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Flying in the face of climate change: a review of climate change, past, present and future

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The distribution and abundance of birds is known to depend critically upon climate variability at a range of temporal and spatial scales. In this paper we review historical changes in climate in the context of what is known about climate variability over the last millennium, with particular reference to the British Isles. The climate of Britain is now warmer than it has been in at least 340 years, with the 1990s decade 0.5 °C warmer than the 1961–1990 average. In addition, the frequency of cold days (mean temperature below 0 °C), particularly during March and November, has declined and there has been a marked shift in the seasonality of precipitation, with winters becoming substantially wetter and summers becoming slightly drier. Current understanding is that the rate of future warming is likely to accelerate with more frequent and more intense summer heatwaves, milder winters, an increase in winter rainfall, an increased risk of winter river floods, and an increase in mean sea-level and associated coastal flooding. All of these aspects of climate change are likely to impact on coastal birds. A range of potential future climate scenarios for the British Isles are presented derived from recently completed global climate model experiments. For migrant bird species, changes in the British climate have also to be seen within the context of remote climate change in both the breeding and the overwintering grounds.

Although we are particularly concerned at the present time about anthropogenic-driven change in the environment, study of the past indicates that change is an integral feature of the world we live in (Tallis 1991, Bennett 1997). This change has been documented widely in terms of biodiversity, plate tectonics, geomorphology, sea-level and climate. Consequently, birds must have been responding to changes in climate and sea-level throughout their evolutionary history. There are essentially five potential responses of species to climate change: no response, persistence, adaptation, extinction and dispersal. Here we review climate change in the past, present and future to place the remaining studies in this issue within context.

OBSERVED CLIMATE TRENDS

Historical trends in global climate

Over the last 65 million years, the Earth's climate system has experienced continuous shifts from warm, ice-free periods to glacial periods of extreme cold (Zachos *et al.* 2001). The most recent glacial stage lasted from approximately 115 000 until about 10 000 years BP. Warming began from about 16 000 years BP and continued until about 10 000 years BP, since when global climates have been more stable. However, the average long-term rate of warming between 16 000 and 7000 years BP is at least an order of magnitude less than that predicted over this century. This is of concern if we wish to extrapolate from historical changes in distribution (generally recorded at a fairly coarse temporal and spatial scale) in response to climate change to how species might respond to climate change in the future (Watkinson & Gill 2002). On the other hand, very rapid warming is known to have occurred at times; for example, Anklin *et al.* (1993) report warming by 7 °C over a few decades in Greenland at the end of the Younger Dryas and the Intergovernmental Panel on Climate Change (IPCC 2001a) concludes that warming may have occurred at rates as large as 10 °C/50 years for a significant part of the Northern Hemisphere at this time. However, Briffa and Atkinson (1997) warn that in general there are considerable problems in

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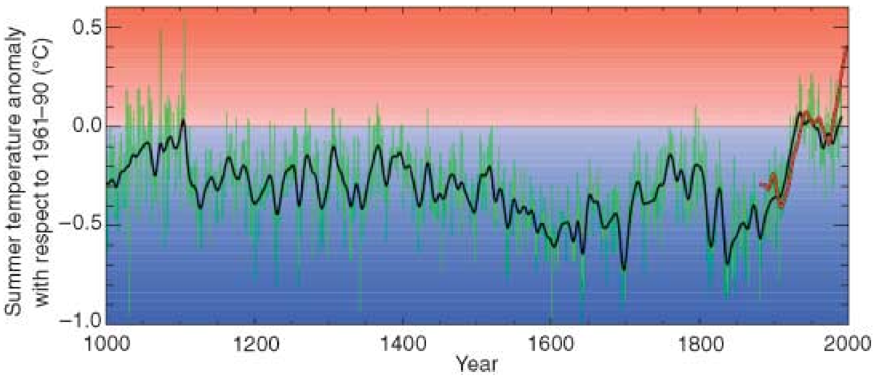

Figure 1. Record of Northern Hemisphere mean summer surface air temperature (1000 AD to 1998 AD) reconstructed using palaeo-data and expressed as deviations from the 1961–1990 average of 20.5 °C. The observed data are shown with a red line (data from Tim Osborn, Climatic Research Unit).

separating the climatic signal from non-climatic noise in reconstructing past climates and that it is consequently often difficult to be precise about rates of temperature change at well-resolved temporal or spatial scales.

The last millennium has seen considerable variations in temperature that have recently been reviewed for the Northern Hemisphere (Briffa *et al.* 2001, Jones *et al.* 2001). The reconstructions of Northern Hemisphere surface air temperature shown in Figure 1 for the last millennium are based on a combination of tree-ring, ice-core, coral and historical documentary evidence. Uncertainty of these time series increases further back in time but it appears that following a relatively warm period during the early part of the millennium, there was a gradual cooling over the 15th and 16th centuries to a minimum in the 17th century. There was then a period of strong warming through the early 1700s, relatively stable temperatures for the remainder of the 18th century, followed by abrupt cooling in the early 19th century. The 20th century has seen a rapid warming with mean global temperatures increasing by 0.15 °C per decade over the latter part; 1998 was probably the warmest year of the last millennium. These reconstructed data also highlight the effect of large volcanic eruptions such as that which occurred in 1601 and suggest that the observed 20th century warming has been most unusual.

Instrumental climate data have allowed us to monitor more accurately the changing global mean air temperature since 1856. These data show a global warming at the surface of 0.4–0.8 °C, with the six warmest years all occurring in the last decade. In contrast, a much shorter time series of data since the 1960s for upper air temperatures (above 8 km) suggest that the lower stratosphere has been cooling at a rate of about 0.5 °C per decade.

Recent trends in the UK climate

The UK possesses some of the longest instrumental climate time series in the world, the longest being the Central England Temperature series, which extends back to 1659 (Parker *et al.* 1992). This presents a unique opportunity to examine climate variability in the UK, in which we are probably observing a mixture of natural climate variability and human-induced climate change, with the contribution of the latter increasing over time. Three things are evident from the Central England Temperature series: (1) there has been a warming of the UK climate since the 17th century, with a linear trend fitted through the data indicating a warming of about 0.7 °C over 300 years and of about 0.5 °C during the 20th century; (2) this warming has been greater in winter (1.1 °C) than in summer (0.2 °C); (3) the cluster of warm years at the end of the record means that the 1990s were the warmest decade in the entire series, with four of the five warmest years since 1659 occurring in this short period. The data on daily temperature extremes since 1772 also indicate that there has been a marked reduction in the frequency of cold days (mean temperature below 0 °C), particularly during November and March, with the annual total falling from 15–20 prior to the 20th century to around 10 per year over most of the 20th century (Fig. 2). There has been a less perceptible increase in the frequency of hot days (mean temperature above 20 °C), but several recent years (1976,

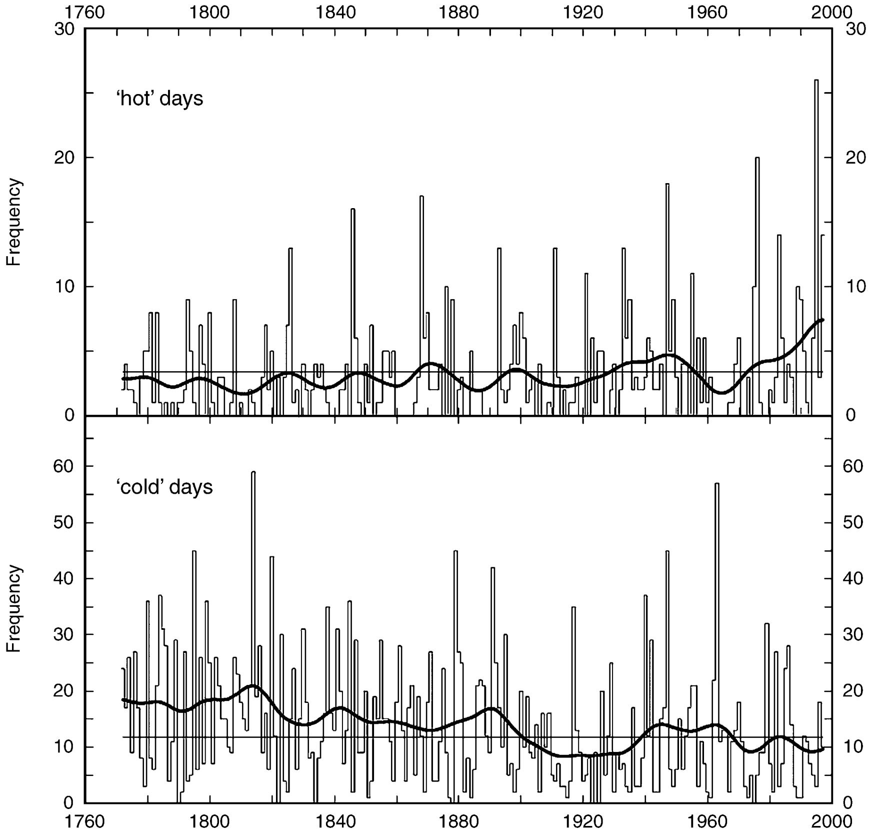

Figure 2. Occurrence of 'hot' and 'cold' days derived from daily mean temperature in the Central England Temperature series from 1772 to 1999. 'Hot' days are those with daily mean temperature greater than 20 °C and 'cold' days are those with daily mean temperature below 0 °C.

1983, 1995 and 1997) have recorded the highest annual frequency of such days, with 26 in 1995, the highest total in 225 measurements.

Temperature changes, and in particular extreme low temperatures during winter, have been documented as a major factor influencing overwinter survival of many coastal bird species (Dugan *et al.* 1981, Davidson & Evans 1982). This has, in some cases, resulted in mass mortality events with significant impacts on local population sizes (Baillie 1980, Clark *et al.* 1993). In addition to severe weather starvation resulting from an inability to meet extreme energetic demands (Marcstrom & Mascher 1979, Davidson 1981), temperature can also significantly influence the abundance and availability of prey species. For example, the abundance of intertidal invertebrates, the major prey of many internationally important populations of wintering waders, is significantly reduced in years following mild winters (Beukema *et al.* 2001).

In contrast to temperature, there are no comparable long-term trends in annual precipitation over the UK. There have, however, been systematic changes in the seasonality of precipitation, with winters becoming wetter and summers becoming drier. This increasingly Mediterranean-like precipitation regime is evident across all of the UK, as is an increase in the proportion of winter precipitation falling in the heaviest intensity storms (Osborn *et al.* 2000, Osborn & Hulme 2002).

The available data on gale frequency over the UK only extend back to 1881 and this series shows no long-term trend over the 120-year period. Gale activity is highly variable from year to year, with the 1961–1990 average being just over 12 'severe gales' in the UK per year, mostly in the period November to March. The highest decadal frequency of 'severe gales' (15.4 per year) since the series began in 1881 was recorded during 1988–1997.

Changing sea-level

The global pattern of sea-level change reflects that of climate (IPCC 2001a) as a consequence of the impact of temperature on thermal expansion in the oceans and ice melt. During the last 140 000 years sea-level has varied by over 100 m, with the lowest sea-levels being recorded at the height of the last ice age. Within the recent past, a long-term series of tide-gauge data from a number of locations around the UK coastline indicate a rise in mean sea-level, ranging from 0.7 mm/yr at Aberdeen to 2.2 mm/yr at Sheerness (Woodworth *et al.* 1999). These raw estimates of sea-level change need adjusting, however, to allow for natural rates of coastline emergence and submergence resulting from long-term geological readjustments to the last glaciation. The adjusted net rates of sea-level rise that are accounted for by changes in ocean volume alone range from 0.3 mm/yr at Newlyn to 1.8 mm/yr at North Shields. These data provide convincing evidence of a rising sea-level around the British Isles coastline.

CLIMATE FUTURES

Global climate

Overall, the evidence for climate warming now appears overwhelming, with evidence not only from climate observations, but also from the physical and biological indicators of environmental change, such as retreating glaciers, thinning of Arctic sea-ice and longer growing seasons (IPCC 2001a). During the latter part of the 20th century, there have been increasing concerns that human activity, in particular the emission of carbon dioxide and other greenhouse gases of fossil origin, is responsible for the observed increases in mean temperature and other aspects of climate change (IPCC 2001a). Global climate can obviously vary naturally, due both to what is called 'internal variability' within the climate system and to changes in external forcing unrelated to human activities; the latter would include changes in the sun's radiation and volcanic activity, for example. Recent model simulations of global climate show, however, that these natural causes of global temperature variability cannot alone explain the observed surface warming (IPCC 2001a). Only when model simulations incorporate the rising historical concentrations of greenhouse gases and shifting distributions of sulphate aerosols can a much better agreement between the observed and modelled global patterns of temperature change be achieved. It is of course difficult to be precise about the exact contribution of human activities to global warming, but the clear consensus is that the planet would not be warming as rapidly if humans were not currently emitting about 6.5 billion tonnes of carbon into the global atmosphere each year. The IPCC concluded in its recent Third Assessment Report (IPCC 2001a) that, '… most of the warming observed over the last 50 years is likely to be attributable to human influence.' What of the future?

Fundamental to the prediction of future climates are estimates of future greenhouse gas emissions, and in particular those of carbon dioxide, the greenhouse gas that causes about 60–65% of the human-induced greenhouse effect. It is predicted that the 2001 CO_2 concentrations of about 370 p.p.m.v. (parts per million by volume) may rise to 540–970 p.p.m.v. by 2100 (IPCC 2001a), compared with the pre-industrial concentrations of 280 p.p.m.v. Concentrations of other important greenhouse gases are also expected to continue rising, with changes in methane (–11 to +112%), nitrous oxide (12–46%) and tropospheric ozone (–12 to +62%) predicted in the same set of emissions scenarios (IPCC 2000).

There are considerable uncertainties in the impact that these changes may have on global climate as a result of uncertainties of how sensitive the Earth's climate is to rising greenhouse gas concentrations. In order to take account of these uncertainties, a range of climate sensitivities have been combined with a range of possible future emissions to calculate a range of future changes in global temperature and sea-level (IPCC 2001a). The projections are that the annual global mean surface air temperature will rise from 14.0 °C (1961–1990 average) to 15.4–19.8 °C by 2100. By comparison, maximum temperatures during the last interglacial about 125 000 years ago are estimated to have reached 15.0–15.5 °C. The latest projections represent rates of change of about 0.1–0.5 °C per decade, which compare with 0.15 °C per decade since the 1970s and with a warming rate of about 0.05 °C per decade since the late 19th century.

Accompanying the predicted warming is a rise in global mean sea-level. Observed sea-level has risen by 10–25 cm over the last century, reaching its highest level during the 1997/98 El Niño event. The recent IPCC calculations (IPCC 2001a) suggest a future rise of 9–88 cm by 2100 compared with the average 1990 level, with the largest contribution to this increase coming from the expansion of warmer ocean waters and up to 20% from the melting of land glaciers.

Mean temperature and sea-level rise are only two aspects of climate change; there are also predicted changes in seasonal and diurnal temperatures together with precipitation and the frequency of extreme events (IPCC 2001a). These will undoubtedly have important consequences for the dispersal and distribution of species. In looking to the future as to the past we are, however, much less certain about such aspects of climate change than those of global mean temperature and sea-level.

Regional climate change scenarios

For policy makers, managers and the general public at large there is obviously considerable interest in translating the global climate change projections to those at a more regional level (e.g. NAST 2000, Hulme *et al.* 2002). The approach taken in the generation of future climates for the UK (Hulme *et al.* 2002) was to adopt a single model that performs well in simulating the observed recent average climate in the UK (the Hadley Centre global climate model HadCM3) with four different emissions scenarios: low emissions, medium–low emissions, medium–high emissions and high emissions. These span almost the full range of emissions described in the IPCC Special Report on Emissions Scenarios (IPCC 2000) and represent changes in global temperature and atmospheric carbon dioxide concentrations for the 2080s of 2.0 °C, 525 p.p.m. (low), 2.3 °C, 562 p.p.m. (medium–low), 3.3 °C, 715 p.p.m. (medium–high) and 3.9 °C, 810 p.p.m. (high).

The analysis indicates that all aspects of the climate of the UK will be affected by changes in global climate. Natural climate variability (i.e. the noise of the system) will in reality modify these magnitudes and patterns of change, whether this variability is internally generated or whether it results from external factors such as solar variability or volcanic eruptions. However, it is generally expected that the UK climate will become warmer by 2–3.5 °C by the 2080s, with greater warming in the south and east than in the north and west, and with greater warming in the summer and autumn than in the winter and spring. It is also expected that high summer temperatures will become more frequent and very cold winters increasingly rare, continuing the trend that is already seen in the observed climate (see above). Consequently, snowfall amounts are expected to decrease throughout the UK. Winters are, however, expected to become wetter with heavier winter precipitation whereas summers may become drier. Given the importance of severe winter weather on mortality of many coastal bird species (described above), reductions in the frequency of severe weather events in winter may therefore reduce the probability of such cold-weather-induced mortality. In addition, however, the decreases in recruitment of intertidal invertebrates following mild winters (Beukema *et al.* 2001) suggest that although reduced frequency of cold winters may reduce the probability of overwinter mortality, it may also decrease the availability of prey to these species. The consequences of temperature changes for coastal birds in winter can therefore be extremely difficult to predict.

In addition to temperature changes, future changes in the seasonality of precipitation may have profound effects on the structure and quality of important habitats for coastal species. For example, both extensive winter and spring flooding and drought during summer could alter the suitability of many grasslands as wintering and breeding sites for the large number of species which use them (Ausden *et al.* 2001, Milsom *et al.* 2002).

Relative sea-level is predicted to continue increasing around most of the UK coast, but the rate of increase will depend on the natural vertical land movements in each region; much of southern Britain is sinking at 1–1.5 mm/yr whereas much of northern Britain is rising at 0.5–1 mm/yr relative to the sea. Under the lower scenarios of climate-induced sea-level rise, these natural land movements can be very significant in exacerbating or reducing the estimated climate-induced change in mean sea-level around the British coast.

A second factor to consider in relation to sea-level rise and coastal flooding risk is the changing nature of storm surges caused by low atmospheric pressure and strong winds. A rise in mean sea-level will result in a lower surge height being necessary to cause a given flood event, leading to an increase in the frequency of coastal flooding. Using the atmospheric winds and pressure that are generated by the climate change model to drive the Proudman Oceanographic Laboratory model of the shelf seas around the UK indicates that the largest increases in surge height (up to 1.4 m) may occur off the southeast coast. It is important to note here though that the modelling uncertainties are very large and hence there is relatively low confidence in the patterns and magnitudes of storm surge height.

A major consequence of future sea-level rise for coastal birds seems likely to be changes to habitat structure and quality (Austin & Rehfisch 2003). For example, the extent to which the invertebrate populations of coastal mudflats will be influenced by sea-level rise is likely to depend on whether rates of sedimentation can compensate for sea-level rise (Beukema 1992). Similarly, the structure of habitats such as saltmarshes and beaches may change significantly as a result of sea-level rise, which is likely to influence the important breeding and wintering populations of wildfowl (Vickery *et al.* 1995), waders (Liley 1999, Norris *et al.* 2004) and passerines (Brown & Atkinson 1996) which use these habitats. Many brackish and coastal freshwater sites also hold internationally important bird populations and sea-level rise may threaten these sites through tidal inundation following breaches of any sea defences. Thus, difficult decisions regarding the protection of coastal habitats are likely to be necessary in the near future.

For coastal birds within the British Isles the projected changes in climate and sea-level might be expected to have considerable impacts on the availability of habitat and resources. Climate change threatens both increased levels of flooding in the coastal and riverine floodplain, as well as the degradation of nationally and internationally important coastal ecosystems such as saltmarsh and coastal grazing marsh (Nicholls & Wilson 2002). However, analysis by Nicholls and Wilson (2002) of a range of socio-economic storylines within the RegIS project to examine the impact of climate change on the soft coasts of eastern England indicates present trends in coastal management are likely to have as profound an effect on the stock of different habitats over the current century as climate change itself. For example, because of sea defenses, sea-level rise might be expected to produce loss of saltmarsh, whereas planned and unplanned coastal realignment will produce gains in saltmarsh and associated intertidal habitats (Atkinson *et al.* 2004). Managed realignment, in turn, will often produce losses of coastal grazing marsh, a habitat which is important to both breeding and wintering waterfowl and waders. The stock of available habitats therefore depends critically not only on the question of climate change and sea-level rise but also on human management of the coast, which is an important determinant of habitat loss and creation.

For migrant birds that overwinter on temperate coasts, changes in climate and sea-level within the breeding grounds in the Arctic, for example, are likely to have as large an impact on populations as changes in the wintering grounds. In considering what may happen to coastal birds as a result of climate change it is therefore important to consider climate change across the breeding, passage and wintering grounds.

CONCLUDING UNCERTAINTIES

Climate change and sea-level rise have the potential to impact considerably on coastal birds through their impacts on habitat availability and a range of demographic processes relating to the fecundity, survival and movement of birds. Inevitably there are uncertainties in future climate scenarios. Some of these relate to uncertainty over future greenhouse gas emissions, whereas others relate to uncertainties in the transformation of these emissions through climate models into future climate change estimates. Although formal levels of confidence cannot easily be applied, we judge that we are more confident about future increases in carbon dioxide concentrations and in mean sea-level than we are about increases in storminess or about more frequent summer droughts (Nicholls & Wilson 2002). In addition, there are uncertainties that arise from a variety of factors (IPCC 2001b), including the effects of natural climatic variability (e.g. volcanic activity, variation in the direct output of the sun), possible changes to the Gulf Stream as a result of the non-linear response of the thermohaline circulation (THC) and the collapse of the Western Antarctic Ice Sheet (WAIS). We highlight here the last two.

Although the THC is expected to weaken over the current century, a sudden, more dramatic collapse has not been seen in any experiment using the most comprehensive climate models. If the THC was to shut down, however, then this could potentially lead to a reversal of the warming trend in northwestern Europe as a result of its impact on the Gulf Stream. The North Atlantic will nevertheless still warm, but parts will warm at a slower rate than if the THC had remained constant.

The disintegration of the WAIS could lead to a far more rapid rise in sea-level than is currently suggested and could potentially lead to a sea-level rise of 4–6 m (IPCC 2001b). Predictions about the WAIS are, however, uncertain for at least two reasons: (i) the complexity of processes determining the stability of the WAIS and (ii) the uncertain relationship between changes in accumulation and discharge of ice due to global warming, and the effects of natural millennial-scale trends in climate. One recent assessment (Vaughan & Spouge 2002) suggests that the WAIS contributes relatively little to sea-level rise in the 20th century, but over the following centuries, higher discharge rates from the ice sheet could increase its contribution to sea-level rise to 50–100 cm per century. Whatever the uncertainties, it is clear that climate change and the associated sea-level rise pose considerable concerns to those interested in the conservation of biodiversity within the coastal zone.

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