Tropical systems tend to be rainfall-limited rather than temperature-limited, and therefore the strongest climate change impacts on tropical migratory passerines are likely to be through changes in precipitation patterns, which are mixed, depending on location **(low confidence)**.

In semi-arid systems, rainfall has a positive impact on the breeding success of a range of North American sparrows (Rotenberry & Wiens 1991; Chase *et al.* 2005), likely mediated through the effects on vegetation growth and invertebrate abundance. In wet years, a greater number of nests are produced, increasing the length of the breeding season (Chase *et al.* 2005; Dean *et al.* 2009). There is a similar relationship for the Little Bustard in Spain (Delgado *et al.* 2009).

In similar ecosystems in Africa, studies of the granivorous Red-billed Quelea support the importance of precipitation in driving grassland bird populations. Rainfall stimulates new grass growth and rapid increases in invertebrate (caterpillar and Orthoptera nymphs) abundance, leading the birds to breed. As soon as the young fledge, the adults move along an advancing rain front to breed again. Six weeks after the rainfall ceases across the species’ range and the birds have stopped breeding, they nomadically track grass seed availability and move ahead of the next rain front which causes the remaining seeds to germinate and the whole cycle starts again (Ward 1971; Cheke *et al.* 2007).

7.2.2 Increased temperatures

There is growing evidence that extreme heat can have negative impacts on tropical species through sudden and catastrophic mortality. This does not appear to result from drought, but from physiological responses to heat stress **(low confidence)**.

Recent heatwaves have led to significant mortality in desert species such as Budgerigars, Zebra Finches and Carnaby's Black Cockatoos (Low 2011; Saunders *et al.* 2011; McKechnie *et al.* 2012; Albright *et al.* 2017).

Studies from similar habitats in Africa indicate that high temperatures mean individuals spend more time keeping cool, reducing foraging opportunities and impacting breeding success in a range of bird species (Bladon *et al.* 2019; Bourne *et al.* 2020; van de Ven *et al.* 2020). It is possible that this could also be an issue for South American passerines depending on the magnitude of future warming, but we are not aware of any research on this.

Even where the risks of mass mortality are low, chronic, sublethal impacts of rising temperatures are projected to cause population declines (e.g. Kalahari Desert: Conradie *et al.* 2019).

7.3 Adaptations and responses

7.3.1 Timing of migration and breeding

Changes in phenology are likely, but limited evidence suggests that many grassland birds are not shifting their breeding phenology enough to keep pace with other environmental changes **(low confidence)**.

Changes in the timing of migration and breeding in response to climate change is commonly noted across migratory bird species. In North America, grassland migrant bird species have not advanced their nesting timing at the same pace as phenological advances in agricultural practices such as hay harvesting, which decreases annual productivity (McGowan *et al.* 2021)

7.3.2 Distribution and range shifts

Suitable climatic conditions for South American grassland birds are shifting poleward. However, the extent to which these species will shift their ranges in response to a changing climate will be affected by suitable habitat and dispersal abilities, and is largely unknown **(low confidence)**.

Climate-driven range shifts are predicted for South American grassland bird species (Marini *et al.* 2009). However, the extent to which species will be able to shift their range to suitable climates will depend on the availability of suitable habitat and their dispersal ability (Marini *et al.* 2009). Further research is required here.

8 Mammalia: Terrestrial mammals

8.1 Overview of migration patterns and distributions

The CMS Appendices list three ape species (Eastern and Western Gorillas, and Chimpanzees), which are 'technical' migrants, crossing Range State boundaries but only moving relatively short distances; one bear species (Gobi Bear); three elephant species; six carnivores; and 32 ungulates (14 African, 16 Asian and two South American species). Importantly, there are a number of widespread migratory terrestrial mammals that occupy temperate and boreal habitats which are not listed in the CMS Appendices, such as Caribou, Elk and Bison. Literature for the impacts of climate change on these species has not been reviewed unless the impacts were more general to other similar species that are on the CMS Appendices. For most terrestrial mammals, migration is driven by availability of food or water, often linked to rainfall which affects primary productivity (e.g. ungulates: Kauffman *et al.* 2021; African Elephants: Owen-Smith 2014).

Habitat loss due to increasing human activities is the biggest threat to most migratory terrestrial mammals, with a second major threat being the increasing barriers that prevent ungulates from migrating to follow seasonal food resources, such as increases in human infrastructure, fences and loss of habitat corridors. Illegal hunting is also an important threat for some species.

8.2 Climate change impacts

8.2.1 Alteration in patterns of precipitation

Changes in rainfall patterns are likely to have a significant impact on many terrestrial mammal populations, particularly in the tropics given the strong links between rainfall, primary productivity and food resources **(high confidence)**.

Across Africa, rainfall declines are predicted over much of the Sahel region, northern Africa and western equatorial Africa, but increases over parts of eastern and southern Africa (Martínez-Freiría *et al.* 2016; Bush *et al.* 2020), and similarly over the Middle East (Lelieveld *et al.* 2012). The distribution and abundance of herbivores, and thus carnivores, in the African savanna is generally closely linked to primary productivity, determined by patterns in rainfall (Owen-Smith 2014; Mukhopadhyay *et al.* 2019) (see also the case study on the African savanna on page 74). Declines in rainfall are likely to cause declines in many terrestrial mammal populations due to the link between rainfall and primary productivity and thus food availability for herbivores (e.g. ungulates: Bastille-Rousseau *et al.* 2016; Mukhopadhyay *et al.* 2019; Giraffe: Owen-Smith *et al.* 2005; Ogutu *et al.* 2008; Duncan *et al.* 2012; Martínez-Freiría *et al.* 2016; Grevy's Zebra: Kigen *et al.* 2013;

Goitered Gazelle: Kaky *et al.* 2023; elephants: Boult *et al.* 2019; Dejene *et al.* 2021). These impacts will be strongest at low latitudes (Pearce-Higgins *et al.* 2015b).

In turn, this has the potential for impacts on carnivore populations that prey on such species, with a positive correlation between carnivore population size and rainfall (Lion: Celesia *et al*. 2010; Leopard: Rodriguez-Recio *et al*. 2022; Zeng *et al*. 2022; Jaguar: Sanderson *et al*. 2022).

Some great ape populations are also positively affected by rainfall: areas of high annual rainfall and high seasonal variation in rainfall generally support high ape populations (Carvalho *et al.* 2021). However, the impacts of variation in rainfall are minor compared to the impact of human disturbance and temperature (Ginath Yuh *et al.* 2020; Carvalho *et al.* 2021).

Conversely, for some species, increases in rainfall are associated with negative impacts. Wild Dog pup survival declines in wet periods (Buettner *et al.* 2007) and gorillas are more stressed in months with high rainfall (Eckardt *et al.* 2019).

8.2.2 Increased temperatures

Rising temperatures can cause heat stress, impacting productivity, and are generally linked to population declines **(high confidence)***, but may benefit some populations in cold environments by reducing the risk of higher mortality linked to severe cold* **(low confidence)**.

Terrestrial mammal species are generally adapted to a species-specific temperature range (Zhou *et al.* 2022; e.g. Goitered Gazelle: Kaky *et al.* 2023; Grevy's Zebra: Kigen *et al.* 2013; Asian Elephant: Kanagaraj *et al.* 2019; African Elephant: Mpakairi *et al.* 2020; Dejene *et al.* 2021; Chimpanzee: Wessling *et al.* 2020). Temperature increases are predicted globally, which can increase terrestrial mammal stress (gorilla: Eckardt *et al.* 2019), reduce reproductive success (Wild Dog: Woodroffe *et al.* 2017; McNutt *et al.* 2019; Abrahms *et al.* 2022) and decrease population size (e.g. Giraffe: Martínez-Freiría *et al.* 2016; Huemul: Riquelme *et al.* 2020; great apes: Carvalho *et al.* 2021; ungulates: Luo *et al.* 2015).

This can be due to difficulties thermo-regulating (African Elephant: Dunkin *et al.* 2013; Pontzer *et al.* 2020; ungulates: Semenzato *et al.* 2021; Wild Dog: Woodroffe *et al.* 2017; Rabaiotti *et al.* 2019) and because of the impacts on the availability of food plant species (e.g. Gobi Bear: Qin *et al.* 2020). Behavioural adaptations can mitigate some temperature increase, such as foraging earlier and later in the day, and altitudinal shifts (e.g. ungulates: Semenzato *et al.* 2021).

Higher temperatures can improve hunting success for some carnivores as prey species struggle to thermoregulate when being hunted (Wild Dog: Creel *et al.* 2016).

There are some instances where warming climates could benefit terrestrial mammals. For example, in colder regions across Asia, very severe winters can reduce fecundity and cause mass mortality events for species such as the Saiga Antelope (Coulson *et al.* 2000) and Przewalski's Horse (Kaczensky *et al.* 2011). Any lessening in the frequency of extreme winters may be beneficial for such species. However, while average temperatures will increase, an increase in extreme weather events is also predicted, so it is uncertain whether winter mortality will increase or decrease.

8.2.3 Extreme weather events

Where droughts are projected to increase in severity and frequency, they are likely to negatively impact populations of migratory mammals. Heavy rain and flooding can cause localised impacts, but generally appear to have weak population impacts **(medium confidence)**.

Floods may increase in frequency and severity in some areas and can increase carnivore mortality as habitat is lost to the flood (Lion cub mortality: Kotze *et al.* 2021), while other carnivore populations are relatively resilient to floods (Jaguar: Burrage *et al.* 2020).

Rainfall declines around the Sahara and the Middle East are likely to lead to increased mortality and local carnivore extinctions (Leopards: Khorozyan *et al.* 2015; Lions: Cooper *et al.* 2021), although some carnivore populations are fairly resilient to droughts (Jaguar: Burrage *et al.* 2020; Lions: Ferreira *et al.* 2021).

Increased levels of drought have been implicated in a rise in the prevalence of mass mortality events. For example, over 300 African Elephants have recently died in Botswana as a result of biotoxins produced by cyanobacteria in drinking water, triggered by extremes of hot, dry weather (Wang *et al.* 2021).

Droughts have also been linked to increases in parasite loads in African Elephants and Lions, as more individuals rely on limited water resources (Munson *et al.* 2008; Obanda *et al.* 2011; Titcomb *et al.* 2021) and an increased prevalence of infectious diseases in Asian Elephants (Mumby *et al.* 2013).

Droughts are also linked to increasing human-wildlife conflicts, for example for African and Asian Elephants, which can lead to increased mortality (Mariki *et al.* 2015; Mukeka *et al.* 2019; Ramesh *et al.* 2022).

8.2.4 Habitat loss

The combined changes in rainfall and temperatures are predicted to cause habitat loss in many species, generally due to reductions in food availability. For some species, particularly those with ranges that are heavily restricted by human activities and land use, direct climate change impacts on distribution may be hard to discern **(medium confidence)**.

Climate change is predicted to cause severe habitat loss for ungulates on the Tibetan Plateau (Luo *et al.* 2015), Iranian Leopards (Sanei *et al.* 2011; Ebrahimi *et al.* 2017; Ashrafzadeh *et al.* 2019) and many great ape populations (Lehmann *et al.* 2010; Junker *et al.* 2012; Sesink Clee *et al.* 2015). Brown bears, the species that Gobi Bears are a subspecies of, are also predicted to lose habitat due to climate change (Su *et al.* 2018; Penteriani *et al.* 2019; Dar *et al.* 2021; Ara *et al.* 2022).

Lion ranges are predicted to be relatively stable, but losses are predicted for southern Africa and West Africa (Peterson *et al.* 2014).

In some countries, suitable Asian Elephant habitat is predicted to decline by the end of the century or earlier due to climate change (Alamgir *et al.* 2015; Li *et al.* 2019). However, other studies have predicted climate change to have a minimal impact on Asian Elephants (Kanagaraj *et al.* 2019; Yang *et al.* 2022b).

The effect of climate change on habitat suitability for African Elephants is also unclear. One study predicted only small effects, with a slight improvement in climatic suitability in southern and eastern Africa, and a reduction in western Africa and northern portions of central Africa (Zacarias & Loyola 2018). However, another study predicted a 40% temperature-driven habitat loss in an area in southeast Africa (Mpakairi *et al.* 2020).

More generally, where habitat is lost due to climate change, interactions between migratory terrestrial mammals, humans and livestock are likely to increase, which will increase the likelihood of disease spillover between them (e.g. great apes: Patz *et al.* 2000; Wild Dog: Rabaiotti *et al.* 2021).

8.3 Adaptations and responses

8.3.1 Distribution and range shifts

Polewards range shifts have been observed and predicted. However, the ability of terrestrial mammals to shift their ranges in response to climate change is often unknown and may be restricted by a lack of suitable habitat in areas with a suitable climate, or by barriers that prevent range shifts **(medium confidence)**.

Some species have already shifted their ranges polewards or to increasing altitudes (Bai *et al.* 2022), while polewards range shifts are predicted for others (e.g. Chimpanzees: Wessling *et al.* 2020; Asian Elephants: Kitratporn & Takeuchi 2022). However, the ability of species to shift their ranges in response to climate change is often unknown; for example, the Gobi Bear's plant food species are predicted to shift range, but the ability of Gobi Bears to follow that shift is unknown (Qin *et al.* 2020). Any range shifts are likely to increase human-wildlife conflicts (Asian Elephants: Kitratporn & Takeuchi 2022) and may be prevented by a lack of corridors or suitable habitat. For many migratory terrestrial mammals, maintaining and creating protected areas and corridors is vital for conserving these species under a changing climate (e.g. Bears: Su *et al.* 2018; Mukherjee *et al.* 2021; Ashrafzadeh *et al.* 2022; Dar *et al.* 2022; Asian Elephant: Li *et al.* 2019; Leopard: Liang *et al.* 2022).

8.3.2 Timing of migration and breeding

Some changes in birthing and migration phenology have been seen in migratory mammals, but cues for when to breed may be maladaptive **(low confidence)**.

For example, Wild Dogs have delayed parturition by 7 days per decade, but this has led to increased temperatures during denning periods, which reduces pup survival (McNutt *et al.* 2019; Abrahms *et al.* 2022)

9 Mammalia: Bats

9.1 Overview of migration patterns and distributions

Bats are the second largest group of mammals, with over 1,400 species described, but the biology of most is poorly known. There are at least 87 species of migratory bats (Krauel & McMracken 2013), of which 58 species are listed on the CMS Appendices. Bat migration is generally shorter than bird migration, with maximum distances of under 2,000 km (Fleming & Eby 2003). Migratory bat species can generally be divided into those with short-distance migration (less than 800 km) to hibernacula (Hutterer *et al.* 2005), and long-distance migrants (less than 1,500 km) migrating to winter in milder climates where food is available (Fleming & Eby 2003). Short-distance migration (100 to 500 km) also occurs within temperate regions as bats move to and from hibernacula sites where they overwinter (Rodrigues & Palmeirim 2008). In tropical and subtropical regions, migration movements are generally in response to the availability of ephemeral food resources (Fleming & Eby 2003).

The main threats to bats include habitat loss, bushmeat hunting and climate change (which includes adaptation to climate change through wind turbines). The families Molossidae, Rhinolophidae and Vespertilionidae (representatives of all of which are listed on CMS Appendix II) have been identified as being among the most vulnerable bats to windfarm collisions (Zimmerling & Francis 2016; Thaxter *et al.* 2017). However, we know significantly less about bat population trends and threats than for other mammals and birds (Frick *et al.* 2020). Recent advances in passive acoustic monitoring of bats are enabling broad-scale bat monitoring schemes, so it is likely that our knowledge of bat population statuses and threats will improve (Frick *et al.* 2020).

9.2 Climate change impacts

9.2.1 Increased temperatures

Changes in temperature are likely to affect foraging efficiency and flight behaviour with uncertain consequences for populations **(low confidence)**. *Warming may also affect the abundance of key invertebrate prey in different and contrasting ways, with variable impacts on bat populations, depending on diet, taxa and climate change context* **(low confidence)**.

The impacts of temperature increases on bats is currently best described for changes in hibernation behaviour, but impacts on overall population status are not well understood. In the UK, increasing temperatures and decreasing precipitation in spring have had a positive effect on the population size of the Greater Horseshoe Bat (Froidevaux *et al.* 2017). It is also suggested that populations of both Greater and Lesser Horseshoe Bats in the UK have recovered over the past 20 years due to milder winters (Battersby 2005; Schofield 2008). Analyses of the impacts of climate changes on UK bat populations more generally suggested the potential for some negative impacts on some species, but noted these were inconclusive and inconsistent (Martay *et al.* 2017).

An overall increase in body size in female Bechstein's Bats with increased temperatures has advanced the onset of reproduction and increased mortality risk, causing a change in the generation time (Mundinger *et al.* 2022).

More frequent winter bat activity with increased temperatures may result in the potential disappearance of a hibernation period over the next 60-80 years on the Mediterranean coast (Mas *et al.* 2022). This study highlights the importance of conserving wetlands as one of the few available winter foraging habitats.

Temperature changes may alter foraging efficiency and flight behaviour in different ways among species. Temperature impacts the distance at which insects can be detected using echolocation, with differing effects depending on the frequency of the call; this suggests that global warming may alter foraging efficiency in different ways for species with different echolocation frequencies (Luo *et al.* 2014).

Heat dissipation and evaporative water loss in migratory and high-altitude flying bats are likely to increase with increasing temperatures and decreasing humidity. Drinking frequency increases with temperature and decreases with humidity (Adams & Hayes 2008); as such, changes in temperature and humidity are predicted to increase the frequency at which high-altitude flying bats return to the ground to drink or alter the aerial layers in which they can forage (Voigt *et al.* 2018).

Warmer temperatures and summer drought conditions may reduce the abundance of aerial insects, which are the primary food source for bats. The impacts of climate change on insect migrations are likely to indirectly affect migratory insectivorous bats, though the consequences are currently unknown (Voigt *et al.* 2018). More generally, large-scale declines in the biomass of aerial insects have been reported in Europe (e.g. Hallman *et al.* 2017), although the causes and even the extent of the decline are debated. Declines in moth populations in the UK may partly be attributed to warming (Martay *et al.* 2017), although trends in other aerial insects appear mixed (Martay *et al.* 2023). There is good evidence that summer drought will reduce the abundance of aerial insects with aquatic life-stages, such as many Diptera (Pearce-Higgins 2010; Pearce-Higgins & Morris 2022). However, the impacts of any changes in insect populations on bats are highly uncertain based on current knowledge.

9.2.2 Reduced water availability

Reduced water availability and drought can reduce breeding success, migration and competitive dynamics amongst species **(low confidence)**.

Breeding success decreases when water availability is low during lactation (Adams & Hayes 2008; Adams 2010). The effect of reduced surface water availability on breeding success as climate change progresses is predicted to negatively impact the population size of a North American species, Fringed Myotis (Hayes & Adams 2017).

Changes in water availability, paired with changes in heat dissipation and evaporative loss, are likely to have negative consequences for migratory bats as they require water along the migratory route (Popa-Lisseanu & Voigt 2009).

Reduction in the size of water sources is likely to negatively impact less manoeuvrable bat species as they are less able to drink efficiently (Hall *et al.* 2016); this is expected to provide a competitive advantage to more agile species.

9.2.3 Extreme weather events

The response of bat populations to extreme events is usually negative, either in terms of range contraction or population reduction **(medium confidence)**.

Extreme heat weather events can reduce survival and breeding success, particularly in flying foxes (*Pteropus* spp.), though responses differ among species. Heatwaves and drought in India cause mass die-offs in the Indian Flying Fox (Dey *et al.* 2015). Extreme heat (42°C) has also caused mortality of wild flying foxes in Australia; in 2002, over 3,500 individuals were killed in one day, and over 30,000 individual bats have been reported dead across 19 events from 1994 to 2007 (Welbergen *et al.* 2008). More recent mortalities have been even larger (Mo *et al.* 2021). Variation in the vulnerability of different *Pteropus* spp. may be linked to the thickness and depth of their fur (Ratnayake *et al.* 2021).

High temperatures may also impact other bat species. The breeding success of the Soprano Pipistrelle in the Mediterranean is reduced when available maternity roosts overheat due to extreme temperatures (Lourenço & Palmeirim 2004).

Cold-related mortality can also impact bats, and would be expected to reduce in a warming climate. During an extreme winter in Germany, two bat species, Daubenton's and Bechstein's Bats, experienced a substantial population crash (Fleischer *et al.* 2017; Reusch *et al.* 2019), whilst another, Natterer's Bat, only showed a small decline (Reusch *et al.* 2019).

9.3 Adaptations and responses

9.3.1 Distribution and range shifts

Range expansions and shifts towards higher latitudes have been observed in a few species and are predicted for many more **(medium confidence)**.

The distribution range of bat species is often heavily influenced by temperature, though precipitation can also have some impact (Lundy *et al.* 2010; Ancillotto *et al.* 2016). Range expansions and shifts towards higher latitudes have been observed in a few species, for example Kuhl's Pipistrelle (Sachanowicz *et al.* 2006; Ancillotto *et al.* 2016), Savi's Pipistrelle (Ancillotto *et al.* 2018), Nathusius' Pipistrelle (Lundy *et al.* 2010) and Brazilian Free-tailed Bat (McCracken *et al.* 2018), and are predicted for many more (Rebelo *et al.* 2010), although accurate knowledge of distributions is missing for many species. The disappearance of a species from regions within their historic distribution receives more support to date through predictive modelling rather than observed records (Arumoogum *et al.* 2019; Razgour *et al.* 2021; Festa *et al.* 2023).

The latitudinal shift of hibernacula in Noctule Bats is suggested to be the result of generational shifts to new locations, driven mostly by first-year males (Kravchenko *et al.* 2020).

Range shifts may have important consequences for trophic interactions, with both bottom-up and top-down impacts; for example, Greater Long-nosed Bats are an important pollinator of agave plants which are in turn a food source for the bats, however, the distribution overlap between them is predicted to reduce by 75% in the next 50 years (Gómez-Ruiz & Lacher 2019).

Increasing spring temperatures can variably affect the migratory behaviour and distribution of different species. For example, the thermal response of Myotis bats' downhill migration in the Rocky Mountains (following hibernation) varies among species; in some cold-adapted species, increased temperature correlates with reduced downhill migration (Adams 2018), indicating a temperature-driven shift in distribution.

9.3.2 Timing of migration

The timing of migration in bats is more affected by weather conditions, such as precipitation and wind, than temperature **(low confidence)**.

Some bat species are able to change the timing of migration in response to wind conditions and precipitation, though not all species show a response to environmental conditions. For example, the timing of spring migration has advanced by 16 days over 22 years in Brazilian Free-tailed Bats; this shift is predominantly driven by the wind conditions at stopover areas during the migration period and not by temperature. The autumn migration was also unaffected by temperature and driven more by precipitation levels (Stepanian & Wainwright 2018; Haest *et al.* 2021).

Photoperiod was the best predictor of migration timing for Natal Long-fingered Bats in South Africa, compared to a range of environmental variables, which may make them vulnerable to phenological mismatch as climate change progresses (Pretorius *et al.* 2020).

10 Mammalia: Marine mammals

10.1 Overview of migration patterns and distributions

There are 130 marine mammals, of which 90 are listed on the CMS Appendices. Marine mammals can be split into several broad groups:

- Pinnipeds – the seals, sea lions and walruses (six CMS species). Pinnipeds generally disperse from breeding grounds on land or ice to feeding waters, with less distinct summer and wintering grounds than other migratory marine mammals.
- Baleen whales – such as Bowhead, Blue, Grey, Fin, North Atlantic Right, Southern Right and Humpback Whales, of which 13 are CMS species. Most baleen whales undertake long seasonal migrations between tropical calving grounds in winter and high latitude (north or south) feeding grounds in summer (Learmonth *et al.* 2006).
- Toothed whales – including dolphins (32 CMS species), porpoises (seven CMS species) and other whales (25 CMS species). Dolphins and porpoises generally undertake shorter migrations between their summer and winter ranges, while Arctic species, such as Narwhal and Beluga, migrate seasonally to follow food resources and access breeding areas.
- Sirenians – encompassing the three manatee species and the Dugong. These are all CMS-listed species, and are mostly coastal species that undertake shorter distance migrations.
- Polar Bears – while mostly land- or ice-based, they are largely reliant on marine species as prey, hence their inclusion as marine mammals. Their migration is seasonal, following the sea ice.
- Otters – of which the two CMS species are coastal species that seasonally follow food resources. There is very little research on climate change impacts for migratory otters.

Whilst pinnipeds retain a link to land, most marine mammals are highly pelagic (i.e. live largely in open ocean), meaning they occur extensively in areas beyond national jurisdiction (Lascelles *et al.* 2014). They are distributed throughout the world's oceans and most are highly migratory, leading to large transfers of biomass between latitudes (see Part 3, section 4.7, of this review). They are highly dependent on patterns of marine productivity and their abundance is highest where marine primary productivity is high, for example around deepwater and coastal upwelling zones. Most are carnivorous, with species taking a range of prey, from amphipods to large fish and other marine mammals; sirenians are herbivorous.

Fifteen percent of marine mammals are currently classified as threatened (i.e. classified by the International Union for Conservation of Nature (IUCN) as Endangered or Vulnerable). They face a wide range of threats, including fishing, pollution and disturbance from human activities (which includes adaptation to climate change through marine renewables developments). Thirteen percent (65 of 480) of 'Level 1' threats (as defined by IUCN) to marine mammals are assigned to climate change or severe weather events (Lascelles *et al.* 2014).

10.2 Climate change impacts

10.2.1 Increased temperatures

Temperature increases are likely to have a major impact on marine mammal populations indirectly via changes in food availability **(high confidence)**.

Marine mammal distribution, abundance and breeding success are often closely linked to prey availability (e.g. prey declines are linked to population declines in South American Sea Lions: Baylis *et al.* 2015; and distribution of Minke and Killer Whales: Albrecht *et al.* 2021; Vogel *et al.* 2021). Temperature increases, causing reduced food availability, are linked to reductions in Humpback Whale abundance and breeding success (Frankel *et al.* 2022) and are predicted to reduce populations of Blue, Fin, Southern Right and Humpback Whales (Tulloch *et al.* 2019). In particular, population declines are predicted for these species at mid- and lower latitudes (Learmonth *et al.* 2006; Kaschner *et al.* 2011; Tulloch *et al.* 2019; Frankel *et al.* 2022).

Krill and other copepods are important for many baleen whales and marine mammals (e.g. timing of migration for Blue Whales: Szesciorka *et al.* 2020; distribution in Humpback, Bowhead and North Atlantic Right Whales: Keiper *et al.* 2005; Silber *et al.* 2017; breeding success in Southern Right Whales and Antarctic Fur Seals: Simmonds & Isaac 2007; Bestley *et al.* 2020). Increasing temperatures are generally linked to declining krill abundance (Simmonds & Isaac 2007; Tulloch *et al.* 2019), particularly in latitudes 50–60°S (Tulloch *et al.* 2019) as observed in the east Pacific (Szesciorka *et al.* 2020). Baleen whale populations are generally predicted to decline due to declines in krill abundance (Learmonth *et al.* 2006).

Temperature increases may have a direct impact on reproductive success and survival for some species, although this relationship may be mediated by unidentified factors such as prey availability. Examples include a strong relationship between Southern Right Whale calving success and temperature (Simmonds & Isaac 2007), and a link between warmer temperatures and low mortality in Bottlenose Dolphins observed in the northern Gulf of Mexico (Meager & Limpus 2014).

Marine mammals reliant on upwelling boundary currents (e.g. Rorqual Whales: López & Methion 2019) are likely to be particularly vulnerable to climate change (Nelms *et al.* 2021).

10.2.2 Reduced sea ice extent

Sea ice decline and increased variability in cover in response to climate change will generally negatively impact on population size for species associated with sea ice, and may accelerate the poleward range expansion in species associated with open water **(high confidence)**.

Sea ice declines are particularly detrimental to population sizes (Stirling & Parkinson 2006; Bromaghin *et al.* 2021), survival (Molnár *et al.* 2010, 2020), body condition (Derocher *et al.* 2004; Stirling & Parkinson 2006) and reproductive success (Peacock *et al.* 2011) of Polar Bears (see case study on page 76). Their main prey, seals, rely on sea ice for breeding, and so declines in (mostly non-migratory) seal populations due to sea ice retreat leads to a reduction in the area of suitable hunting habitat (Bromaghin *et al.* 2015), causing bears to undertake increasingly long migrations compromising their survival (Pagano & Williams 2021). Polar Bears are extremely vulnerable to climate change due to sea ice decline reducing hunting habitat. Many sub-populations are likely to become extinct over the next few decades (Castro de la Guardia *et al.* 2013). Some models predict almost complete extinction by 2100 (Hunter *et al.* 2010; Molnár *et al.* 2020).

Sea ice declines have a mixed impact on krill. Declines may increase primary productivity in some areas, increasing both food density and the seasonal availability of food for species that feed on krill (Simmonds & Isaac 2007; Laidre *et al.* 2008; Tulloch *et al.* 2019). This has positive impacts on some species (e.g. Arctic Bowhead Whale population growth and better body condition may be linked to low summer sea ice: Laidre *et al.* 2008; George *et al.* 2015). In contrast, in other areas, sea ice declines were linked to declines in abundance of krill (Truchon *et al.* 2013) and other prey species; for example, the density and distribution of Arctic Cod are predicted to decline due to sea ice reduction (Steiner *et al.* 2019).

Seal and sea lion species that are reliant on sea ice for breeding may be particularly vulnerable to climate change (Tynan & DeMaster 1997; Bestley *et al.* 2020). The Caspian and Grey Seals are the only CMS species that regularly breed on ice.

Sea ice declines may increase predation risk (Minke Whale declines have been partly linked to sea ice declines due to lack of shelter from predators: Risch *et al.* 2019). Ice entrapments for Beluga Whales and Narwhals may increase due to increasing variability in sea ice (Laidre *et al.* 2008).

Sea ice declines open the Arctic and Antarctic to migratory species earlier, leading to phenology shifts and greater use of polar regions by species that are less ice-adapted, such as Humpback, Fin, Minke, Grey, Blue, Pilot and Killer Whales, and Harbour Porpoises (Laidre *et al.* 2008; Moore & Huntington 2008; Bestley *et al.* 2020). Humpback Whale migration from Central and South America to the Antarctic peninsula has advanced by nearly 30 days in 30 years, and populations appear to be increasing (Avila *et al.* 2020). Earlier migration may lead to increased competition and predation for Arctic species (Laidre *et al.* 2008).

Increases in human activity in the Arctic enabled by sea ice loss may increase levels of toxic chemicals, pollution, boat strikes, noise pollution (which has been shown to alter migration in Bowhead Whales and other cetaceans), and fisheries interactions (entanglement in fishing gear is common) (Burek *et al.* 2008). Concentrations of persistent organic pollutants in samples taken from Polar Bears are increasing due to prolonged fasting periods (due to sea ice decline) and may be causing adverse health effects (Jenssen *et al.* 2015). On the other hand, traditional hunting of marine mammals is likely to reduce because of dangerous sea ice conditions.

Narwhals (Most Vulnerable), Beluga and Bowhead Whales are predicted to be particularly vulnerable to climate change due to decreasing habitat availability and increased competition from sub-Arctic species expanding their range northwards (Learmonth *et al.* 2006; Simmonds & Isaac 2007; Laidre *et al.* 2008; Moore 2008; Chambault *et al.* 2020; van Weelden *et al.* 2021). However, population declines in Arctic marine mammals have not been documented to date (Huntington *et al.* 2017). Arctic Bowhead Whale populations were increasing from 1978 to 2001 (some of which could reflect recovery from past over-harvesting) and had better body condition in low sea ice years (Laidre *et al.* 2008; George *et al.* 2015). There was some evidence that changes in Beluga Whale habitat selection can mitigate some effects of sea ice loss (Hauser *et al.* 2018).

10.2.3 Sea level rise

Sea level rise will reduce habitat availability for some coastal breeding seals **(medium confidence)**.

Seals that breed on coastal habitats will be particularly vulnerable to climate change as many coastal habitats are likely to be lost due to sea level rises (Simmonds & Isaac 2007).

10.2.4 Frequency of extreme weather events

An increase in storms and freshwater flooding can impact vulnerable coastal habitats, detrimentally affecting marine mammal species that rely on them such as inshore dolphins and Dugongs **(low confidence)**.

Freshwater floods and coastal storms threaten and reduce seagrass productivity which has been linked to high mortality of inshore dolphins and Dugongs (Meager & Limpus 2014), and reduced reproductive success and survival in the North Atlantic Right Whale (Lanyon & Burgess 2019).

10.2.5 Changes in ocean circulation

Changes in the frequency and intensity of El Niño and La Niña events will have significant impacts on marine mammal distribution and mortality, but impacts will vary between species and locations **(high confidence)**.

Oceanic weather system events such as El Niño and La Niña are predicted to increase in frequency and intensity (McPhaden *et al.* 2020), with significant influences on marine mammal distribution (Keiper *et al.* 2005), generally due to changes in food availability. For example, there is low food availability for the Subantarctic Fur Seal in years with La Niña events (Prado *et al.* 2016), there was almost complete mortality of Northern Fur Seal pups in an extreme El Niño year (Keiper *et al.* 2005), and low calving rates in North Atlantic Right Whale were associated with NAO index shifts (Simmonds & Isaac 2007). However, some dolphins have expanded their ranges in El Niño years and retained the expansions in other years (Simmonds & Isaac 2007).

Strandings increase in response to prey declines (e.g. Subantarctic Fur Seal strandings are highest in La Niña years when food availability is low: Prado *et al.* 2016; high stranding events of Beluga and Minke Whales were seen in years with low krill abundance: Truchon *et al.* 2013). Strandings of marine mammals are associated with large-scale oceanic events more widely, although effects vary between species: strandings of Atlantic White-sided Dolphin and the Minke Whale were negatively and positively correlated with the previous year NAO index respectively, while stranding numbers of Beluga Whales were positively correlated with the previous winter NAO index (Truchon *et al.* 2013). Overall, the frequency of stranding events is predicted to rise due to climate change (van Weelden *et al.* 2021).

10.2.6 Toxins, parasites and disease

Temperature increases have been associated with increased mortality as a result of toxic algal blooms, disease and elevated parasite levels **(low confidence)**.

Climate change may increase or change the frequency and distribution of toxic algal blooms, likely due to increased temperature, micronutrient availability and changes in salinity (Burek *et al.* 2008). High rates of strandings across many species are associated with toxic algal blooms, for example Harbour Porpoises and Minke Whales (Truchon *et al.* 2013).

Infectious diseases and parasites in marine mammals have also increased over the last 30 years, linked to temperature increases and sea ice declines (Burek *et al.* 2008; Sanderson & Alexander 2020; Pilfold *et al.* 2021). Mass mortality events caused by disease have increased, particularly in pinnipeds (seal and sea lions) (Burek *et al.* 2008; Sanderson & Alexander 2020) but another example includes Mediterranean Striped Dolphins in the 1990s (Simmonds & Isaac 2007).

10.3 Adaptations and responses

10.3.1 Distribution and range shifts

Range shifts have been observed in many species, with consequent declines in polar species and increases in subtropical and tropical species **(high confidence)**.

Most marine mammals are relatively able to adapt their ranges in response to changes in temperature and food availability (e.g. poleward range shifts seen in sub-Arctic whales: van Weelden *et al.* 2021; Common Dolphin, White-beaked Dolphin, Harbour Porpoise, Sperm Whale: Simmonds & Isaac 2007; Dall's Porpoise: Keiper *et al.* 2005). There is also evidence of historic and prehistoric climate-associated range shifts in whales, walruses, Narwhals, Common Dolphins and Harbour Porpoises (Laidre *et al.* 2008; Fontaine *et al.* 2010; Amaral *et al.* 2012).

In general, decreases in pinniped and cetacean species richness have been predicted at lower latitudes (below 40°), along with increases at higher latitudes (Kaschner *et al.* 2011).

River dolphins, such as the Ganges River Dolphin, and coastal cetaceans and sirenians are likely to be particularly vulnerable to climate change due to physical constraints preventing range shifts and limited patches of habitat (Learmonth *et al.* 2006; Simmonds & Isaac 2007).

10.3.2 Foraging behaviour

Species may alter their diet and foraging behaviour in response to climatic impacts on prey availability, but this may not compensate for losses in key prey **(low confidence)**.

Some species may also be able to adapt foraging behaviour to new prey species (e.g. Humpback Whales: Benson *et al.* 2002; Fleming *et al.* 2016). There is a lot of evidence of Polar Bear diet shifting to include more non-pinniped species such as ground-nesting birds (Prop *et al.* 2015), whales (Rode *et al.* 2022), fish and blueberries (Dyck & Kebreab 2009). However, these food sources are not likely to be sufficient to make up for the reduced availability of seal prey (Petherick *et al.* 2021; Rode *et al.* 2022).

10.3.3 Timing of migration

Changes in the timing of migration have been observed, with many species now arriving on the breeding grounds earlier, but population effects are mostly unknown **(low confidence)**.

Many migratory marine mammals may be able to change their phenology to adapt to changes in food availability and timing of sea ice melt (van Weelden *et al.* 2021). In general, whales that feed in the Antarctic and breed in the tropics now arrive in the tropics earlier (e.g. Humpback and Blue Whales: Avila *et al.* 2020; Ingman *et al.* 2021). Similarly, sub-Arctic breeding whales are now arriving earlier in the Arctic and departing later, as sea ice is present for less of the year (van Weelden *et al.* 2021).

However, as sea ice freeze-up becomes later, Polar Bear migration from land to sea ice is delayed, and this risks starvation for cubs, so migration cannot be delayed further (Cherry *et al.* 2013; Miller *et al.* 2022).

11 Reptiles

11.1 Overview of migration patterns and distributions

There are seven species of marine turtles, all of which are listed on the CMS Appendices, and six of which are listed as Endangered and/or Threatened (and Flatback Turtle is listed as Data Deficient). In addition to the marine turtles, the other reptiles listed on the CMS Appendices are one freshwater turtle, the Arrau Turtle, and two crocodile species. The majority of research on climate change impacts on migratory reptiles focuses on marine turtles. Marine turtles are found in all oceans, except polar regions, but typically they nest on tropical and subtropical sandy beaches. They all migrate long distances between feeding and breeding grounds, although migration patterns vary between species and even between populations. Although populations of marine turtles have undergone historic declines as a result of harvesting (of both adults and eggs), bycatch and habitat loss, the majority of populations now appear to be on an upward trajectory as a result of sustained conservation efforts (Mazaris *et al.* 2017).

11.2 Climate change impacts

11.2.1 Increased temperature

Increasing temperatures are resulting in a higher proportion of female turtle and crocodile hatchlings **(high confidence)**.

Turtles and crocodiles have temperature-dependent sex determination (Valenzuela 2001; Hamann *et al.* 2007; Patrício *et al.* 2021) and increases in the female:male hatchling sex ratio, due to increasing temperatures, are being observed (see Poloczanska *et al.* 2009; Santidrián Tomillo & Spotila 2020 for reviews). Changes in operational sex ratios are less well understood (Rees *et al.* 2013) and are context-dependent (Roberts *et al.* 2023). They may also be affected by adjacent land use (Jensen *et al.* 2018). The population-level impact of this is likely to be positive in most populations, as there are still enough males in most populations to fertilise eggs (Perez *et al.* 2016; Santidrián Tomillo & Spotila 2020; Maurer *et al.* 2021). However, in the future, extremely limited male populations could lead to population declines through reduced fertilisation or limited genetic diversity (Mitchell & Janzen 2010) if range shifts are not possible.

11.2.2 Sea level rise and increased storms

Rises in sea levels and an increase in the frequency and intensity of storms are causing loss of nesting habitat **(high confidence)**.

Sea level rises, and an increasing frequency and intensity of storms, will cover or inundate some current marine turtle and Salt-water Crocodile nesting beaches, leading to loss of habitat and embryo mortality (Varela *et al.* 2019; see Fukuda *et al.* 2022, Poloczanska *et al.* 2009, Fuentes *et al.* 2020, Patrício *et al.* 2021 and Dimitriadis *et al.* 2022 for reviews).

In the Mediterranean, over half of nesting sites for Loggerhead and Green Turtles are predicted to be lost by 2100 (Katselidis *et al.* 2014; Varela *et al.* 2019; Dimitriadis *et al.* 2022), and similar levels of loss are predicted in the west Atlantic for Loggerhead Turtles (Reece *et al.* 2013). One study predicted a loss of 80% of marine turtle nesting habitat by 2050 in the west Atlantic (Fuentes *et al.* 2020).

Loss of nesting habitat to sea level rise is especially a problem where there are barriers to landward movement, such as cliffs and coastal development (Katselidis *et al.* 2014; Perez *et al.* 2016; Varela *et al.* 2019).

(See also the case study on page 77 for an overview of the full range of impacts on Loggerhead Turtles.)

11.3 Adaptations and responses

11.3.1 Distribution and range shifts

Poleward range shifts have been observed but are likely to be constrained by anthropogenic pressures in potential new areas, although conservation actions can be targeted in such areas **(medium confidence)**.

Range shifts will be the key to marine turtle adaptation to climate change, as they shift their distribution poleward in response to warmer temperatures (Perez *et al.* 2016). The major threat that will prevent range shifts is human coastal development and the availability of suitable nesting beaches in new areas (Fuentes *et al.* 2020). Turtles typically return to the beaches where they were born to lay eggs; this may limit their ability to shift ranges, but the extent to which this occurs is not clear (Wright *et al.* 2012). There is evidence of Loggerhead Turtle range shifts in the Mediterranean Sea (Girard *et al.* 2021) but more research into the ability of sea turtles to shift their ranges is required (Hawkes *et al.* 2009).

Human interventions could include shading beaches e.g. by tree planting (Mitchell & Janzen 2010), preventing coastal development on emerging nest beaches (Girard *et al.* 2021) and translocation of eggs (Hawkes *et al.* 2007).

11.3.2 Timing of migration

Phenology shifts, particularly earlier nesting, may help to prevent extreme sex ratios if this means that the turtle eggs develop at lower temperatures after being laid earlier in the season (Laloë *et al.* 2016).

12 Actinopterygii (Bony fish)

12.1 Overview of migration patterns and distributions

Many fish migrate to some extent, either within their freshwater or marine environments, or by crossing the two, with anadromous fish, such as Salmon, migrating to freshwater areas to breed, and catadromous fish, such as eels, migrating to marine areas to breed. Some fish, particularly pelagic species such as tuna, can migrate large distances, and are classified as Highly Mobile Species by the UN Convention on the Law of the Sea. Twenty species are listed on the CMS Appendices, of which 18 species are in the family Acipenseridae (sturgeons), with the other two species being Giant Catfish and European Eel. One species listed on Appendix II, the Chinese Paddlefish, was declared extinct in 2022. Sturgeon live in subtropical, temperate and subarctic rivers and coastal regions of Eurasia and North America. Most migratory sturgeon species live in the ocean for most of their lives but migrate, generally in the spring or early summer, to freshwater rivers and streams to spawn. Some migratory sturgeon, such as the Lake Sturgeon, are freshwater species that migrate from larger lakes and rivers to smaller streams to spawn.

Fish that migrate from oceans to freshwater have experienced dramatic population declines, with many having reduced by over 90% since the 1970s (Limburg & Waldman 2009; He *et al.* 2019). For example, the European Sturgeon has been lost from all European rivers except one, a 99% range reduction (He *et al.* 2019). The main drivers of these declines are habitat loss (especially from damming) and degradation, overfishing and pollution (Limburg & Waldman 2009; Arthington *et al.* 2016; Ruban *et al.* 2019). Climate change has been identified as a ‘key threat’ to migratory fish in less than 10% (31 of 358) of cases (Lascelles *et al.* 2014).

The impact of climate change on fish (not just migratory ones) has recently been reviewed by Dahms & Killen (2023). Poleward shifts in distribution were fastest in tropical populations, and inversely correlated with depth shifts which, in turn, dominated at the trailing edges of population ranges, with niche a key factor influencing responses to temperature change. Temperature, river flow, salinity, oceanic conditions and changes in food webs can all have large impacts on these species, but there is also evidence of adaptability. This makes population-level impacts difficult to predict. However, the evidence suggests that climate change will have increasingly negative impacts on these species.

12.2 Climate change impacts

12.2.1 Increased temperature

Temperature increases are generally associated with reductions in spawning and survival **(medium confidence)**.

Temperature increases in freshwater rivers and streams reduces the dissolved oxygen (Ficke *et al.* 2007) and reduces flow rates as evaporation is increased. The combination of these effects generally reduces the frequency and success of spawning in anadromous fish (Goto *et al.* 2018; Delage *et al.* 2020; Crichigno & Cussac 2022). Spawning generally occurs within a specific temperature window, so for many sturgeon species the spawning season is shortening as temperatures rise (Elisio *et al.* 2015; Limburg *et al.* 2016; e.g. Chinese Sturgeon: Zhang *et al.* 2019; Zhang *et al.* 2021). However, in some species and populations, warming has increased the spawning window (Domagala *et al.* 2014).

Increasing temperatures can alter fish metabolism, lowering body condition when food availability is low (e.g. Green Sturgeon: Poletto *et al.* 2018) and increasing the toxicity of pollutants (Ficke *et al.* 2007; Grunow *et al.* 2021).

Sturgeon appear to have high physiological adaptability to changes in temperature (Zhang *et al.* 2017; Jay *et al.* 2020; e.g. Siberian Sturgeon: Yang *et al.* 2023). However, cellular stress increased with temperature (e.g. Lake Sturgeon: Wassink *et al.* 2019) which reduced body condition and increased mortality in the long term (Bard & Kieffer 2019; e.g. Russian Sturgeon: Castellano *et al.* 2017; Lake Sturgeon: Bugg *et al.* 2020).

Temperature increases reduce spawning habitat availability (e.g. Lake Sturgeon: Lyons & Stewart 2014). This has led to reduced populations for many, if not most, migratory fish (Goto *et al.* 2018) and is likely to lead to the disappearance of species at the warm edges of their ranges (Lassalle *et al.* 2010; Kynard *et al.* 2016).

The warming of coastal waters reduces recruitment numbers and survival of the European Eel in wetlands around the Mediterranean Sea, and causes earlier colonisation through increased migratory responses (Borges *et al.* 2019) (see the case study on Mediterranean wetlands on page 78).

Increasing temperatures may occasionally be favourable, although high fidelity to natal spawning grounds may limit opportunities for range expansion (Rothermel *et al.* 2020). Increasing temperatures in the Baltic Sea may be favourable for European Sturgeon and it has been suggested this might facilitate reintroduction efforts there, although intensive fishing activities would need to be reduced first (Popov 2017).

Other impacts of temperature increases include increased migration distances and increased competition between juveniles as habitat is lost (Niklitschek & Secor 2005; Goto *et al.* 2018). Sturgeon migration and spawning generally occurs earlier due to rising temperatures (Limburg *et al.* 2016; Delage *et al.* 2020; del Fresno *et al.* 2021), although this can vary between populations (e.g. Lake Sturgeon: Buchinger *et al.* 2022).

Warming generally has a negative impact on fish populations (Pearce-Higgins *et al.* 2015b), and the overall effects of temperature rises are predicted to be detrimental to fish health and populations globally (Huang *et al.* 2021; Levangie *et al.* 2022).

Climate change is likely to have complex impacts on food webs that will impact migratory fish (Ficke *et al.* 2007). Warming sea surface temperatures can cause changes in timing and abundance of plankton blooms, reducing food availability for small fish (Burthe *et al.* 2012).

Increasing temperatures and changes in flow rates are also likely to impact freshwater food availability, although there is little research on this. Prey availability for Green Sturgeon is predicted to decline as temperatures increase (Vaz *et al.* 2015; Zarri & Palkovacs 2019).

In Arctic regions, warming may increase the productivity of inshore marine habitats used by anadromous fishes, but this may be counterbalanced by decreased flows in spawning rivers (Limburg & Waldman 2009).

12.2.2 Reduced flow of rivers

Alterations in river flow will impact populations, with climate-driven reductions in flow rates likely to negatively impact the abundance and breeding success of species **(medium confidence)**.

Climate change will alter river flow patterns and increase the frequency and severity of droughts and floods, which will lessen the frequency of successful reproduction, leading to losses in suitable catchments (Limburg & Waldman 2009; Pfeiffer *et al.* 2021). For example, increased fluctuations in flow in the Volga River is thought to have contributed to declines in reproduction in Beluga and Russian Sturgeons (Ruban *et al.* 2019).

Migratory sturgeon abundance (Hammen *et al.* 2018) and reproductive success (Scarnecchia *et al.* 2019) are likely to be negatively impacted by declines in waterflow in spawning grounds, particularly in the late spring and summer (Limburg & Waldman 2009; Limburg *et al.* 2016). For example, projected declines in May river flow are predicted to increase the extinction risk for many Lake Sturgeon populations (van der Lee *et al.* 2022).

Higher flow rates can also be negative: increased winter flow rates can scour stream beds and damage spawning grounds (Limburg *et al.* 2016). Increased flow can also flush young fish out of rivers before they are physiologically ready for the transition (Limburg *et al.* 2016). High flow rates can also affect food availability: Green Sturgeon prey decreased at higher flow rates (Zarri & Palkovacs 2019).

There is a predicted increase in hurricanes which have been found to cause mass mortality events in sturgeon. However, recruitment after hurricanes has been found to increase, making long-term impacts difficult to predict (Dula *et al.* 2022).

12.2.3 Increased acidification of water

Increased CO_2 acidifies salt and freshwater, but impacts on migratory sturgeon appear to be limited so far **(low confidence)**.

An increase in CO_2 concentrations causes salt and freshwater to become more acidic, which has complex effects on fish physiology and marine and aquatic communities (see Havas & Rosseland 1995; Heuer & Grosell 2014; Nagelkerken *et al.* 2016; and Esbaugh 2018 for reviews). In particular, ocean acidification can reduce the growth of zooplankton (Reynolds *et al.* 2022) which could reduce food availability for sturgeon.

Acidification of the ocean has also been shown to hinder migratory responses of European Eels by reducing their ability to follow riverine cues for migration (Borges *et al.* 2019) (see also the case study on Mediterranean wetlands on page 78).

However, migratory sturgeon, at least, appear to be able to adapt to increasingly acidic conditions (Hannan & Rummer 2018), so there is little evidence currently of negative effects and more research is needed.

12.2.4 Changes in salinity

Changes in salinity associated with changes in the flow of freshwater may impact migratory fish, although with uncertain population-level impacts **(low confidence)**.

Climate change is likely to bring changes in the salinity of estuaries and rivers. Increases in winter river discharge will decrease estuary salinity (Sardella & Kultz 2014), while temperature rises and a reduction in summer rainfall can bring brackish water further upstream in the summer (Breece *et al.* 2013). Increased summer salinity has caused spawning habitat loss in some species (Breece *et al.* 2013).

Green Sturgeon were found to be able to acclimate to salinity changes, but it did cause cellular stress in individuals, making long-term population-level impacts difficult to predict (Sardella & Kultz 2014; Vaz *et al.* 2015).

12.2.5 Changes in ocean currents

Changes in ocean currents may impact oceanic migration, potentially affecting phenology, distribution and survival **(low confidence)**.

It is predicted that climate change will alter oceanic currents and weather patterns. For example, weather events such as El Niño and La Niña are predicted to increase in frequency and magnitude (McPhaden *et al.* 2020). The impacts of these changes are likely to be complex and vary between location and species, and there is no research on how predicted changes to ocean currents will affect migratory sturgeon.

Changes in the Gulf Stream could have negative impacts on the migration of American and European Eels which rely on it for food and transport (Limburg & Waldman 2009).

12.3 Adaptations and responses

12.3.1 Distribution and range shifts

Poleward shifts in range have been observed, but are likely to be constrained by the distribution, and accessibility, of spawning grounds **(low confidence)**.

There are many examples of poleward range shifts in migratory fish (Jeon *et al.* 2020). However, many migratory fish return to their natal spawning grounds, which will reduce their ability to shift ranges (Rothermel *et al.* 2020), so translocation may be necessary for some species if natural range shifts are not occurring. There is evidence of successful translocation of Lake Sturgeon (Boothroyd *et al.* 2018).

Conservation efforts to restore freshwater and tidal wetlands, increase floodplain connectivity and remove dams can stabilise or increase population sizes (Limburg *et al.* 2016). However, the long-term survival of many sturgeon species, such as the Adriatic and Chinese Sturgeons, currently depends on artificial stocking (He *et al.* 2019).

12.3.2 Timing of migration

Earlier migration and breeding timings have been observed, but evidence is lacking as to whether this is adaptive or maladaptive **(low confidence)**.

Sturgeon migration and spawning generally occurs earlier due to rising temperatures (Limburg & Waldman 2009; Limburg *et al.* 2016; Delage *et al.* 2020; del Fresno *et al.* 2021). In some cases, this may be adaptive behaviour, while for some species these life-cycle stages may be driven by physiological cues and could be maladaptive.

13 Chondrichthyes (Sharks and rays)

13.1 Overview of migration patterns and distributions

The Chondrichthyes (sharks, rays, skates and sawfish) are a large group of, mostly marine, fish, typified by their cartilaginous skeleton, possessing a series of paired gill arches and a rigid dorsal fin. They are widely distributed throughout the world's oceans, with some species spending most of their lives in the open ocean and others living or reproducing in shallow waters and coastal habitats. Migration patterns and distances vary between species, but many are migratory, and some cover large distances and are recognised as Highly Mobile Species on Annex I of the UN Convention on the Law of the Sea.

Thirty-nine species are listed on the Appendices of the CMS and most of these are classified as Endangered (or, indeed, Critically Endangered) on the IUCN Red List. Since 1970, the global abundance of oceanic sharks and rays has declined by 71%, largely due to an 18-fold increase in relative fishing pressure (Dulvy *et al.* 2014; Pacoureau *et al.* 2021). Another major threat is coastal habitat loss, mainly from fishing activities such as trawling (Lawson *et al.* 2020). Somewhat remarkably, climate change has not been formally identified as a key threat to any cartilaginous fish species (Lascelles *et al.* 2014), although more recent assessments suggest that around 10% of threatened shark and ray species are impacted by climate change (in addition to overfishing), due to poleward range shifts (e.g. Tanaka *et al.* 2021) and habitat loss and degradation (Jorgensen *et al.* 2022).

The impacts of climate change on sharks and rays are complex, due to various physiological, behavioural and ecological changes (Heath *et al.* 2012). For most species, research on the impacts of climate change has been limited. In general, sharks and rays may be more vulnerable to climate change than most other fish, invertebrate and mammal taxa in the marine environment because they have low reproduction rates and a potentially lower ability to adapt (Field *et al.* 2009; Hazen *et al.* 2013; Walker *et al.* 2021).

13.2 Climate change impacts

13.2.1 Increased temperatures

Temperature increases are likely to have widespread impacts on shark and ray distributions and populations, with many species likely to decline in abundance **(medium confidence)**.

Temperature is a key determinant of shark and ray distribution (e.g. Silky Shark: Kindong *et al.* 2022) and some species have been shown to be extremely sensitive to very small changes in temperature (e.g. Basking Sharks: Brown *et al.* 2003). There is evidence of past climate-driven changes in population size and distribution. In general, species more reliant on coastal habitats were more affected by climate change, positively or negatively depending on the species (O'Brien *et al.* 2013; Schlaff *et al.* 2014).

Abundance changes of many species are linked to temperature. Abundance changes are often mediated in the short term by food availability, (e.g. Whale Sharks: Grose *et al.* 2020) but in the long term by physiological thermal preferences based on metabolic rates and trade-offs (Sims 2008; Deepananda & Macusi 2012; Heath *et al.* 2012; Schlaff *et al.* 2014; Reynolds *et al.* 2022). For example, Basking Shark abundance in British waters is positively correlated with temperature, linked to increases in their copepod prey (Cotton *et al.* 2005; Robinson *et al.* 2009). Conversely, Scalloped Hammerhead Shark and *Mobula* rays declined substantially in the tropics when sea surface temperature rose by a few degrees (Osgood *et al.* 2021). Declines in deep-water Mediterranean sharks have also been linked to temperature increases (Cartes *et al.* 2013).

Temperature increases are predicted to lead to habitat loss for many shark species (Hazen *et al.* 2013; Jorgensen *et al.* 2022). A large decline in range extent is predicted for most open-water species in the north Pacific, with an exception for the White Shark where habitat increases are predicted (Hazen *et al.* 2013). A decline in Silky and Dusky Shark habitat has been predicted, particularly in south Asian waters (Diaz-Carballido *et al.* 2022).

Larger species tend to be less tolerant of high temperatures (Di Santo 2016; Vilmar & Di Santo 2022). In the North Sea, larger species have declined in recent years while smaller species have increased (Sguotti *et al.* 2016).

Smaller body size and lower body condition at warmer temperatures have been found in many species, potentially due to decreased nutrient uptake (Koenigstein *et al.* 2016; Vilmar & Di Santo 2022). However, muscle performance is improved by warmer temperatures (Vilmar & Di Santo 2022). Reproduction may be more successful and development time quicker at higher temperatures (Schlaff *et al.* 2014; Pistevos *et al.* 2015; Poulakis & Grubbs 2019; Santos *et al.* 2021).

Temperature increases could reduce the risk of lower temperature-related mortality events (i.e. 'cold kills'), often of juveniles or eggs, while increased temperature variability could increase this risk (Schlaff *et al.* 2014; Pistevos *et al.* 2015; Rosa *et al.* 2017; Poulakis & Grubbs 2019).

Other potential impacts of temperature rise, that require more research, include competition from invading non-native species and the increasing prevalence of disease (Field *et al.* 2009).

13.2.2 Increased ocean acidification

The effect of acidification on sharks and rays is very uncertain but, in general, acidification is linked to declines in shark fitness **(low confidence)**.

An increase in CO_2 causes seawater to become more acidic, which can reduce the growth of zooplankton and has been predicted to lead to population declines for Whale Sharks and other planktivorous sharks (Reynolds *et al.* 2022).

Acidification can reduce olfactory function in sharks and rays, reducing sharks' ability to hunt (Pistevos *et al.* 2015; Koenigstein *et al.* 2016; Jorgensen *et al.* 2022). Acidification may also affect swimming rates, skeletal density, locomotor performance, brain development and function (Pistevos *et al.* 2015; Di Santo 2016; Jorgensen *et al.* 2022; Vilmar & Di Santo 2022). However, the extent of these impacts, when interacting with temperature increases is unclear.

13.2.3 Increased frequency and severity of storms

Increased frequency and severity of storms may impact coastal habitats and salinity, with uncertain long-term impacts on species **(low confidence)**.

Increasing rainfall and storms will cause declines in salinity in many coastal regions (Grose *et al.* 2020). Many shark and ray species rely on coastal habitats, particularly in juvenile stages and most species occupy very narrow salinity ranges (Schlaff *et al.* 2014).

Movement out of areas after extreme rainfall events has been noted in many species (Schlaff *et al.* 2014; Gutowsky *et al.* 2021) and declines may arise if movement is not possible or salinity increases cause habitat loss (Morash *et al.* 2016). However, some species have shown high resilience to rapid changes in salinity, for example Smalltooth Sawfish (Brame *et al.* 2019) and Tope Shark (Morash *et al.* 2016).

Oceanic weather systems events such as El Niño and La Niña are predicted to increase in frequency and magnitude (McPhaden *et al.* 2020) and have a big influence on shark and ray abundance, often due to changes in food availability. However, responses to these events are species- and region-specific. Whale Sharks (southwest Pacific), Blue Sharks (southeast Pacific) and Scalloped Hammerhead Sharks (southeast Pacific) increased during La Niña conditions (Sleeman *et al.* 2010; Adams *et al.* 2016; Osgood *et al.* 2021); Scalloped Hammerhead Sharks declined during El Niño conditions (southeast Pacific: Osgood *et al.* 2021) while oceanic Manta Rays did not respond to El Niño events in the southeast Pacific but increased in the southwest Pacific (Beale *et al.* 2019; Osgood *et al.* 2021).

(See the case study on page 80 for other examples of the impacts of storms and cyclones.)

13.3 Adaptations and responses

13.3.1 Distribution and range shifts

Poleward shifts of distribution are expected but some species may be constrained by their use of specific breeding habitats **(medium confidence)**.

Temperature increases are likely to lead to poleward range shifts and altered migration routes (Field *et al.* 2009; Deepananda & Macusi 2012; Heath *et al.* 2012; Heupel *et al.* 2019; Osland *et al.* 2021). Examples of impacted species include the Scalloped Hammerhead Shark (Rodriguez-Burgos *et al.* 2022), Whale Shark (Sequeira *et al.* 2013), Basking Shark (Field *et al.* 2009) and White Shark (Bastien *et al.* 2020; Tanaka *et al.* 2021). Species reliant on particular habitats, such as reefs, may be less able to shift their range and therefore be more vulnerable to climate change (Heupel *et al.* 2019).

Actions to reduce the impacts of overfishing can make additional climate change impacts less significant. Marine Protected Areas have proved to be beneficial for many sharks (White *et al.* 2017; Walker *et al.* 2021); for example, a targeted fisheries ban for Undulate Rays in 2009 benefitted this and similar species (Elliott *et al.* 2020).

13.3.2 Timing of migration

Changes in migration patterns may result from increased water temperatures **(low confidence)**.

Changes in migration phenology have been linked to rising temperatures (Field *et al.* 2009; Schlaff *et al.* 2014). For example, the timing of sawfish movement from the shallows, where they tend to be as juveniles, to deep water is influenced by temperature (Poulakis & Grubbs 2019). However, there are few documented cases of phenology changes in sharks and rays.

14 Insects

14.1 Overview of migration patterns and distributions

Insects from many groups are migratory, with some migrating long distances and having significant ecological impacts, although these are often underappreciated (Satterfield *et al.* 2020). Most insect migration, though, involves multi-generational cycles, with a series of successive stationary and movement phases, thus the seasonal 'journey' is undertaken at the population rather than individual level. Hundreds of species of insects are known to migrate, particularly in the orders Lepidoptera (butterflies/moths), Orthoptera (grasshoppers), Anisoptera (dragonflies) and Hemiptera (aphids), although only one species, the migratory Monarch Butterfly, is included on the CMS Appendices.

Monarch Butterflies are most commonly found in North America but also occur in Central America, South America and the Caribbean islands. There has been some expansion into Oceania coinciding with the introduction of their host plants (milkweed *Asclepias* species), and more recently towards North Africa/Southern Europe (Malcolm 2018). Not all populations of Monarch migrate, although the majority of the North American populations show a multi-generational migration moving between Canada, USA and Mexico (Dingle *et al.* 2005). They have been intensively studied, and responses to climate and other factors vary between populations. A study comparing the contributions of climate change, deforestation and milkweed abundance suggests that the decline in Monarch population size over the past 21 years is driven more by a reduction in the abundance of milkweeds linked to an increased use of genetically modified crops (Flockhart *et al.* 2015).

14.2 Climate change impacts

14.2.1 Increased temperatures

Monarch Butterflies generally benefit from warmer and wetter conditions through spring and summer, and warmer winters, but are negatively affected by extreme heat or cold **(high confidence)**.

The abundance of Monarchs in the American Midwest in summer is higher when spring in Texas is wetter (Saunders *et al.* 2016; Saunders *et al.* 2018) and, similarly, warmer winters and warmer and wetter springs are associated with increased population sizes in Northern California; however, this did not explain the long-term negative population trends in the region (Espeset *et al.* 2016).

Population size is projected to decrease in Mexico and in areas where summer temperature will increase greatly, and to increase in areas that become wetter and show less extreme temperature rises (Zylstra *et al.* 2022). The increase in population size across North America in summer is suggested to currently compensate for the decrease in population over winter (Crewe *et al.* 2019; Crossley *et al.* 2022).

The effect of temperature on developmental success differs depending on the exposure of the larval microclimate: in exposed locations, high temperatures reduce success but in shaded areas, high temperatures increase success (Yang *et al.* 2022a). The authors suggest that habitat heterogeneity may therefore buffer the impacts of climate variability.

14.3 Adaptations and responses

Climate change is likely to result in a northward breeding range shift associated with likely changes in milkweed distribution. The effect of this on range extent is unclear, as are potential future changes in migration **(medium confidence)**.

Climate change is predicted to result in a northward breeding range shift. Milkweed distribution is an important driver of Monarch Butterfly distribution, and both are predicted to expand northward. It has been suggested that these range shifts may reduce the amount of suitable habitat for Monarch Butterflies during their northward migration (Batalden *et al.* 2014; Lemoine 2015), but others predict the range size of suitable habitat to remain relatively consistent as the distribution shifts north (Svancara *et al.* 2019).

Temperature and precipitation can impact migration timing, but impacts seem to be variable with some study areas demonstrating effects (New Jersey: Culbertson *et al.* 2022), whilst others do not (Ohio: Zipkin *et al.* 2012).

15 Conclusions and recommendations

15.1 Key messages from the evidence base

This Part 1 review builds on a growing evidence base of the impacts of climate change on biological systems. These **impacts are increasingly apparent across a range of scales from genetic to ecosystems** (Scheffers *et al.* 2016). The increasing magnitude of climate change (and its increasing variability) means that these impacts on the distribution of, and interactions between, organisms, and hence ecosystems, are increasingly altered; and also that this, if not abated, will exceed the adaptive capacity of many ecosystems (Pörtner *et al.* 2021). As noted in a previous review of climate change impacts on migratory species by Robinson *et al.* (2005), the long-distance movements of these species make them particularly vulnerable, exposing them to multiple and differential impacts throughout their annual cycle, any one of which may be limiting. That review highlighted the importance of these impacts at high latitudes, where warming has been greatest and migratory species make up the greatest proportion of biological communities. Migrants were thought to be particularly vulnerable to emerging impacts of changes in the timing of biological events (e.g. Møller *et al.* 2008) and, more broadly, to impacts on highly productive seasonal habitats which their migratory movements enable them to exploit (Robinson *et al.* 2009).

Our review extends and updates that previous work. In the sections below, we list summary impact statements for each broad driver of impacts for each species group/subgroup, and offer a brief commentary on the strength of evidence for each. In each section, groups for which there is high confidence in the level of impacts are listed first, followed by those with medium and low confidence. But first, using those highlights, we identify what we regard as some of the key changes in the evidence available from the last decade or more of scientific research on the impacts of climate change on migratory species.

There is now particularly strong evidence of the impacts of climate change on migratory species in aquatic, especially marine, environments. This evidence is apparent across the range of taxa reviewed, including marine mammals, migratory fish, sharks and rays, and seabirds. These impacts tend to be more negative than found in the terrestrial environment, and appear to be particularly a consequence of cascading impacts through the food chain (e.g. Carroll *et al.* 2015a; Johnston *et al.* 2022). In marine systems, warming disrupts the timing and abundance of plankton food, particularly in highly seasonal shallow seas, which then affects the productivity and abundance of fish and other secondary consumers, which in turn can affect the productivity, survival, distribution and abundance of top marine predators. A key message from this report is therefore that **migratory marine predators, across a range of taxa, are highly vulnerable to negative impacts of warming**. Although well described in many medium- and high-latitude shallow seas that are highly seasonal, these processes also affect tropical species where El Niño years can reduce the breeding success of central-place foraging seabirds (e.g. Ancona *et al.* 2012) or cause mortality in marine mammals.

The impacts of temperature affecting high-latitude systems are widely documented, and the evidence for these has strengthened, with mixed consequences for migratory species, either directly or indirectly as it is more likely to increase the abundance of non-migratory species (e.g. Pearce-Higgins *et al.* 2015a) with which they may compete. **The effects of warming will be most important at mid- and high latitudes, whilst changes in precipitation will have the greatest impacts at low latitudes**, where reduced water availability will negatively impact wetland species such as waterbirds (e.g. Breiner *et al.* 2021) and fish (e.g. Pfeiffer *et al.* 2021), through the loss of wetlands or changes in river flow affecting migratory movements. Terrestrial species such as migratory land mammals, trans-Saharan migrants and grassland passerines (e.g. Dejene *et al.* 2021) will also be widely affected by changes in rainfall patterns in the tropics, mediated through impacts on vegetation productivity. Thus, these terrestrial systems are similarly affected by a cascade of impacts through the food chain (Ockendon *et al.* 2014). In addition, recent research has highlighted the additional vulnerability of tropical birds and bats, particularly in arid and semi-arid environments, to extreme heat, which can cause large-scale sudden mortality (e.g. Dey *et al.* 2015). Increased frequency of heatwaves may therefore be a key driver of changes in the distribution and abundance of migratory species in these environments. Tropical species are therefore particularly impacted by a combination of changes in precipitation (drought) and heat stress.

Increases in the severity of extreme events, particularly storms, can have large, but localised, negative consequences, for example leading to the abandonment of breeding attempts in seabirds and waterbirds (Weston & Fraser 2020), or causing large-scale mortality. These events are most likely to have significant consequences for species' extinction risk if that species has fragmented, small and localised populations. For coastal species, sea level rise will exacerbate population vulnerability to extreme events associated with storm surges.

Overall, **there is widespread evidence of changes in the distribution and phenology of migratory species**. In particular, poleward range shifts and earlier migration and breeding are occurring in temperature-driven medium and high latitudes, and more mixed directional shifts are apparent in the tropics, depending on changes in rainfall (VanDerWal *et al.* 2013). While changes in climate suitability may drive distributional change, these will be strongly constrained by land use, with range spread most likely where large areas of suitable habitat remain close to existing populations (Howard *et al.* 2020, 2023). Despite concerns about the potential for changes in phenology driving asynchrony in the timing of resource availability and the peaks in food requirements of migratory species, the evidence for this having significant and large-scale population consequences remains weak (Franks *et al.* 2018; Samplonius *et al.* 2021). This suggests that direct impacts of climate change on prey abundance are more significant than changes in timing.

In this review, we examined the evidence for the impacts of climate change on migratory species. It was not within the scope of this review to examine literature on the impacts of human adaptations to climate change, such as increasing numbers of wind turbines and other renewable energy technologies, or predicted changes in agriculture. This may have large impacts on some migratory animals. For example, a major cause of mortality in bats is the installation of wind turbines, and this can also impact migratory birds (Thaxter *et al.* 2017). **A further review of the impacts of human adaptations to climate change on migratory species would be useful**.

A further point to emphasise is that **the evidence base on the impacts of climate change on biodiversity is biased**, particularly towards northern and higher latitudes, especially from Europe and North America, with a relative lack of research from the tropics and the Global South (Ockendon *et al.* 2014; Dahms & Killen 2023). This means there is considerable uncertainty about the impacts of climate change on species in the tropics, where the majority of species are found. Further, the strong latitudinal gradients that exist in relation to the importance of temperature and precipitation on biological systems (Pearce-Higgins *et al.* 2015b), mean that the evidence that does exist from better studied systems cannot simply be extrapolated to those understudied regions, habitats and taxa. As the summary below highlights, whilst some key migratory groups are relatively well studied, particularly some of the bird groups, others are relatively poorly studied, such as bats, leading to an urgent need to better document the impacts of climate change on those taxa. Such evidence is critically important not just to inform vulnerability assessments to climate change (Foden *et al.* 2019), but also to inform climate change adaptation – with growing evidence that targeted conservation actions can actually help species adapt to climate change (Bowgen *et al.* 2022).

Finally, although we tried to approach the review in a systematic way, and have recorded our search terms so that it could be repeated, **we recommend that a useful next step would be to convene appropriate experts across the range of taxa groups and geographical regions to review this evidence synthesis and identify priority areas for action**.

Summary impact statements and an evidence commentary follow below.

15.2 Increased temperatures

Globally, temperatures have increased and will continue to do so. There is strong evidence that such increases in temperatures have already affected most migratory species groups. There is a wide range of mechanisms for climate-driven changes in distribution, abundance and migration, such as changes in food availability and thermal limits, which will vary between species and species groups, but impacts are mostly negative.

15.2.1 High confidence

Seabirds: Many seabird species show generally negative associations with sea surface temperature, with well-demonstrated effects on survival, breeding success and population abundance.

Waterbirds: The effect of increased temperatures on breeding success and survival varies between species, but generally seems to have a short-term neutral or positive effect, at least for species breeding at higher latitudes.

Marine mammals: Temperature increases are likely to have a major impact on marine mammal populations indirectly via changes in food availability.

Reptiles: Increasing temperatures are resulting in a higher proportion of female turtle and crocodile hatchlings.

Monarch Butterflies: Monarch Butterflies generally benefit from warmer and wetter conditions through spring and summer, as well as warmer winters, but are negatively affected by extreme heat or cold.

Terrestrial mammals: Rising temperatures can cause heat stress, impacting productivity, and are generally linked to population declines.

15.2.2 Medium confidence

Waterbirds: Extreme temperatures (both hot and cold) are detrimental to waterbirds.

Afro-Palearctic passerines: Increased temperatures generally promote an abundance of insect prey, which are the primary source of food in the breeding season (less so in the boreal winter months), and often result in higher breeding success, if temperatures are not too extreme.

Bony fish: Temperature increases are generally associated with reductions in spawning and survival.

Sharks and rays: Temperature increases are likely to have widespread impacts on shark and ray distributions and populations, with many species likely to decline in abundance.

15.2.3 Low confidence

Raptors: The effects of temperature change appear relatively weak, with no strong impact of temperature upon breeding success.

Afro-Palearctic passerines: Increased temperatures in the spring can lead to earlier insect emergence, and hence asynchrony with the timing of breeding.

Grassland passerines: There is growing evidence that extreme heat can have negative impacts on tropical species through sudden and catastrophic mortality. This does not appear to result from drought, but from physiological responses to heat stress.

Terrestrial mammals: Rising temperatures may benefit some populations in cold environments by reducing the risk of higher mortality linked to severe cold.

Bats: Changes in temperature are likely to affect foraging efficiency and flight behaviour with uncertain consequences for populations. Warming may also affect the abundance of key invertebrate prey in different and contrasting ways, with variable impacts on bat populations, depending on diet, taxa and climate change context.

Marine mammals: Temperature increases have been associated with increased mortality as a result of toxic algal blooms, disease and elevated parasite levels.

15.3 Changes in water availability

Alongside increased temperatures, in many regions there will be a reduction in water availability through reduced precipitation and increased frequency of droughts, and also increased human abstraction of water. However, in some areas, rates of precipitation will increase. Species occurring in drier temperate and subtropical areas, or relying on freshwater habitats, will be negatively affected whether they are migratory or not. The migration of fish and waterbirds is likely to be particularly impacted by loss of wetlands and reduced river flows, especially where these reduce the coherence of networks of stopover sites.

15.3.1 High confidence

Afro-Palearctic passerines: Annual variation in the survival and abundance of long-distance migratory passerines, especially those that spend the boreal winter in African drylands (such as the Sahel), tends to be most strongly linked (positively) to variation in rainfall there.

Terrestrial mammals: Changes in rainfall patterns are likely to have a significant impact on many terrestrial mammal populations, particularly in the tropics given the strong links between rainfall, primary productivity and food resources.

15.3.2 Medium confidence

Waterbirds: Increased precipitation can have a positive effect on breeding success, and drought a negative impact, at least on temperate breeding waterbirds. Where precipitation is predicted to fall, especially in the summer months, overall effects are likely to be negative.

Raptors: Changes in precipitation can affect breeding success, although the direction of the effect varies depending on the general climate and habitat the birds breed in. Rainfall tends to have a positive effect on tropical breeding raptor populations through impacts on prey abundance, whilst at higher latitudes, more negative responses to precipitation are likely due to chilling and reduced foraging opportunities.

Bony fish: Alterations in river flow will impact populations, with climate-driven reductions in flow rates likely to negatively impact the abundance and breeding success of species.

15.3.3 Low confidence

Grassland passerines: Tropical systems tend to be rainfall-limited, rather than temperature-limited, and therefore the strongest climate change impacts on tropical migratory passerines are likely to be through changes in precipitation patterns, which are mixed, depending on location.

Bats: Reduced water availability and drought can reduce breeding success, migration and competitive dynamics amongst species.

15.4 Extreme weather events

The frequency of storms and other extreme weather events is expected to increase, although, by their very nature, the pattern of occurrence is hard to predict. Evidence of long-lasting impacts is scattered, but they are likely to be negative where they do occur.

15.4.1 High confidence

Seabirds: Increased frequency of stormy weather can impact on the survival and breeding success of some species, depending on the timing, with potential consequences for population size.

Reptiles: An increase in the frequency and intensity of storms is causing loss of nesting habitat.

15.4.2 Medium confidence

Terrestrial mammals: Where droughts are projected to increase in severity and frequency, they are likely to negatively impact populations of migratory mammals. Heavy rain and flooding can cause localised impacts, but generally appear to have weak population impacts.

Bats: The response of bat populations to extreme events is usually negative, either in terms of range contraction or population reduction.

15.4.3 Low confidence

Marine mammals: An increase in storms and freshwater flooding can impact vulnerable coastal habitats, detrimentally affecting populations that rely on them, particularly for coastal species such as inshore dolphins and Dugongs.

Sharks and rays: Increased frequency and severity of storms may impact coastal habitats and salinity, with uncertain long-term impacts on species.

15.5 Sea level rise

Globally, sea levels are rising and there is strong evidence that species breeding in low-lying coastal areas will be negatively impacted through loss of habitat, especially in areas with high levels of human developments.

15.5.1 High confidence

Waterbirds: Sea level rise is predicted to cause habitat loss, particularly at stopover sites along the migratory routes and wintering grounds.

Reptiles: Rises in sea levels are causing loss of nesting habitat.

15.5.2 Medium confidence

Marine mammals: Sea level rise will reduce habitat availability for some coastal breeding seals.

15.5.3 Low confidence

Seabirds: Many seabirds are cliff-nesters, but for those nesting in low-lying areas, such as albatrosses, penguins and terns, rising sea levels threaten to inundate nest sites.

15.6 Reductions in sea ice extent

As temperatures increase, the area of sea ice is reducing. Although affecting only a small number of distinctive marine species, there is strong evidence of negative impacts.

15.6.1 High confidence

Seabirds: Reductions in sea ice extent reduce the area of high quality foraging habitats for seabirds.

Marine mammals: Sea ice decline and increased variability in cover in response to climate change will generally negatively impact population size for species associated with sea ice, and may accelerate the poleward range expansion of species associated with open water.

15.7 Changes in oceanic currents

Changes in oceanic currents are likely to have far-reaching consequences due to the scale of ecosystem alteration. There is strong evidence that migratory seabirds and marine mammals will be impacted, but evidence for other groups (such as migratory fish) is so far apparently lacking due, in part, to the difficulties of gathering evidence.

15.7.1 High confidence

Seabirds: Large-scale changes in oceanic currents can greatly alter food availability, especially for central-place foragers like seabirds that have to return to a specific location, the breeding colony.

Marine mammals: Changes in the frequency and intensity of El Niño and La Niña events will have significant impacts on marine mammal distribution and mortality, but impacts will vary between species and locations.

15.7.2 Low confidence

Bony fish: Changes in ocean currents may impact their oceanic migration, potentially affecting phenology, distribution and survival.

15.8 Changes in water chemistry

Changes in salinity, due to altered freshwater flows, and increases in oceanic acidity are predicted as CO_2 emissions increase. However, so far, there is limited published evidence of direct impacts on migratory species. It should be noted that such changes are having marked impacts on particular marine habitats, such as coral reefs, which will have impacts on any migratory species that use such habitats as nursery areas, for example.

15.8.1 Low confidence

Bony fish: Changes in salinity associated with changes in the flow of freshwater may impact migratory fish, although with uncertain population-level impacts. Increased CO_2 acidifies salt and freshwater, but impacts on migratory sturgeon appear to be limited so far.

Sharks and rays: The effect of acidification on sharks and rays is very uncertain but, in general, acidification is linked to declines in shark fitness.

15.9 Distribution and range shifts

Poleward range shifts are one of the most frequently demonstrated impacts of climate change and will affect all groups of migratory animals; however, whether such impacts are positive or negative depends very much on the individual species' ecology.

15.9.1 High confidence

Seabirds: The response of seabird distribution ranges to climate change varies among species; shifts or expansions that have been observed are most often polewards.

Waterbirds: Poleward and elevational range shifts have been observed and are predicted to intensify throughout a wide range of wetland and coastal bird species.

Marine mammals: Range shifts have been observed in many species, with consequent declines in polar species and increases in subtropical and tropical species.

15.9.2 Medium confidence

Raptors: Changes in temperature and precipitation are expected to influence species distribution ranges, with some current evidence of range losses.

Afro-Palearctic passerines: Migratory passerines are shifting or expected to shift polewards in both their breeding and wintering grounds, though the Sahara presents a barrier for those north of the Equator in their African wintering grounds.

Terrestrial mammals: Polewards range shifts have been observed and predicted. However, the ability of terrestrial mammals to shift their ranges in response to climate change is often unknown and may be restricted by lack of suitable habitat in areas with a suitable climate or barriers that prevent range shifts. The combined changes in rainfall and temperatures are predicted to cause habitat loss in many species due to reductions in food availability. For some species, particularly those with ranges that are heavily restricted by human activities and land use, direct climate change impacts on distribution may be hard to discern.

Bats: Range expansions and shifts towards higher latitudes have been observed in a few species and are predicted for many more.

Reptiles: Poleward range shifts have been observed but are likely to be constrained by anthropogenic pressures in potential new areas, although conservation actions can be targeted in such areas.

Sharks and rays: Poleward shifts of distribution are expected but some species may be constrained by their use of specific breeding habitats.

Monarch Butterfly: Climate change is likely to result in a northwards breeding range shift associated with likely changes in milkweed distribution. The effect of this on range extent is unclear, as are potential future changes in migration.

15.9.3 Low confidence

Waterbirds: Waterbird species vary in their capacity to alter migratory routes. Shorebirds seem highly site faithful, with changes only coming about as young birds learn new routes, whilst adult birds of other waterbird species appear able to occupy new wintering areas.

South American grassland birds: Suitable climatic conditions for South American grassland birds are shifting polewards. However, the extent to which these species will shift their ranges in response to a changing climate will be affected by suitable habitat and dispersal abilities, and is largely unknown.

Marine mammals: Species may alter their diet and foraging behaviour in response to climatic impacts on prey availability, but this may not compensate for losses in key prey.

Bony fish: Poleward shifts in range have been observed but are likely to be constrained by the distribution, and accessibility, of spawning grounds.

15.10 Phenology

There is strong evidence for changes in the timing of migration, mostly reflecting increased temperatures. Responses vary between species and groups, and impacts on population status may be either positive or negative.

15.10.1 High confidence

Waterbirds: The timing of migration and breeding is most often advancing in response to warmer temperatures, with generally positive impacts on breeding success.

Afro-Palearctic passerines: Temperature, in particular, positively influences the timing of breeding and spring arrival, although these effects can be modified by more local weather conditions en route.

Seabirds: Seabirds may be vulnerable to mismatch with the timing of spring peaks in prey abundance, as a result of the timing of those peaks being strongly temperature-dependent. Temperature-related reductions in prey abundance can also limit the ability of seabirds to shift their timing of breeding.

15.10.2 Medium confidence

Seabirds: The timing of migration or breeding can be sensitive to temperature and large-scale atmospheric systems, though responses vary within and between species.

Raptors: The timing of migration and onset of breeding responds to temperature and precipitation, though responses vary among species.

15.10.3 Low confidence

Seabirds: Some species may have adaptive responses to variations in climate that allow them to alter migratory routes or destinations.

South American grassland birds: Changes in phenology are likely, but limited evidence suggests that many grassland birds are not shifting their breeding phenology enough to keep pace with other environmental changes.

Terrestrial mammals: Some changes in birthing and migration phenology have been seen in migratory mammals, but cues for when to breed may be maladaptive.

Bats: The timing of migration in bats is more affected by weather conditions, such as precipitation and wind, than temperature.

Marine mammals: Changes in the timing of migration have been observed, with many species now arriving on the breeding grounds earlier, but population effects are mostly unknown.

Bony fish: Earlier migration and breeding timings have been observed, but evidence is lacking as to whether this is adaptive or maladaptive.

Sharks and rays: Changes in migration patterns may result from increased water temperatures.

CASE STUDY

16 Red Knot *Calidris canutus*

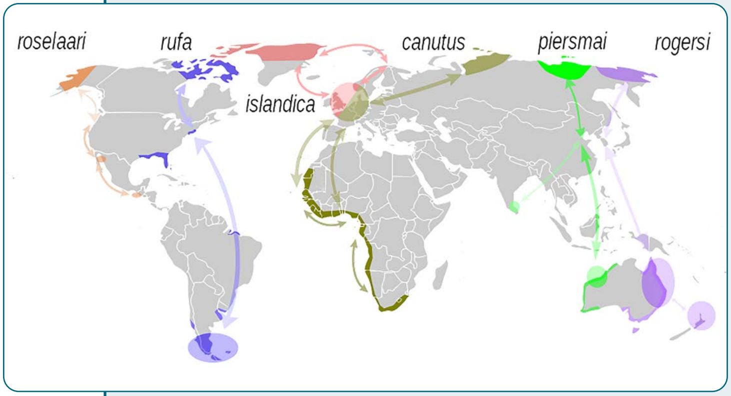
Status: Near Threatened; CMS Appendix II (*C. canutus rufa* Appendix I)

Distribution: Breeding range stretches from Alaska to northern Russia. Wintering range consists of Atlantic and Pacific coasts of the Americas, north-western Europe, west coast of Africa, southern Asia and Australasia (van Gills & Wiersma 1996).

Migration: There are six Red Knot subspecies, each with distinct migratory routes (see map below). The *rufa* subspecies has one of the longest migratory journeys among birds, of up to 15,000 km. Migration stopover sites are normally coastal (van Gils & Wiersma 1996).

Threats: Human infrastructure development and overfishing threaten habitat and food availability at stopover sites (McGowan *et al.* 2011; Mu *et al.* 2022).

Trends: Many subspecies have decreased greatly over both the short and long term (Andres *et al.* 2012; van Roomen 2014).



Migration of Red Knot subspecies (map by Shyamal published on Wikimedia Commons, based on information from Buehler D.M. *et al.* 2006. Reconstructing palaeoflyways of the late Pleistocene and early Holocene Red Knot Calidris canutus. *Ardea* 94 (3), 485–498)

Extreme rainfall: Wader species decline in abundance at wintering sites under the impacts of increasing cumulative rainfall (Kelly 2001).

Temperature increase: Red Knot offspring are smaller with shorter bills at warmer breeding grounds, which negatively impacts foraging success at their wintering grounds (van Gils *et al.* 2016). Chick growth rate is related to the timing of peak invertebrate abundance; whilst no mismatch is evident yet between hatching dates and invertebrate peaks, their vulnerability to this is high in a changing climate (Tulp & Schekkerman 2007; Lameris *et al.* 2022).

Climate change impacts: Northward shifts in the occurrence of tundra, predators and competitors is reducing the area of suitable breeding habitat for Arctic waders like the Red Knot (Anderson *et al.* 2023).

Extreme wind and storms: Severe weather can lock up foraging areas under ice and drive invertebrate prey deeper into the sediments, making it harder to forage and increasing mortality in many waders (Clark 2007).

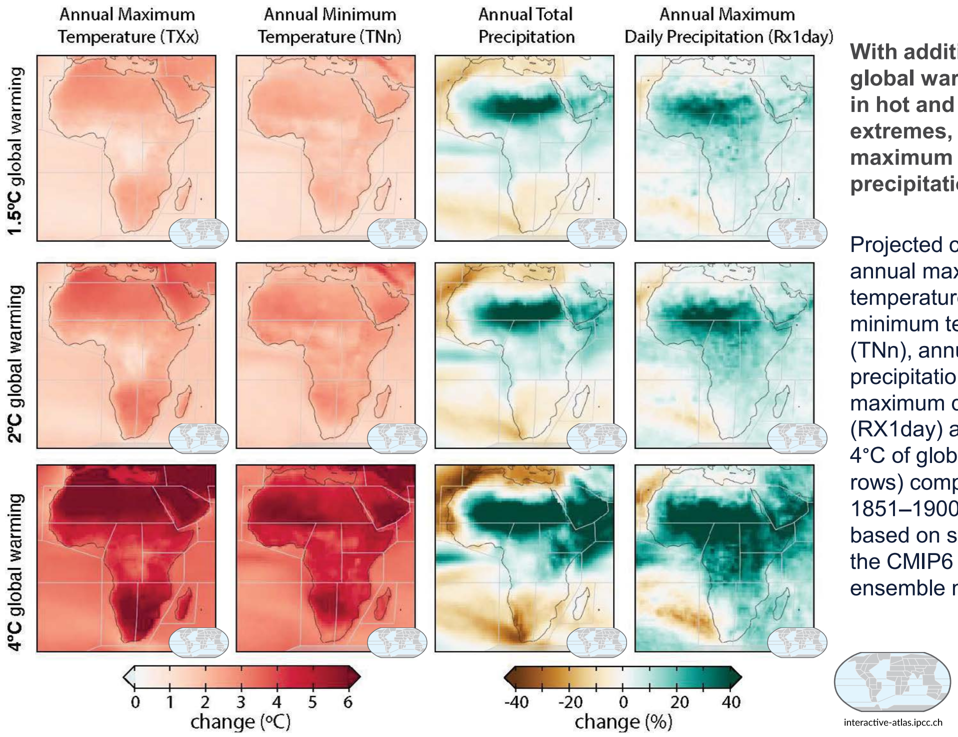
Sea level rise: Coastlines at stopover and non-breeding sites are predicted to change from sea level rise and encroaching human development (e.g. Galbraith *et al.* 2014), which will reduce available foraging time for waders.

Conservation action: The co-ordinated protection and conservation management of key wetland habitat along Red Knot migratory routes will help to mitigate climate change impacts and support potential range shifts, which are already occurring in some arctic waders (Anderson *et al.* 2023).

17 Impacts of climate change on the African savanna

Ecosystem – savanna: African savannas are open landscapes dominated by grasses and dotted with shrubs and trees. They are found in tropical regions south of the Saharan desert and are often rich in wildlife, many of which seasonally migrate following patterns in rainfall and primary productivity (Mukhopadhyay *et al.* 2019). African savanna species include the African Elephant (Endangered; CMS Appendix II), Grevy's Zebra (Endangered; CMS Appendix I), Red-fronted Gazelle (Vulnerable; CMS Appendix I), Giraffe (Vulnerable; CMS Appendix II), Cheetah (Vulnerable; CMS Appendix I) and Lion (Vulnerable; Appendix II), as well as a wide range of birds including raptors, such as the White-headed Vulture (Critically Endangered; CMS Appendix I and II), shorebirds, such as the Curlew Sandpiper (Near Threatened; CMS Appendix II) and passerines, such as the Blue Swallow (Vulnerable; CMS Appendix I and II).

Predicted climate change: Temperature and carbon dioxide (CO_2) levels are predicted to rise across Africa with climate change (see graphic below, IPCC 2021; Conradi *et al.* 2020). Rainfall increases are predicted over the Sahel region, northern Africa and western equatorial Africa, whereas rainfall declines are expected over



With additional increases in global warming, changes in hot and cold temperature extremes, mean and maximum one-day precipitation get larger.

Projected changes in annual maximum temperature (TXx), annual minimum temperature (TNn), annual mean precipitation and annual maximum daily precipitation (RX1day) at 1.5°C, 2°C, and 4°C of global warming (in rows) compared to 1851–1900. Results are based on simulations from the CMIP6 multi-model ensemble mean.

Climate change projections for Africa (IPCC 2021) highlighting not only changes in temperature but also substantial changes in rainfall pattern. (From: Gutiérrez, J.M. *et al.* 2021. Regional Fact Sheet for Africa - Interactive Atlas. In: V. Masson-Delmotte *et al.* (eds.). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Available from http://interactive-atlas.ipcc.ch/)

parts of eastern and southern Africa (IPCC 2021). This is likely to increase desertification along the boundaries between savanna and desert in some areas, and increase woody encroachment on savanna in other areas; the area of savanna habitat is therefore likely to reduce.

Rainfall declines and drought: There are likely to be declines in many terrestrial mammal populations in areas with decreased rainfall due to the link between rainfall and primary productivity, which will limit food availability for herbivores (Mukhopadhyay *et al.* 2019; Dejene *et al.* 2021), and thus prey for carnivores (Celesia *et al.* 2010; Sanderson *et al.* 2022). Increased levels of drought have also been attributed to a rise in the prevalence of mass mortalities (Wang *et al.* 2021), increased parasite loads as animals are forced to aggregate around limited resources (Munson *et al.* 2008; Titcomb *et al.* 2021), and negative human-wildlife interactions as wildlife stray into human settlements in search of alternative resources (Mukeka *et al.* 2019).

Rainfall increases and CO_2 increases: Where rainfall increases, this may lead to shrub encroachment on savannas (Tews & Jeltsch 2004). Savannas are also predicted to become woodier due to increasing concentrations of atmospheric CO_2, as woody plants will benefit more from this than grasses (Conradi *et al.* 2020). Any declines in large herbivores, particularly African Elephants, will further allow shrub encroachment (Stevens *et al.* 2016). Evidence suggests this shift is already occurring (Conradi *et al.* 2020) and it is predicted to threaten many species that rely on grassy habitats (Tews & Jeltsch 2004). Across southern Africa, bird species associated with open savanna are generally declining, whilst ones associated with closed, woody savanna are increasing (Sirami *et al.* 2009). For example, an increase in trees might benefit many vulture species, which require trees for nesting (Rushworth *et al.* 2018).

Temperature increases: Increasing temperatures may reduce reproductive success (Abrahms *et al.* 2022) and decrease population size (Martínez-Freiría *et al.* 2016) in some migratory savanna animals. This is largely due to difficulties thermoregulating (Rabaiotti *et al.* 2019; Pontzer *et al.* 2020; Semenzato *et al.* 2021), as species are generally adapted to a specific temperature range. Behavioural adaptations can mitigate some temperature increase, such as foraging earlier and later in the day (Semenzato *et al.* 2021), but this can reduce foraging opportunities and hence total energy intake (Bladon *et al.* 2019; Bourne *et al.* 2020). Conversely, higher temperatures can improve hunting success for some carnivores, as prey often struggle to thermoregulate more than predators during hunting events (Creel *et al.* 2016).

Climate change adaptation: While poleward range shifts and range expansions are generally predicted for many species (Beale *et al.* 2013; Phipps *et al.* 2017), the ability of some species to shift their ranges in response to climate change is often unknown. Anthropogenic barriers, such as transport/energy infrastructure and human settlements, may limit range shifts for some species, particularly large mammals. Maintaining and creating protected areas and wildlife corridors is vital to support migratory species' range shifts and adaptation to a changing climate (Li *et al.* 2019; Liang *et al.* 2022).

Key to abbreviations: CMS = Convention for the Conservation of Migratory Species of Wild Animals; Vulnerable/Near Threatened/Endangered refers to status under the International Union for Conservation of Nature (IUCN) Red List Assessment for the global population.

CASE STUDY

18 Polar Bear *Ursus maritimus*

Status: Vulnerable; CMS Appendix II

Distribution: Arctic and near-Arctic Greenland and Canada (see graphic below, Derocher 2010).

Migration: Polar Bears migrate in the autumn to sea ice edges, following their main prey, seals. In the spring, they follow retreating sea ice, moving on land for the summer months, where they hunt other prey, such as birds.

Threats: The reduction in sea ice caused by climate change is the key threat to Polar Bears (Atwood *et al.* 2015).

Trends: Most populations are declining and many sub-populations are likely to go extinct over the next few decades (Castro de la Guardia *et al.* 2013; Bromaghin *et al.* 2021). Almost complete extinction is predicted by 2100 (Hunter *et al.* 2010; Molnár *et al.* 2020).

Distribution of the Polar Bear (from A.E. Derocher. 2010. The prospects for Polar Bears. *Nature*, 468, 905-906. © 2010, Springer Nature Limited)

Temperature increase: The Arctic is warming twice as fast as the global mean, and sea ice extent is rapidly decreasing (IPCC 2021). As sea ice contracts, hunting habitat for Polar Bears declines, which reduces population sizes (Stirling & Parkinson 2006; Bromaghin *et al.* 2021), survival (Molnár *et al.* 2010, 2020), body condition (Derocher *et al.* 2004; Stirling & Parkinson 2006) and reproductive success (Peacock *et al.* 2011). As seals rely on sea ice for breeding, Polar Bear populations will also be impacted by likely declines in seal populations (Tynan & DeMaster 1997).

Pollution: Prolonged fasting due to declines in food availability will increase the tissue concentrations of dangerous pollutants, which is likely to have population-level impacts on reproduction and survival (Jenssen *et al.* 2015; Nuijten et al. 2016).

Adaptations: The Polar Bear's diet is shifting to include other species, such as ground-nesting birds (Prop *et al.* 2015), whales (Rode *et al.* 2022), fish and blueberries (Dyck & Kebreab 2009). However, these food sources are not likely to sufficiently replace their seal prey (Petherick *et al.* 2021; Rode et al. 2022).

Polar Bears are now migrating further, or spending more time on land (Pilfold *et al.* 2017). Both strategies reduce survival, particularly for cubs (Cherry *et al.* 2013; Miller *et al.* 2022), and increase the risk of conflict with humans.

Conservation action: Efforts to limit global warming will reduce the rate of sea ice loss, key to Polar Bear survival.

CASE STUDY

19 Loggerhead Turtle *Caretta caretta*

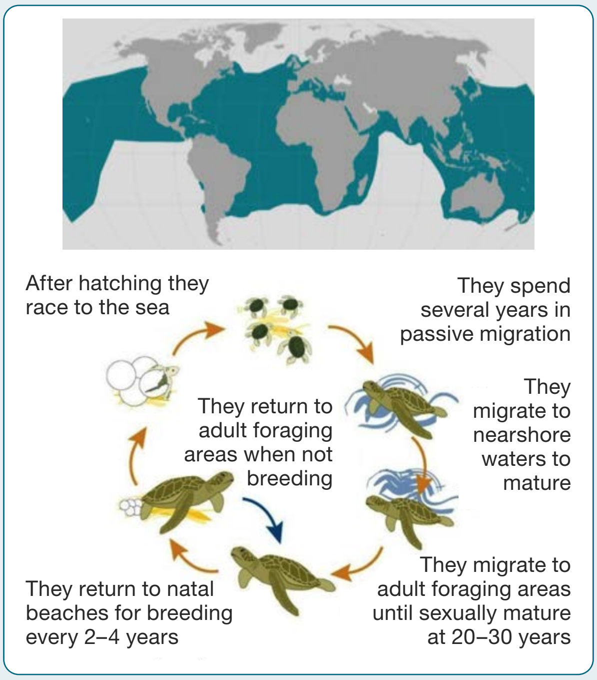
Status: Vulnerable; CMS Appendix I and II.

Threats: The key threats to Loggerhead Turtles are bycatch in fishing gear and human development on their nesting beaches (Fuentes *et al.* 2013).

Trends: Trends vary between populations, but most have declined in the last few decades, some by up to 90% (NOAA Fisheries 2021).

Migration and distribution: Long-distance migration occurs between nesting beaches and feeding grounds. For example, many Loggerhead Turtles that hatch in the western Atlantic migrate to feeding grounds in the eastern Atlantic or the Mediterranean.

Sea level rise and storms: Many nesting beaches will disappear as sea levels rise or storms wash them away (Poloczanska *et al.* 2009; Patrício *et al.* 2021). It is predicted that around 60% of current Mediterranean nesting sites will disappear by 2100 (Dimitriadis *et al.* 2022), and over 80% of Atlantic USA sites by 2050 (Fuentes *et al.* 2020).



Upper image: Approximate representation of the Loggerhead Turtle's range (courtesy: NOAA Fisheries)
Lower image: The life-cycle of the Loggerhead Turtle

Increasing temperatures: As turtles have temperature-dependent sex determination, higher temperatures are increasing the female:male sex ratio (Patrício *et al.* 2021). This currently has a positive impact in most populations (Perez *et al.* 2016). However, in the future, the potential for extremely limited male populations could cause population declines (Hays *et al.* 2014).

Adaptations: Poleward range shifts in response to higher temperatures have been observed and will be key to Loggerhead Turtle adaptation to climate change (Perez *et al.* 2016; Girard *et al.* 2021). However, human coastal developments reduce the availability of suitable nesting beaches in new areas (Perez *et al.* 2016; Fuentes *et al.* 2020).

Phenology shifts in nesting have been observed (Mazaris *et al.* 2008); egg laying earlier in the season allows turtle eggs to develop at lower temperatures, preventing female skewed sex ratios (Laloë *et al.* 2016).

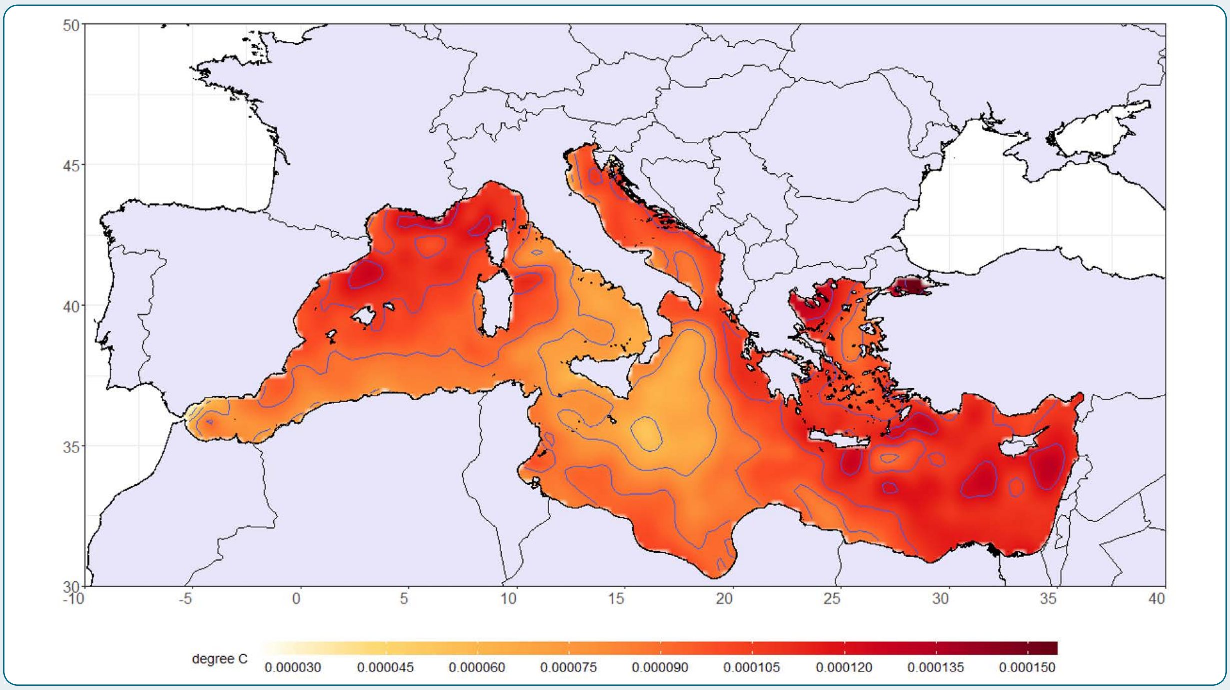
Conservation actions: Shading beaches through tree planting (Mitchell & Janzen 2010) or translocating eggs to cooler locations (Hawkes *et al.* 2007) may prevent severely skewed sex ratios. Preventing coastal developments on nesting beaches and protecting those with adjoining sand dunes will conserve vital habitat and facilitate potential range shifts (Katselidis *et al.* 2014; Girard *et al.* 2021). Various Memoranda of Understanding and action plans under the CMS provide a mechanism for international co-ordination on turtle conservation.

CASE STUDY

20 Impacts of climate change on Mediterranean wetlands

Ecosystem - Mediterranean wetland: There are approximately 18.5 million ha of wetlands around the Mediterranean Sea, comprising 1.1 to 1.5% of wetlands worldwide. They incorporate a range of natural habitats such as salt, brackish or freshwater lakes and marshes, permanent and temporary rivers, and riverine forests. In the past century, around 50% of Mediterranean wetlands have disappeared, and many that remain have been degraded or are now artificial wetlands – rice fields, reservoirs, saltpans and oases (Beltrame *et al.* 2012; Geijzendorffer 2018). A variety of different species utilise Mediterranean wetlands, including waterbirds such as the White-headed Duck (Endangered; CMS Appendix I and II), seabirds such as Audouin's Gull (Vulnerable; CMS Appendix I and II), raptors such as the Western Marsh Harrier (Least Concern; CMS Appendix II), Mediterranean Monk Seals (Endangered; CMS Appendix I and II), Green Turtles (Endangered; CMS Appendix I and II) and European Eels (Critically Endangered; CMS Appendix II).

Predicted climate change: Some climate change effects have already impacted the Mediterranean Sea and its wetlands – in particular sea level has risen by 22 cm over the course of the 20th century (Beltrame *et al.* 2012). In general, the expected risks for the Mediterranean Sea's wetlands are: greater warming than average; an overall decline in rainfall; greater variability in rainfall and temperature; heat waves during summer months; and an increased frequency of extreme events (e.g. droughts and floods)



Daily warming trend in the Mediterranean basin from 1982 to 2019. Each contour denotes a change of 1.5 × 10^{-5} °C/day. (From Pastor F. *et al.* 2020. A Warming Mediterranean: 38 Years of Increasing Sea Surface Temperature. *Remote Sensing*, 12 (17), 2687)

(IPCC 2021). Land areas within the region have warmed by almost 2°C in Iberia, southern France and North Africa, and rainfall has significantly decreased, with a 20% decline in southern European countries around the Mediterranean (Plan Bleu 2008).

Rainfall declines and drought: Flamingo colonies breed within wetlands but depend on a minimum level of rainfall. The lower precipitation levels predicted with increased climate change are likely to reduce the probability of successful breeding of Greater Flamingos (Least Concern; CMS Appendix II) in the Mediterranean, particularly in the south (Béchet *et al.* 2012). For species like the Aquatic Warbler (Vulnerable; CMS Appendix I and II) that use wetland areas in the Mediterranean for staging on their migrations, droughts will reduce the amount of habitat available, and hence the number of individuals that can be supported during the passage period (Birdlife International 2008).

Temperature increases: Nesting grounds for Green Turtles and Loggerhead Turtles (Vulnerable; CMS Appendix I and II) are predicted to increase in average temperature, giving rise to potential changes in sex ratios (greater numbers of females, Dissanayake *et al.* 2021). Warming of coastal waters reduces recruitment numbers and survival of the European Eel, and causes earlier colonisation through increased migratory responses (Borges *et al.* 2019).

Extreme weather patterns: El Niño events are predicted to become more frequent and intense, and to increase global temperatures (McPhaden *et al.* 2020). The impacts of El Niño events on Atlantic fish stocks will have a knock-on effect on fish stocks in the Mediterranean, threatening Mediterranean Monk Seals (CMS 2005).

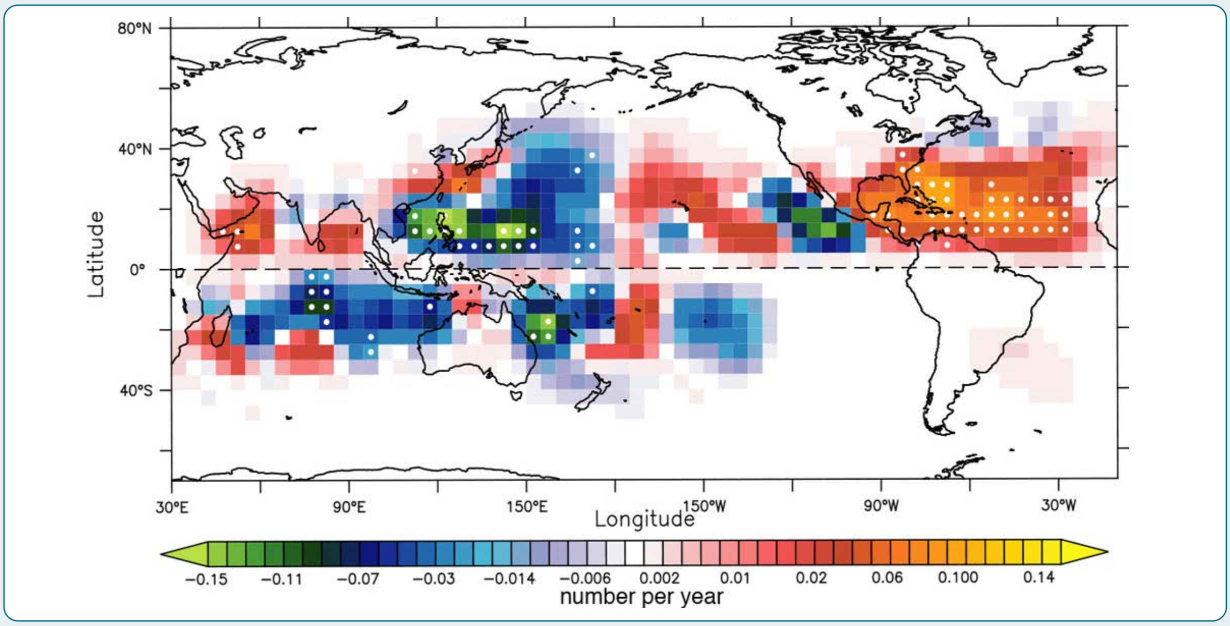
Flooding and increasing water levels: Cold-dwelling species are most likely to be disadvantaged from increasing water levels. Given that general assemblages of waterbirds are shifting their ranges northwards, more birds may shift their wintering range to the Mediterranean Basin from sub-Saharan Africa (Beltrame *et al.* 2012). Coastal erosion and flooding from sea level rise may reduce the extent of suitable areas for Monk Seals to breed (CMS 2005) and turtles to nest (Dissanayake *et al.* 2021). On the other hand, in periods of excess rainfall and sea level rise, the Greater Flamingo's preferred saline sites are predicted to improve in quality for breeding (Béchet & Johnson 2008).

Sea acidification: Acidification of the ocean, caused by increasing carbon dioxide emissions slowly changing seawater chemistry, has been shown to hinder migratory responses of European Eels by reducing their ability to follow riverine cues for migration (Borges *et al.* 2019).

21 The impacts of storms and cyclones on migratory species

Predicted climate change: Storms and cyclones are predicted to increase in frequency and severity over the coming decades. An increase in the intensity of cyclones has already been observed, particularly in the North Atlantic since the 1980s (see graphic below, Murakami *et al.* 2020). The strong winds, heavy rainfall and resulting floods that come with storms can cause large population declines across taxa and habitats (Maxwell *et al.* 2019). Coastal ecosystems are particularly vulnerable to such storms, which can cause declines in body condition, survival, breeding success and population size across many coastal and marine migratory species, including seabirds, marine mammals, reptiles and fish.

Seabirds: Storms have been linked to several mass-mortality events in seabirds (Camphuysen *et al.* 1999). Strong winds can blow birds away from feeding areas, severely limit foraging efficiency (Darby *et al.* 2022), or cause complete breeding failures (Yannic *et al.* 2014). Coastal storms can also result in the loss of low-lying coastal nests (Weston & Fraser 2020) or exposed cliff nests (Newell *et al.* 2015) in many seabird species. For example, a landslide caused by heavy rainfall in a storm destroyed over 5% of White-chinned Petrel (Vulnerable; CMS Appendix II) burrows on an island in New Zealand, killing over 2% of the population (Elliot & Walker 2022). Avian mass-mortality events have also been attributed to severe hailstorms (Higgins & Johnson 1978; Narwade *et al.* 2014). For example, 95% of individuals in a Black-billed Gull (Near Threatened) colony in New Zealand were killed in a severe hail storm (Weston & Fraser 2020).



Observed linear trends in tropical cyclone frequency for the period 1980 to 2018 (number per year) (From Murakami, H. *et al.* 2020. Detected climatic change in global distribution of tropical cyclones. *Proceedings of the National Academy of Sciences*, 117, 10706–10714. Open access article distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND))

Other seabirds that have suffered increased mortality due to storm activity include Atlantic Yellow-nosed Albatrosses (Endangered; CMS Appendix II) and Magellanic Penguins (Tavares *et al.* 2020).

Marine mammals: Coastal storms can scour the seabed and cause freshwater floods, as well as reduce seagrass productivity, which has been linked to high mortality of inshore dolphin species and Dugongs (Vulnerable; CMS Appendix II) (Meager & Limpus 2014), and to reduced reproductive success and survival of North Atlantic Right Whales (Critically Endangered; CMS Appendix I) (Lanyon & Burgess 2019).

Reptiles: An increasing frequency and intensity of storms will cover or inundate some nesting beaches currently used by marine turtle species and Salt-water Crocodiles (Least Concern; CMS Appendix II), leading to loss of habitat and embryo mortality (Fukuda *et al.* 2022; Patrício *et al.* 2021).

Sharks and other Chondrichthyes: Increasing storms and rainfall will cause declines in salinity in many coastal regions (Grose *et al.* 2020). Many shark and ray species rely on coastal habitats, particularly in juvenile stages, and occupy very narrow salinity ranges (Schlaff *et al.* 2014). Movement out of areas after extreme rainfall events has been noted in many shark species (Schlaff *et al.* 2014; Gutowsky *et al.* 2021) and therefore population declines may arise if movement is not possible or salinity declines cause habitat loss (Morash *et al.* 2016). However, some species have shown high resilience to rapid changes in salinity, such as Smalltooth Sawfish (Critically Endangered; CMS Appendix I and II) (Brame *et al.* 2019) and the Tope Shark (Critically Endangered; CMS Appendix II) (Morash *et al.* 2016). The population-level impacts of storms on many Chondrichthyes are largely unknown.

Bony fish: For some species, the impacts of storms may be severe but short-lived. For example, a population of Pink Salmon declined by 90% after an extreme rainfall event, but recovered to pre-disturbance levels within two generations (Milner *et al.* 2013; Maxwell *et al.* 2019). In some cases, cyclones may benefit marine species due to the disturbance increasing food availability downstream. For example, Striated Surgeonfish densities increase after cyclones pass through, having disturbed the water column (Maxwell *et al.* 2019). However, invasive estuarine fish species in particular have been observed to benefit from storm-related floods (Ilarri *et al.* 2022).

Key to abbreviations: CMS = Convention for the Conservation of Migratory Species of Wild Animals; Vulnerable/Near Threatened/Critically Endangered refers to status under the International Union for Conservation of Nature (IUCN) Red List Assessment for the global population.

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22.2 Case studies

Red Knot *Calidris canutus*

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Polar Bear *Ursus maritimus*

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23 Supplementary material: Species list

List of species considered in articles within the literature review. Where species are included in CMS Appendix I or II (or both), the CMS instruments for conservation are also provided. Note: key to abbrevations at end of the table.

Common name	Scientific name	CMS Appendix	Conservation instruments
Aves: Seabirds			
Adélie Penguin	*Pygoscelis adeliae*		
African Penguin	*Spheniscus demersus*	II	CMS, AEWA
Atlantic Puffin	*Fratercula arctica*		
Balearic Shearwater	*Puffinus mauretanicus*	I	CMS
Black-footed Albatross	*Phoebastria nigripes*		CMS, ACAP
Blue-footed Booby	*Sula nebouxii*		
Brünnich’s Guillemot	*Uria lomvia*		
Bulwer's Petrel	*Bulweria bulwerii*		
Common Tern	*Sterna hirundo*	II	CMS, AEWA
Cory's Shearwater	*Calonectris borealis*		
Crested Auklet	*Aethia cristatella*		
Emperor Penguin	*Aptenodytes forsteri*		
Galápagos Penguin	*Spheniscus mendiculus*		
Gentoo Penguin	*Pygoscelis papua*		
Glaucous Gull	*Larus hyperboreus*		
Great Shearwater	*Puffinus gravis*		
Herring Gull	*Larus argentatus*		
Laysan Albatross	*Phoebastria immutabilis*		CMS, ACAP
Light-mantled Sooty Albatross	*Phoebetria palpebrata*	II	CMS, ACAP
Little Auk	*Alle alle*		AEWA
Little Penguin	*Eudyptula minor*		
Magellanic Penguin	*Spheniscus magellanicus*		
Manx Shearwater	*Puffinus puffinus*		
Pacific Loon	*Gavia pacifica*		

Common name	Scientific name	CMS Appendix	Conservation instruments
Parakeet Auklet	*Aethia psittacula*		
Ringed-billed Gull	*Larus delawarensis*		
Roseate Tern	*Sterna dougallii*	II	CMS, AEWA
Shag	*Gulosus aristotelis*		
Snow Petrel	*Pagodroma nivea*		
Sooty Shearwater	*Puffinus griseus*		
Southern Fulmar	*Fulmarus glacialoides*		
Southern Rockhopper Penguin	*Eudyptes chrysocome*		
Yellow-nosed Albatross	*Thalassarche chlororhynchos*	II	CMS, ACAP
Aves: Waterbirds			
American White Pelican	*Pelecanus erythrorhynchos*		
Barnacle Goose	*Branta leucopsis*	II	CMS, AEWA
Black-faced Spoonbill	*Platalea minor*	I	
Black-necked Crane	*Grus nigricollis*	I	CMS
Black-tailed Godwit	*Limosa limosa*	II	CMS, AEWA
Dalmatian Pelican	*Pelecanus crispus*	I&II	CMS, AEWA
Great Bittern	*Botaurus stellaris*	II	CMS, AEWA
Great White Pelican	*Pelecanus onocrotalus*	I&II	CMS, AEWA
Greater Flamingo	*Phoenicopterus roseus*		
Lesser Snow Goose	*Anser caerulescens caerulescens*		
Northern Lapwing	*Vanellus vanellus*	II	CMS, AEWA
Pink-footed Goose	*Anser brachyrhynchus*	II	CMS, AEWA
Purple Heron	*Ardea purpurea*	II	CMS, AEWA
Red-crowned Crane	*Grus japonensis*	I	CMS
Red Knot	*Calidris canutus*	II	AEWA
Redshank	*Tringa totanus*	II	CMS, AEWA
Semipalmated Sandpiper	*Calidris pusilla*	I	CMS
Slavonian Grebes	*Podiceps auritus*	II	CMS, AEWA
Whimbrel	*Numenius phaeopus*	II	CMS, AEWA
White-headed Duck	*Oxyura leucocephala*	I	CMS, AEWA
White Stork	*Ciconia ciconia*	II	CMS, AEWA
Whooping Crane	*Grus americana*		

Common name	Scientific name	CMS Appendix	Conservation instruments
Aves: Raptors			
Aplomado Falcon	*Falco femoralis*		
Arctic Peregrine Falcon	*Falco peregrinus tundrius*		
Eurasian Scops Owl	*Otus scops*		Raptors
Golden Eagle	*Aquila chrysaetos*	II	CMS, Raptors
Little Owl	*Athene noctua*		
Montagu's Harrier	*Circus pygargus*	II	CMS, Raptors
Oriental Honey Buzzard	*Pernis ptilorhynchus*	II	CMS, Raptors
Red Kite	*Milvus milvus*	II	CMS, Raptors
Snowy Owl	*Bubo scandiacus*		Raptors
Wedge-tailed Eagle	*Aquila audax*		
Aves: Afro-Palearctic passerines			
Alpine Swift	*Tachymarptis melba*		
American Redstart	*Setophaga ruticilla*		
Barn Swallow	*Hirundo rustica*		
Black-throated Blue Warbler	*Setophaga caerulescens*		
Great Reed Warbler	*Acrocephalus arundinaceus*		
Great Tit	*Parus major*		
Pied Flycatcher	*Ficedula hypoleuca*	II	
Reed Warbler	*Acrocephalus scirpaceus*		
Sand Martin	*Riparia riparia*		
Sedge Warbler	*Acrocephalus schoenobaenus*		
Tree Swallow	*Tachycineta bicolor*		
Aves: Grassland passerines			
Budgerigar	*Melopsittacus undulatus*		
Carnaby’s Black Cockatoo	*Zanda latirostris*		
Little Bustard	*Tetrax tetrax*	I&II	CMS
Red-billed Quelea	*Quelea quelea*		
Zebra Finch	*Taeniopygia castanotis*		
Mammalia: Terrestrial mammals			
African Elephant	*Loxodonta africana*	II	CMS, West African Elephants

Common name	Scientific name	CMS Appendix	Conservation instruments
Asian Elephant	*Elephas maximus*	I	CMS
Bison	*Bison*		
Caribou (Reindeer)	*Rangifer tarandus*		
Chimpanzee	*Pan troglodytes*	I&II	CMS
Giraffe	*Giraffa camelopardalis*	II	CMS
Gobi Bear	*Ursus arctos gobiensis/ isabellinus*	I	CMS
Goitered Gazelle	*Gazella subgutturosa*	II	CMS, Central Asian Mammals Initiative
Eastern Gorilla	*Gorilla beringei*	I	CMS, Gorilla Agreement
Western Gorilla	*Gorilla gorilla*	I	CMS, Gorilla Agreement
Elk	*Cervus elaphus*		
Grevy's Zebra	*Equus grevyi*	I	CMS
Jaguar	*Panthera onca*	I&II	
Leopard	*Panthera pardus*	II	CMS, African Carnivores Initiative, Central Asian Mammals Initiative
Lion	*Panthera leo*	II	CMS, African Carnivores Initiative
Przewalski's Horse	*Equus ferus przewalskii*	I	CMS, Central Asian Mammals Initiative
Saiga Antelope	*Saiga tatarica*	II	Central Asian Mammals Initiative, Saiga Antelope
South Andean Huemul	*Hippocamelus bisulcus*	I	CMS
Wild Dog	*Lycaon pictus*	II	CMS, African Carnivores Initiative
Mammalia: Marine mammals			
Antarctic Fur Seals	*Arctocephalus gazella*		
Atlantic White-sided Dolphin	*Lagenorhynchus acutus*	II	CMS, ASCOBANS
Beluga	*Delphinapterus leucas*	II	CMS
Blue Whale	*Balaenoptera musculus*	I	CMS, ACCOBAMS, Pacific Islands Cetaceans
Bottlenose Dolphin	*Tursiops truncatus*	I&II	ASCOBANS, Western African Aquatic Mammals, CMS, ACCOBAMS
Bowhead Whale	*Balaena mysticetus*	I	CMS
Caspian Seal	*Pusa caspica*	I&II	CMS

Common name	Scientific name	CMS Appendix	Conservation instruments
Common Dolphin	*Delphinus delphis*	I&II	CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Dall's Porpoise	*Phocoenoides dalli*	II	CMS
Dugong	*Dugong dugon*	II	CMS, Dugongs
Fin Whale	*Balaenoptera physalus*	I&II	CMS, ACCOBAMS, Pacific Islands Cetaceans
Ganges River Dolphin	*Platanista gangetica*	I&II	CMS
Grey Seal	*Halichoerus grypus*	II	CMS, Wadden Sea Seals
Grey Whale	*Eschrichtius robustus*		ACCOBAMS
Harbour Porpoise	*Phocoena phocoena*	II	CMS, ASCOBANS, ACCOBAMS, Western African Aquatic Mammals
Humpback Whale	*Megaptera novaeangliae*	I	CMS, ACCOBAMS, Pacific Islands Cetaceans
Killer Whale	*Orcinus orca*	II	CMS, ACCOBAMS, ASCOBANS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Minke Whale	*Balaenoptera acutorostrata*		
Narwhal	*Monodon monoceros*	II	ASCOBANS
North Atlantic Right Whale	*Eubalaena glacialis*	I	CMS, ACCOBAMS
Northern Fur Seal	*Callorhinus ursinus*		
Polar Bear	*Ursus maritimus*	II	
Rorqual Whale	*Balaenoptera*		
South American Sea Lion	*Otaria flavescens*	II	CMS
Southern Right Whale	*Eubalaena australis*	I	CMS, Pacific Islands Cetaceans
Sperm Whale	*Physeter macrocephalus*	I&II	CMS, ACCOBAMS, Pacific Islands Cetaceans
Striped Dolphin	*Stenella coeruleoalba*	II	ACCOBAMS, ASCOBANS, Western African Aquatic Mammals, Pacific Islands Cetaceans
Subantarctic Fur Seal	*Arctocephalus tropicalis*		
White-beaked Dolphin	*Lagenorhynchus albirostris*	II	CMS, ASCOBANS

Common name	Scientific name	CMS Appendix	Conservation instruments
Mammalia: Bats			
Bechstein's Bat	*Myotis bechsteinii*	II	CMS, EUROBATS
Brazilian Free-tailed Bat	*Tadarida brasiliensis*	I	
Daubenton's Bat	*Myotis daubentonii*	II	CMS, EUROBATS
Greater Horseshoe Bat	*Rhinolophus ferrumequinum*	II	CMS, EUROBATS
Greater Long-nosed Bat	*Leptonycteris nivalis*		
Fringed Myotis	*Myotis thysanodes*		
Indian Flying Fox	*Pteropus giganteus*		
Kuhl's Pipistrelle Bat	*Pipistrellus kuhlii*	II	CMS, EUROBATS
Lesser Horseshoe Bat	*Rhinolophus hipposideros*	II	CMS, EUROBATS
Natal Long-fingered Bat	*Miniopterus natalensis*	II	CMS
Nathusius's Pipistrelle Bat	*Pipistrellus nathusii*	II	CMS, EUROBATS
Natterer's Bat	*Myotis nattereri*	II	CMS, EUROBATS
Soprano Pipistrelle	*Pipistrellus pygmaeus*	II	CMS, EUROBATS
Savi's Pipistrelle Bat	*Hypsugo savii*	II	CMS, EUROBATS
Mexican Free-Tailed Bat	*Tadarida brasiliensis*	I	CMS
Noctule Bat	*Nyctalus noctule*	II	CMS, EUROBATS
Reptiles			
Arrau Turtle	*Podocnemis expansa*	I&II	CMS
Flatback Turtle	*Natator depressus*		
Green Turtle	*Chelonia mydas*	I	CMS, IOSEA Marine Turtles, Atlantic Turtles
Loggerhead Turtle	*Caretta caretta*	I	CMS, IOSEA Marine Turtles, Atlantic Turtles
Saltwater Crocodile	*Crocodylus porosus*	II	CMS
Actinopterygii (Bony fish)			
Adriatic Sturgeon	*Acipenser naccarii*	II	CMS
American Eel	*Anguilla rostrata*		
Beluga Sturgeon	*Huso huso*	II	CMS
Chinese Paddlefish	*Psephurus gladius*	II	
Chinese Sturgeon	*Acipenser sinensis*	II	CMS

Common name	Scientific name	CMS Appendix	Conservation instruments
European Eel	*Anguilla anguilla*	II	
European Sturgeon	*Acipenser sturio*	I&II	CMS
Giant Catfish	*Pangasianodon gigas*	I	
Green Sturgeon	*Acipenser medirostris*	II	CMS
Lake Sturgeon	*Acipenser fulvescens*	II	CMS
Russian Sturgeon	*Acipenser gueldenstaedtii*	II	CMS
Siberian Sturgeon	*Acipenser baerii*	II	CMS
Chondrichthyes (Sharks and rays)			
Basking Shark	*Cetorhinus maximus*	I&II	CMS, Sharks
Blue Shark	*Prionace glauca*	II	CMS
Dusky Shark	*Carcharhinus obscurus*	II	CMS, Sharks
Manta Ray	*Mobula/Manta birostris*	I&II	CMS, Sharks
Mobula Ray	*Mobula*		
Scalloped Hammerhead Shark	*Sphyrna lewini*	II	CMS, Sharks
Silky Shark	*Carcharhinus falciformis*	II	CMS, Sharks
Smalltooth Sawfish	*Pristis pectinata*	I&II	CMS, Sharks
Tope Shark	*Galeorhinus galeus*	II	CMS
Undulate Ray	*Raja undulata*		
Whale Shark	*Rhincodon typus*	I&II	CMS, Sharks
White Shark	*Carcharodon carcharias*	I&II	CMS, Sharks
Insects			
Monarch Butterfly	*Danaus plexippus*	II	

Key to abbreviations: **AEWA** = Agreement on the Conservation of African-Eurasian Migratory Waterbirds; **ACAP** = Agreement on the Conservation of Albatrosses and Petrels; **Raptors** = Memorandum of Understanding on the Conservation of Migratory Birds of Prey in Africa and Eurasia; **West African Elephants** = Memorandum of Understanding concerning Conservation Measures for the West African Populations of the African Elephant (Loxodonta africana); **Gorilla Agreement** = Agreement on the Conservation of Gorillas and their Habitats; **Saiga Antelopes** = Memorandum of Understanding concerning Conservation, Restoration and Sustainable Use of the Saiga Antelope; **ASCOBANS** = Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas; **ACCOBAMS** = Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area; **Pacific Islands Cetaceans** = Memorandum of Understanding for the Conservation of Cetaceans and their Habitats in the Pacific Islands Region; **Western African Aquatic Mammals** = Memorandum of Understanding concerning the Conservation of the Manatee and Small Cetaceans of Western Africa and Macaronesia; **Dugongs** = Memorandum of Understanding on the Conservation and Management of Dugongs (Dugong dugon) and their Habitats throughout their Range; **Wadden Sea Seals** = Agreement on the Conservation of Seals in the Wadden Sea; **EUROBATS** = Agreement on the Conservation of Populations of European Bats; **IOSEA Marine Turtles** = Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats of the Indian Ocean and South-East Asia; **Atlantic Turtles** = Memorandum of Understanding concerning Conservation Measures for Marine Turtles of the Atlantic Coast of Africa; **Sharks** = Memorandum of Understanding on the Conservation of Migratory Sharks.

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