WCMC Biodiversity Series No. 11

Water Birds on the Edge

First circumpolar assessment of climate change impact on Arctic breeding water birds

World Conservation Monitoring Centre

prepared by

Christoph Zöckler and Igor Lysenko

WORLD CONSERVATION MONITORING CENTRE

WWF

CAFF
Conservation of Arctic Flora and Fauna

WCMC - World Conservation Press

2000

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ACKNOWLEDGEMENTS

EXECUTIVE SUMMARY

The purpose of this study is to investigate the potential impacts of climate change on a number of water bird species breeding in the Arctic. The study applies the HadCM2GSa1 general circulation model (GCM) of the Hadley Centre to assess the direct impacts of a changing climate on the breeding conditions of five selected Arctic water bird populations. Additionally, the current distribution of 25 species is compared with changes in vegetation predicted by two climate scenarios, a moderate one based on rise in temperature of only 1.7^0C (HadCM2GSa1) and an extreme scenario with a rise of 5^0C (UKMO) at the time of CO_2 doubling (2070-2099).

Analysis of spring and summer data of temperature and precipitation over the last 50 years, interpolated over the area of the species' currently known distribution, demonstrate a significant correlation between the mean June temperature and the juvenile percentage as a measure of breeding success in the Arctic in both of the tested populations of the White-fronted Goose (*Anser albifrons*) and in the Taimyr population of the Knot (*Calidris c. canutus*). The Nearctic population of the Knot (*C. c. islandica*), as well as the Curlew Sandpiper (*Calidris ferruginea*) breeding on the Taimyr Peninsula, do not show a correlation with the mean June temperature.

Under the HadCM2GSa1 model, an increase of 1% CO_2/yr results in a moderate increase of the mean June temperature in the Taimyr-breeding area of the White-fronted Goose. The conditions for the Taimyr population are particularly favourable for the period around 2020. According to the scenario, the temperature falls again by 2050 but never below the average of the last 30 years. However, a considerable cooling of the breeding grounds of the goose population in West Greenland could lead to a drop in size of the fragile population, which winters only in the western part of the British Isles. According to the climate model, the temperature around 2080 would not be above the mean values of today.

For the three wader populations that were tested, the pattern of response towards certain climate variables is not consistent, and for these species, the projection of the mean June temperature or other climate variables into a future scenario was not performed. More species need to be tested to ensure the inclusion of the right variables into future scenarios. Despite these uncertainties, the study maintains that all Arctic water bird populations breeding in the predicted area of cooler spring and summer temperatures, between Northeastern Canada and West Greenland, remain of special concern. Most of them, including the Nearctic Knot and the Sanderling (*Calidris alba*) winter regularly in British coastal waters.

The results of the vegetation models show a large variation in the impact of predicted changes in vegetation on the 25 species. According to the moderate HadCM2GSa1 model, 76% of Tundra Bean Geese (*Anser fabalis rossicus/serrirostris*) will be affected by the alteration of tundra habitats, whilst only 5% of the Sanderling will be affected. For two of the three water bird species which are considered globally threatened, namely the Red-breasted Goose (*Branta ruficollis*) and the Spoon-billed Sandpiper (*Eurynorhynchus pygmaeus*), 67% and 57% of their current breeding range will change from tundra to forest, respectively. The values for the extreme UKMO scenario are even higher, reaching 85% for the Red-breasted Goose. This additional loss of habitat will place these two species at a higher risk of extinction. The Emperor Goose (*Anser canagicus*), already in decline and with 54% of its small range affected, is highlighted as needing further conservation attention.

The results from this study require careful interpretation. Although in Alaska there is already evidence of an increase in forest area, and with pollen analyses from the Holocene indicating that vast shifts in forest areas occurred during interglacial periods, scientists still argue about the likelihood of such scenarios and about the rate, speed and scale of forest growth into the tundra. However, the results of this study reflect an important component in a matrix of factors affecting the future development of Arctic-breeding water birds. They have to be interpreted in relation to other factors affecting the populations of these birds, such as natural predation, hunting (mainly outside the Arctic) and the

effects of climate change (in particular sea-level rise) outside the Arctic. Further research will be carried out to refine the existing results, based on improved and updated data on distribution and refined GCMs. Other important components such as sea level rise and change in river runoff in the Arctic and on the major staging areas during migration will be taken into account.

1. INTRODUCTION

During the course of the past century global temperature increased by 0.5°C. This is strongly correlated with carbon dioxide levels, which have steadily increased from 280 ppmv before industrialisation to 355ppmv at present. Warming has been most pronounced in the Arctic region. Recently, Oechel *et al.* (1993) observed a rise in summer temperature over the last 25 years in North Alaska.

Globally, all general circulation models (GCM) predict a sharp increase in temperature ranging from 1.3°C to 2.4°C over the next 50 to 80 years with a doubling of carbon dioxide in the atmosphere. The Arctic region will experience the strongest warming - up to 5°C, depending on the model (Neilson & Drapek 1998) - with the most notable warming in winter and spring. There are also regional differences with the greatest warming over the land areas of the Mackenzie and NW Canada, Alaska and Central Northern Russia. However, one region extending from East Canada through South Greenland to Iceland will actually experience a cooling throughout all seasons, which has been explained by the strengthening of the Icelandic low to the southeast, resulting in increased northerly to northwesterly flow over the area (Maxwell 1996).

As a result of these changes, Arctic biomes will be among the most severely affected under a warming climate, and will be among the first biomes to show direct impacts. The Arctic is also a valuable region for studying climatic change, as other human impacts are expected to be very low in these regions, hence it is easier to show direct links between observed changes in biological communities and climate change.

The Arctic is of major importance for many water birds. More than two thirds of all geese and almost 95% of all Calidrid sandpipers breed in the Arctic (Zöckler 1998). Hence these species were chosen for a first impact assessment in this study. Changes in the climate will directly impact on the breeding success of Arctic water birds. Indirectly, the vegetation and habitat structure will alter and will become less suitable. This study focuses on both direct and indirect influences of climate change and demonstrates the likely impact on water birds in the Arctic.

The well-being of Arctic birds depends on many different factors, some operating wholly outside of the Arctic. Although the birds spend most of their annual life cycle outside the Arctic region, the three to four months that they spend in the Arctic each year are critically important. Here they breed and rear their young. Geese and ducks also molt in the Arctic and hence they are very sensitive to climate changes. Weather and climate is only part of a complex matrix of factors influencing the life cycle of water birds (Figure 1).
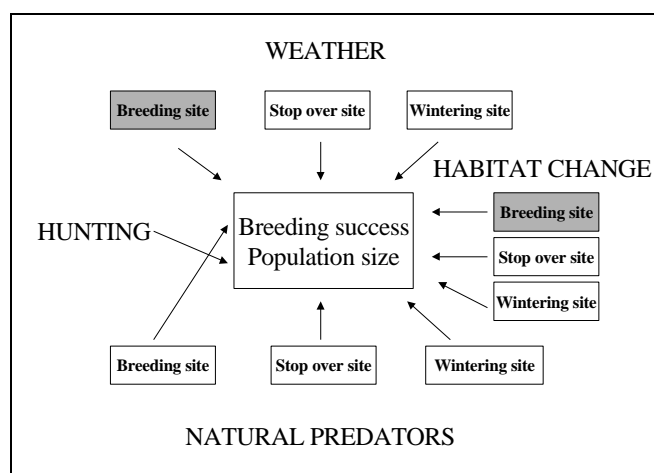

Figure 1: Matrix of factors influencing the survival and breeding success of Arctic water birds. Those which have been analysed in this study are highlighted.

Studies on the impacts of climate change on Arctic water birds have already been undertaken, including among others, Boyd (1966, 1987, 1992) and van Impe (1988). However, none of these previous studies considered a circumpolar approach or used GIS techniques to compute the large amount of data involved in this analysis.

2. METHODOLOGIES

Two broad approaches have been chosen to assess the impact of climate change on Arctic water birds at their breeding sites in the Arctic. The first investigates the direct impact on the water birds, utilising climate parameters, which are of significance for the birds in the Arctic. The second approach investigates the indirect impact through the change of habitat caused by climate change.

Information on the breeding distribution of Arctic water birds has been compiled at WCMC and is available in digital format for about 40 species (Zöckler 1998). To compare the data on distribution with those of climate they have been converted into a 0.5^o lat./long. grid.

Direct impact of climate

To assess the direct impact of the climate, this study first analysed the critical parameters influencing the breeding success of a given species breeding in the Arctic. Information about the breeding success for geographically distinct populations is only available in the form of the juvenile percentage in wintering populations from counts at the traditional wintering sites. These are available for most geese populations (e.g. Madsen *et al*. 1999), but only a few exist for waders and are often unpublished (Underhill 1987, Underhill *et al*. 1989, Schekkerman *et al*. 1998, BTO unpublished data).

These data were compared with climate data for the same period and from the current breeding area of the species' population. Past climate data were provided by the Climate Research Unit at the University of East Anglia (UEA) (New *et al*. 1999). The data were generated from interpolations of observed data and are available in the same 0.5^o lat./long grid as the species information. In the first stage of the study, the correlation of climate variables and the juvenile percentage for two populations of the White-fronted Goose (*A. a. albifrons and A. a. flavirostris*) was tested. Then, a GIS based macro was run, using the mean of all grid values of the entire range of each population to compare climate variables with the juvenile percentage and check for any significant correlation. The parameters tested are shown in Table 1.

As a second step, the selected climate variables, which can vary between species, were projected into the future. The HadCM2GSa1 integration (with 1% increase of CO_2 /yr) was applied, summarising the mean values for the area where the population is currently breeding and mean values for certain time periods (2017- 2023; 2047- 2053 and 2077- 2083). Although information on the juvenile percentage is available for more populations, in this initial analysis only five populations of three different species (one goose and two waders) were tested. Two regions hosting two separate populations were selected. One is the Taimyr Peninsula, an area with the highest proportion of tundra and the major breeding area for most of Western European wintering birds. The Taimyr Peninsula is also an area where warming has been recently observed. The second region is the northeastern Canadian archipelago and West Greenland, an important breeding area for water bird populations wintering in Europe, especially for those wintering in the British Isles. This is an area where cooling has recently been observed (Maxwell 1996).

Change in habitat

All vegetation models that are currently available use a rather broad classification of vegetation types. For the Arctic, only three major types are distinguished: tundra, taiga/tundra and boreal forest (mainly coniferous), which are broad but sufficient for a first approximation of the impact study. Recent literature on vegetation scenarios under changing climates, using a range of models, all predict considerable changes (Cramer 1997, Haxeltine & Prentice 1996, Huntley & Cramer 1997, Neilson & Drapek 1998, White *et al*. 2000).

From the GCMs used for mapping vegetation changes, it was decided to apply the MAPSS equilibrium biogeography model (Mapped Plant Soil System), as this is available on a circumpolar scale in the same 0.5^o lat./long. grid, as is the species and climate information. Projected towards the time of CO_2 doubling (2070 - 2099) the change in vegetation is mapped using Dynamic General Vegetation Models (DGVM) on the basis of the HadCM2GSa1 model. This is derived from the Hadley Centre simulations with combined greenhouse gas and sulphate aerosol forcing, and is based on a moderate warming of 1.7^oC globally and 4^oC for high (Arctic) latitudes. Other, mainly older models, predict temperature increases of up to 5.2^oC globally and 7^oC for high (Arctic) latitudes (Neilson & Drapek 1998). The area of change in Arctic vegetation types is compared with the current species distribution to demonstrate the effects of the habitat changes for the species. However, it has to be borne in mind that some important biomes, such as forest and mountain tundra were interpreted in a misleading way. The value could in fact be substantially higher, as unclassified areas in this GIS analysis may contain different tundra types e.g. mountain tundra (see selection of maps provided in the Annex).

In order to contrast the results of the HadCM2GSa1 model, the more extreme United Kingdom Meteorological Office model (UKMO low resolution) was also applied for the Arctic. Despite being a relatively old model, this model is very similar to the more recent Canadian General Circulation Model (CGCM1). However the latter, is currently only available for North America (Neilson, pers. com.).

3. RESULTS

Direct impact by weather
When comparing mean, maximum and minimum temperature and precipitation for the months May to August with the juvenile percentage of five selected species, mean June temperature is of significance ($p< 0.01$ and $p< 0.05$) for the breeding success of all the tested goose populations. This is particularly obvious for the nominate population of *Anser albifrons* and less so for *A. a. flavirostris* from Greenland (see trends in Figure 2A - see Annex 2). However, even with the latter, June temperature remains more significant than any other parameter (Table 1). In addition, Table 1 shows very high values for Tmin8 and Tmax8 (Table 1). These do not correspond with values from other populations and are not supported by any other research and are regarded here as random. Precipitation seems to be of no significance at all, but it has been widely stated that the values for precipitation are the least reliable in all climate models (Viner pers. com.).

Table 1: Correlation between the juvenile % of two different populations of the White-fronted Goose (*Anser albifrons*) and the minimum (min), maximum (max) and mean temperature (T) and precipitation (P) for May (5) to August (8) averaged over the entire breeding area of the population for the years 1957-95 or 1962-95 respectively. (Ø) = Correlation of average juvenile %. Data were available from two different wintering areas in Western Europe of *A. a. albifrons* in the Lower Rhine area in Germany (Lrh.) (Mooij *et al*. 1995) and in Zeeland (NL, The Netherlands) (van Impe 1996) and from two wintering populations of *A. a. flavirostris*, in Wexford/Ireland and on the Isle of Islay (Fox *et al*. 1999).

Parameter	A.a.alb. Lrh.	A.a.alb. (NL)	Ø A.a.alb.	A.a.flav. Wexford	A.a.flav. Islay	Ø A.a.flav.
Tmean 5	-0.122	-0.124	-0.124	0.112	0.183	0.329
Tmin 5	-0.060	-0.067	-0.064	0.058	0.110	0.224
Tmax 5	-0.122	-0.124	-0.124	0.058	0.110	0.224
Tmean 6	**0.492**	**0.434**	**0.468**	0.320	**0.445**	**0.464**
Tmin 6	**0.493**	**0.406**	**0.455**	0.270	0.339	0.348
Tmax 6	0.230	0.148	0.191	0.319	**0.408**	0.322
Tmean 7	-0.023	-0.034	-0.029	0.046	0.130	0.262
Tmin 7	0.030	0.022	0.027	0.057	0.108	0.140
Tmax 7	0.350	0.322	0.340	0.019	0.092	0.157
Tmean 8	0.147	0.096	0.123	0.019	0.092	0.157
Tmin 8	0.085	0.060	0.073	0.282	0.297	**0.603**
Tmax 8	0.085	0.060	0.073	0.268	0.220	**0.449**
Pmean 5	-0.174	-0.206	-0.192	-0.124	-0.159	-0.362
Pmin 5	-0.194	-0.221	-0.210	-0.159	-0.141	-0.340
Pmax 5	0.006	-0.001	0.002	-0.129	-0.227	-0.261
Pmean 6	0.136	0.110	0.124	-0.193	-0.179	-0.254
Pmin 6	-0.006	0.019	0.006	-0.111	-0.081	-0.265
Pmax 6	0.171	0.112	0.143	-0.169	-0.214	-0.247
Pmean 7	-0.340	-0.320	-0.334	-0.047	0.005	0.321
Pmin 7	-0.246	-0.309	-0.280	0.013	0.118	0.159
Pmax 7	-0.311	-0.243	-0.280	0.006	-0.118	0.043
Pmean 8	-0.208	-0.260	-0.236	-0.059	-0.141	-0.238
Pmin 8	-0.165	-0.166	-0.167	-0.075	-0.109	-0.298
Pmax 8	-0.226	n/a	n/a	-0.104	-0.139	-0.130

Table 2 summarises the correlation results for all five of the tested populations. In the Calidrid sandpipers the correlation for the mean June temperature is not as strong (p<0.05 for the Taimyr Knot population) if at all - as shown for the geese (Table 2). A significant negative correlation in both of the tested wader populations breeding on Taimyr could be found for mean May temperature. A positive correlation (p<0.05) exists for the Nearctic Knot population between the mean May temperature and the breeding success. Both correlations cannot be explained at this stage and require further investigation.

Table 2: Correlation between the juvenile percentage and the monthly mean temperature in the breeding area of five selected Arctic water bird populations, wintering in Western Europe and South Africa. (Sources: Boyd 1966, Mooij & Kostin 1996, van Impe 1996, Fox *et al*. 1999, Underhill 1987, Underhill et al. 1989, BTO unpubl. data).

Population (breeding)	(wintering)	Period	MAY	JUNE	JULY
Anser a. albifrons (Taimyr)	Germany/NL	1947-1995	-0.146	**0.450**	-0.037
A. a. flavirostris (Greenland)	British Isles	1962-1995	0.157	**0.406**	0.094
Calidris ferruginea (Taimyr)	South Africa	1969-1994	**-0.519**	0.210	0.263
C. c. islandicus (Nearctic)	England	1971-1986, excl.1977	**0.419**	-0.106	0.304
C. c. canutus (Taimyr)	South Africa	1971-1986, excl.1977	**-0.552**	**0.423**	-0.066

Snow cover, which has been recognized by other authors to be crucial for many Arctic birds (Whitfield *et al*. 1996, Meltofte 1985, Summers & Underhill 1996) has not been investigated due to inadequate data quality and availability, but needs to be considered in future investigations.

Change in habitat (vegetation)

In its Second Assessment Report (SAR), the Intergovernmental Panel on Climate Change (IPCC 1998) predicted a major change in vegetation types based on the MAPSS (Mapped Atmosphere - Plant Soil System) and BIOME3 (Haxeltine & Prentice 1996) models, including a stated decrease of 40-57% of the area currently covered by tundra vegetation. Huntley & Cramer (1997) using the BIOME model, found that the tundra will suffer the greatest changes of all biomes with losses to current coverage of 48.6%, with a concurrent gain of tundra in new areas by only 5.1%. Tundra is the most relevant biome for Arctic water birds and hence there are major implications for population size and development. In particular, geese and Calidrid waders will be heavily affected as they breed almost entirely in tundra areas. Table 3 shows the estimated amounts of tundra loss and gain at the time of CO_2 doubling (2070-99) under both the HadCM2GSa1 and UKMO models.

Table 3: Change of the tundra by CO_2 doubling due to HadCM2GSa1 Climate Change integration and the UKMO model (in sq. km).

Tundra	Area of tundra HadCM2GSa1	HadCM2GSa1 (%)	Area of tundra UKMO	UKMO (%)
Total area (current)	6,163,150	100.0	6,163,150	100.0
Area lost 2070/99	3,025,581	49.1	4,565,623	74.1
Area gained 2070/99	345,500	5.6	225,552	3.7

An estimated 8.4 to 10.4 million geese and about 14.5 million Calidrids breed in the Arctic (Zöckler 1998). Although a change of the breeding habitat into unsuitable vegetation types is only one factor of many influencing the population, a first simple assessment can indicate the magnitude of possible change for both of these considered groups. A simplistic extrapolation from these statistics would suggest that a loss of 40-57% of tundra would mean the loss of habitat for 4 to 5 million geese and about 7.5 million Calidrid waders by the period 2080-2099. Of course, the patterns of tundra loss will not be even, while the patterns of bird distribution within these habitat areas varies between the species.

Utilising the species specific distribution data, it is possible to develop a clearer picture of the extent of habitat losses on these species. Table 4 and Figures 3 to 25 (a selection is provided in the Annex) show the results for 25 species, eleven geese species, and nine waders, of which eight are Calidrid sandpipers. From these it can be seen that the area of habitat loss for geese is somewhat less significant than might be predicted by simply using the overall changes in vegetation distribution patterns, while for the Calidrid sandpipers habitat loss is greater than predicted. Application of the same techniques utilising the more extreme UKMO model suggests an even greater degree of change, as illustrated in Table 6.

It is important to note that habitat area may not be the most important factor limiting population size or breeding success. In addition, the species may be able to adapt to the changing environment, as discussed below. Hence species decline is unlikely to be directly proportional to habitat loss. The population figures in Table 4 are therefore only indicative of change rather than real numbers, and illustrate the interspecific variation in climate change impacts.

Table 4: Possible scenario of changes to tundra habitat areas as predicted due to CO$_2$ doubling during the period 2070-2099, applying the HadCM2GSa1 model for 25 Arctic breeding water birds (areas in million sq. km), ranked by the degree of impact. (For sources of distribution and population size, see Rose & Scott 1997, Van Gils & Wiersma 1996, Zöckler 1998).

Species		Total area of breeding distribution	Tundra within current distribution	Current Arctic pop. size	Tundra lost by 2070/99*	Proportion of tundra lost (%)*	Displaced pop. by change of habitat	Simplified pop. size by 2077/2099
Tundra Bean Goose	*Anser fabalis rossicus/serrirostris*	2.009	2.009	140,000	1.529	76	106,000	34,000
Red-breasted Goose	*Branta ruficollis*	0.408	0.348	88,000	0.274	67	59,000	29,000
Spoon-billed Sandpiper	*Eurynorhynchus pygmaeus*	0.063	0.042	2,400	0.036	57	1,400	1,000
Emperor Goose	*Anser canagicus*	0.074	0.047	120,000	0.040	54	65,000	55,000
Ross's Gull	*Rhodosthetia rosea*	0.172	0.157	50,000	0.088	51	26,000	24,000
Red-necked Stint	*Calidris ruficollis*	0.457	0.399	460,000	0.218	48	221,000	239,000
Sharp-tailed Sandpiper	*Calidris acuminata*	0.129	0.122	166,000	0.059	46	76,000	90,000
Little Stint	*Calidris minuta*	1.048	0.905	1,411,000	0.474	45	635,000	776,000
Curlew Sandpiper	*Calidris ferruginea*	0.814	0.786	1,096,000	0.332	41	449,000	647,000
Pectoral Sandpiper	*Calidris melanotos*	2.576	2.068	150,000	0.968	38	57,000	93,000
Ross's Goose	*Anser rossii*	0.147	0.081	1,000,000	0.053	36	360,000	640,000
Dunlin	*Calidris alpina*	2.350	1.579	2,300,000	0.846	36	828,000	1,472,000
White-fronted Goose	*Anser albifrons*	3.549	2.382	2,137,000	1.267	36	769,000	1,368,000
Long-billed Dowitcher	*Limnodromus scolopaceus*	0.610	0.429	120,000	0.191	31	37,000	83,000
Great Knot	*Calidris tenuirostris*	1.109	0.536	280,000	0.340	31	87,000	193,000
Lesser White-fronted Goose	*Anser erythropus*	0.099	0.029	22,000	0.028	28	6,000	16,000
Barnacle Goose	*Branta leucopsis*	0.107	0.085	340,000	0.022	21	71,000	269,000
Western Sandpiper	*Calidris mauri*	0.150	0.038	2,500,000	0.029	19	475,000	2,025,000
Sabine's Gull	*Xema sabini*	0.438	0.331	n/a	0.078	18	n/a	n/a
Brent Goose	*Branta bernicla*	1.180	1.036	590,000	0.193	16	94,000	496,000
Knot	*Calidris canutus*	1.145	1.000	1,190,000	0.184	16	190,000	1,000,000
Snow Goose	*Anser caerulescens*	1.549	1.415	3,889,000	0.213	14	545,000	3,344,000
Canada Goose	*Branta canadensis*	8.549	1.935	1,400,000	1.112	13	182,000	1,218,000
Pink-footed Goose	*Anser brachyrhynchus*	0.116	0.079	264,000	0.012	10	26,000	238,000
Sanderling	*Calidris alba*	1.182	1.131	478,000	0.062	5	24,000	454,000

*Value could be substantially higher as unclassified areas in this GIS analysis may contain different tundra types e.g. mountain tundra.

The level of impact varies considerably between species, ranging from 5% for Sanderling to 76% for the Tundra Bean Goose (Table 4) which rises to 93% according to the extreme scenario of the UKMO model (Table 6). This impact could in fact be substantially greater, as unclassified areas in this GIS analysis may contain different tundra types e.g. mountain tundra.

These results are still a broad approximation under unchanged assumptions of an even distribution of the species in its known range. A further refinement of the analyses is possible for at least some species taking into account information about areas of high breeding density (core areas). This reveals a more refined estimate of the future development of selected populations. Table 5 shows figures resulting from the application of the HadCM2GSa1 for five selected species, for which information on core areas is available in digital form.

Table 5: Possible scenario of changes to tundra habitat areas, with the addition of information on population densitites in core areas, applying the HadCM2GSa1 model, based on a breeding density for Curlew Sandpipers of 4.0 pairs/ sq. km for core areas and 1.4 pairs/ sq. km in the other areas ; for Dunlin of up to 33 pairs/ sq. km in core areas and maximal 5 pairs /sq. km in low density areas. (Lappo 1996). Assuming that 5/6 of all pairs breed in core areas, 50-60,000 Red-breasted Geese are affected (Syroechkovski 1995). Density data do not exist for Sharp-tailed Sandpipers or Pectoral Sandpipers, these estimates are based on data derived from Curlew Sandpipers, which needs to be verified) (Areas in million sq. km).

Species		Total area of breeding distribution	Tundra within the current distribution	Current Arctic pop. size	Tundra lost by 2070/99*	Proportion of tundra lost (%)*	Area of high density (core areas)	Core area lost by 2070/99*	Proportion of core area lost (%)*	Scenario for pop. size (exc. core areas)	Scenario for pop. size (inc. core areas)
Dunlin	*Calidris alpina*	2.350	1.579	2,300,000	0.846	36	0.234	0.115	49	**1,472,000**	**1,094,000**
Curlew Sandpiper	*Calidris ferruginea*	0.814	0.786	1,096,000	0.332	41	0.271	0.039	14	**650,000**	**888,000**
Sharp-tailed Sandpiper	*Calidris acuminata*	0.129	0.122	166,000	0.059	46	0.021	0.009	43	**81,300**	**103,000**
Pectoral Sandpiper	*Calidris melanotos*	2.576	2.068	150,000	0.968	38	0.064	0.039	61	**94,500**	**64,500**
Red-breasted Goose	*Branta ruficollis*	0.408	0.348	88,000	0.274	67	0.097	0.086	89	**30,000**	**10,600**

*Value could be substantially higher as unclassified areas in this GIS analysis may contain different tundra types e.g. mountain tundra.

Table 6: Loss of breeding area in % for 23 Arctic water bird species applying two different circulation models (HadCM2GSa1 = moderate warming; UKMO = extreme warming); their globally threatened status (VU = Vulnerable as a globally threatened species, CR = a critically endangered species, according to Collar *et al.* (1994); ! = suggested for inclusion into the Red List) and their relative abundance in the United Kingdom; occurs in the U.K. x = up to 1,000, xx = 5,000 to 50,000, xxx = > 100,000 according to Cranswick *et al.* (1997).

Species		HadCM2GSa1*	UKMO*	Red List	U.K.
Tundra Bean Goose	*Anser fabalis rossicus/serrirostris*	76	93		x
Red-breasted Goose	*Branta ruficollis*	67	85	VU	
Spoon-billed Sandpiper	*Eurynorhynchus pygmaeus*	57	57	CR	
Emperor Goose	*Anser canagicus*	54	54	!	
Ross's Gull	*Rhodosthetia rosea*	51	73		
Red-necked Stint	*Calidris ruficollis*	48	68		
Sharp-tailed Sandpiper	*Calidris acuminata*	46	74		
Little Stint	*Calidris minuta*	45	65		xx
Curlew Sandpiper	*Calidris ferruginea*	41	70		x
Pectoral Sandpiper	*Calidris melanotos*	38	60		
Dunlin	*Calidris alpina*	36	58		xxx
White-fronted Goose	*Anser albifrons*	36	57		xx
Long-billed Dowitcher	*Limnodromus scolopaceus*	31	54		
Great Knot	*Calidris tenuirostris*	31	42		
Lesser White-fronted Goose	*Anser erythropus*	28	29	VU	
Barnacle Goose	*Branta leucopsis*	21	27		xx
Western Sandpiper	*Calidris mauri*	19	21		
Brent Goose	*Branta bernicla*	16	44		xxx
Knot	*Calidris canutus*	16	33		xxx
Snow Goose	*Anser caerulescens*	14	46		
Canada Goose	*Branta canadensis*	13	22		
Pink-footed Goose	*Anser brachyrhynchus*	10	10		xxx
Sanderling	*Calidris alba*	5	25		xx

*Value could be substantially higher as unclassified areas in this GIS analysis may contain different tundra types e.g. mountain tundra.

4. DISCUSSION

WEATHER

For geese, the mean June temperature in the Arctic seems to be of significance, as shown for the White-fronted Goose in this study and concluded elsewhere for other goose species (Boyd 1987, Kostin & Mooij 1995). Boyd found a stronger correlation between the breeding success of five goose species breeding in Arctic Canada and daily mean June temperature than any other climatic variable (Boyd & Madsen 1996). It was concluded that the mean June temperature serves as an integrator of factors affecting: the ability of geese to nest at all; the ability to lay large clutches; and the rate and growth of food plants. Fewer young are produced when June temperature is lower than average and more when it is higher than average. Skinner *et al*. (1998) demonstrated the significance of early season climatic variables compared to early summer variables in the example of the Lesser Snow Goose. Van Impe (1988) was unable to show any correlation between examined parameters. However, the results were based on a much smaller set of data and not extrapolated for the entire range of each species. More is known today about the distribution and flyways of these species. Whilst the findings in this report appear to support those of most previous authors, it was only possible to test 2 out of the 51 Arctic goose populations. Further research on more populations is needed to prove the correlation between the June Tmean and the breeding success in geese.

The correlation found for geese is also the case at least in one of the Calidrid sandpipers (*C. c. canutus*, see Table 2) that were tested. Two species that were tested, which breed on Taimyr, the Curlew Sandpiper and the Knot, did not show a significant correlation with the June temperature. The mean July temperature appears to have some influence on the breeding success of the Nearctic Knot population, and although not statistically significant (with a correlation coefficient of 0.3, Table 2), may be worthy of further investigation. The breeding range of the Nearctic population extends widely from Northeast Canada to East Greenland (see Figure 15 in Annex) covering a large variety of different weather patterns. There is no clear definition of the exact Arctic breeding area from where the data of juvenile percentage originates, and hence could be subject to some errors. Schekkerman *et al*. (1998) also suspected a correlation with the mean July temperature rather than with the mean June temperature, when studying the Curlew sandpiper. The significant negative correlation between the mean May temperature and the breeding success of the Nearctic Knot needs further verification, but could reflect a relationship between warm May temperatures and an early snowmelt favouring the breeding conditions of the species (Whitfield *et al*. 1996). These results need to be supported and tested with more data and with more species.

Due to a lack of a clear correlation with any specific climatic variable in the case of the sandpipers, no future scenarios for any climate variable were run.

The future climate for geese

In the future, it will be crucial for the breeding success of most geese, whether June becomes milder or remains cold enough to reduce population growth. The future data calculated as a mean of a period of seven years around 2020, 2050 and 2080 indicate a slight increase of June temperature in Taimyr, and hence more favourable weather conditions for at around 2020 for the Taimyr geese (*A. a. albifrons*) (Figure 2B - see Annex 2). Surprisingly, the future warming for Taimyr is not as spectacular as forecast by many scenarios or by the dynamic vegetation models. Even more surprising is the result of a stabilisation or even slight fall in mean June temperature to 3.95°C by 2050, and only rising to 4.05°C by 2080.

These results point to the importance of considering the impacts at the level of specific populations. The nominate race *A. albifrons* of the White-fronted Goose, for example, appears to benefit from rising June temperatures. On the other hand, the Greenland White-fronted Goose (*A. a. flavirostris*) will experience severe cooling in its breeding range by around 2020. Even by 2080 the temperature will not return to the mean values of the last thirty years (Figure 2B - see Annex 2). This cooling trend has already been observed for at least the last 30 years (Figure 2A - see Annex 2). However, thus far it has not been reflected by a decrease in the population (Fox *et al*. 1999).

Cold June months may not become less frequent with further summer warming. The variation between the seasons is reflected in regional differences from north to south. High Arctic breeding Brent Geese are more exposed to extreme variations in weather conditions and react in an "all or nothing" pattern, i.e. they either breed well or fail completely (Ogilvie & St. Joseph 1976). However, they seem to adapt to cold and late summers, as demonstrated in the example of Brent Geese breeding 35 km further east than their traditional site in high Arctic Canada (Boyd & Maltby 1979). Conversely, the Baltic Barnacle Geese population, breeding in the temperate zone, shows hardly any fluctuation in breeding success with fluctuations in climate (Ganter *et al*. 1999).

Longer and warmer summers enable the build-up of greater biomass prior to migration, a factor that has been regarded as one of the "bottlenecks" limiting the Svalbard nesting Barnacle Goose population (Owen & Black 1989). Global warming might offset some of these limitations to the population growth of Arctic geese. However, it is not known what impacts cloud cover, precipitation and other factors, such as strong winds may have. The data available vary largely between the models and our testing of past data did not show any direct correlation with breeding success. One possible scenario is that increased winter precipitation might lead to increased snow cover with later snowmelt and greater runoff, leading to flooding of important breeding sites.

As shown in Figure 1 and discussed elsewhere (Boyd & Madsen 1997), the recent increase of many goose populations depends on a variety of factors, of which reduced hunting and the warmer climate have been named as the major factors. In this study, only the impact of climate change on water birds in the Arctic has been discussed. Hunting in the Arctic still occurs today, although is of minor importance, but significant impacts continue to exist due to hunting outside the Arctic during migration.

One other factor of great importance in the Arctic is a clear link between breeding success and lemming and predator abundance. In years of low lemming densities, predators appear to change their prey from lemming to birds, including young geese and waders (Summers & Underhill 1987, Underhill *et al*. 1993). These and other factors (see Figure 1) will additionally influence the breeding performance and might disguise a clearer correlation between the mean temperature of June or July and the breeding success.

HABITAT LOSS

The northward shift of forests
Before discussing the shift of vegetation under a warming climate, it must be emphasised that the applied models were equilibrium and not transient vegetation models. They are not coupled with ocean circulation components and do not include feedback reactions of the vegetation itself (Maxwell 1996, Schimel 1995). Several authors discuss the likelihood of a forest shift, and the level and the speed at which it might happen.

According to previous records in the Quaternary, large forest shifts of up to 2000km have been recorded (Huntley 1996). Deglaciation caused an average migration (even of long-lived trees) of between 200-500m/year in response to the rapid environmental changes. Such rates were sustained over several millenia, leading to range boundary shifts of 1000 to 2000km. In extreme cases, migration rates between 1-2km/year have been attained, and such changes are more frequent amongst boreal trees than of those of temperate zones (Huntley 1996). An estimate of global warming of about 2.5°C is about half that which occurred in the Holocene (Schneider 1989), whereas the upper limits of the range of forecasts is of the same magnitude or even twice as great as the last warming, which may result in warmer global conditions than any measured during the Quaternary. Huntley (1996) also mentioned the coarse resolution of the models, which omit several important feedback mechanisms, the majority of which are expected to be positive feedbacks (Schimel 1995). These limitations of the GCM may hide changes of even greater magnitude, such as those seen in the palaeoclimate records from ice cores (Huntley 1996).

However, some authors list a number of constraints for the northward migration of forest, such as glacially scoured, rocky, thin or podzol soils, cold soils with underlying permafrost, bogs and

wetlands, mountain ridges (Alaska), lack of bird or mammal seed vectors, increasing storm activity and improving conditions for pest insects (Billings 1996, Scott *et al*. 1996). Grazing mammals, often neglected in consideration of the vegetation development, might prevent the rate of tree growth considerably and keep tundra habitats actively open. Mainly reindeer, but also moose and locally domestic cattle, may be the most important natural drivers against the northward migrating tree line. The impact of wild and domestic reindeer is hard to assess, which will also be altered due to the warming conditions. Fires have been mentioned both as negative and positive influences on forest growth. Landhäuser & Wein (1993) found that fires can significantly accelerate the conversion of previously unforested tundra into forest by reducing the insulating surface organic layer. An expected increase in carbon dioxide, as well as an increasing mineralisation of Arctic organic soils will favour forest growth (Oechel & Vourlitis 1996). There is no common understanding of whether the upper soil layers may dry out under a warming climate or become wetter under increased precipiation in summer and winter (Oechel & Vourlitis 1996, Rowntree 1996). The latter can be very favourable to growing forests.

There is evidence of a recent northward migration of forest in Alaska. However, the rate of observed movement is still far slower than those derived from prehistoric times (Scott *et al*. 1996), which supports the theory of a lagged response to an accelerating change in climate.

There is thus a complex interaction of factors which complicates the prediction of the impacts of climate change on Arctic water birds. A shift in the vegetation is likely, though dependent on various preconditions. The time scale of forest migration is estimated by Huntley (1996) to range between 200 and 2000m/year. As a consequence of the lag behind the rapid warming, this may lead to successional and intermediate vegetation types, including the broadening of zones with tall shrubs and, regionally, the development of birch forests between the slowly expanding boreal forests and the remaining tundra (Huntley 1996). Both vegetation types are unsuitable for most of the water bird species studied.

Species response
Even if the rates of change predicted by different GCMs vary, the differential between species will remain. The Tundra Bean Goose (*Anser fabalis rossicus/serirostris*) seems to be highly affected with a 76% loss (93%, according to the UKMO model) of its tundra habitat. By contrast, only 5% of the tundra habitat currently occupied by the Sanderling (*Calidris alba*) will change due to its high Arctic distribution. The occasional variation of impact predicted by different models is illustrated by the Snow Goose, with 14% habitat loss predicted from the HadCM2GSa1 model, but almost 50% loss under the UKMO model. This is a result of its scattered northern distribution, as well as the underrepresentation of the southern type of American tundra habitat in both models. A more thorough analysis is needed for this species, as its breeding is largely concentrated in a few colonies, that are currently in such high densities, causing damage to the tundra vegetation by overgrazing (i.e. Jefferies *et al*. 1995), so that at least locally no threat of overgrowing habitats is expected.

Of major concern is the fact that two of the three globally threatened species among the studied Arctic water birds will be strongly affected (Table 6). The Red-breasted Goose, although recovered in recent years (Yerochow & Tolvanen 1997) still remains threatened and vulnerable due to its small range. The population might decrease by two thirds or more, considering that the majority is breeding in a core area, which may be reduced by almost 90% (Table 5). If this species is unable to shift northwards into the remaining tundra or adapt to shrub tundra habitats, there could be serious implications for an already globally threatened species. The Spoon-billed Sandpiper is already one of the rarest and most threatened water birds in the Arctic, breeding only in the Russian Far East with a population estimate of only 2,000 to 2,800 individuals (van Gils & Wiersma 1996). A loss of 57% of its current habitat area, as predicted here, could lead to the loss of this species globally.

Similarly restricted in its range is the Emperor Goose, mainly breeding in the coastal marsh tundra in Beringia. Changes in the habitat structure will affect this rare goose considerably. In addition to the replacement of tundra by shrub or tree dominated habitats, the coastal wetlands in this area may be threatened by sea level rise. Detailed analyses of sea level rise in the Arctic have not been undertaken to date. The Emperor Goose's status is already under consideration for listing into the Red Data Book

(Andreev pers. com.) of globally threatened species. The additional threat of climate change would justify its inclusion.

The White-fronted Goose, as well as most of the typical tundra breeding sandpipers, the Dunlin, the Red-necked Stint and the Curlew Sandpiper may all lose between a third and a half of their potential breeding range. For the Curlew Sandpiper, the situation is ameliorated when taking into account areas of high breeding density (Table 5). Dunlin (Figure 21) and Red-breasted Goose (Figure 13) are affected in their current core areas.

It is important not to interpret the figures in Tables 4 and 5 as actual predicted population losses at the time of CO_2 doubling (2070-2099). The figures should rather be considered as indicative of the potential magnitude and scale of the impact and of the variation of impact between species. Numerous variables will affect the actual interplay between climate change and population sizes. These are compounded by the very real problems of the modelling, including innaccurcy of the data sources, and uncertainties derived from simplifications required for computing. Last, but not least, it has to be remembered that it is species that are being dealt with here, rather than static objects. With increasing accuracy of the models and better information of the distribution, the flyways and the breeding success of different species, it will be possible to refine these scenarios.

Impacts on other biomes/species

This first analysis focuses on the loss of tundra. Other, more southerly distributed biomes will also be affected by a changing climate. These include southern subartic forest tundra, mountain tundra and oceanic tall grass meadows, all of which currently provide suitable habitats for some southerly distributed species, mentioned in Tables 4 to 6. All of these biomes, but in particular southern subarctic forest tundra, are very likely to become more forested and hence less suitable, so that the level of impact discussed here, especially for the more southerly distributed species, might be even higher. Current vegetation models do not distinguish other Arctic habitats to a sufficient resolution, to be able to include them into the scenarios. Future analyses should take all suitable habitats into account.

The third Red Data listed species, the Lesser White–fronted Goose (*Anser erythropus*) (Table 6) appears less impacted by vegetation changes in the model. However this species has its major stronghold in the forest tundra. A more detailed study of the impacts of climate change on the forest tundra and its species might provide more detail on the potential impacts on this species.

ABILITY TO ADAPT

Species will not react statically to climate change, and will certainly respond to changing habitats. Many species will be able to extent their range along with the northward shifting distribution of their favourite habitat. But naturally there are limits and in particularly those species breeding on the edge in high Arctic habitats will find less and less suitable conditions as the climate warms up.

A number of scenarios can be envisaged.

- **Increasing densities in the remaining area of suitable habitats**
  Very little is known about the natural population carrying capacity of particular habitats. Population densities are also determined by factors outside the breeding range, along the migration routes and in the wintering areas. In addition to potential intraspecific interactions which may limit population densities, the potential for interspecific competition will certainly increase, especially if all populations are increasing in remaining habitat areas.

  Meltofte (1985) found the highest breeding densities of the Knot in the middle ranges of East Greenland. The south was shown to have too much summer precipitation, while the far north is too dry to provide sufficient food. Global warming would move the optimal zone further northwards with a consequent compression of the available breeding range. For birds dependent

on high Arctic biomes this compression may be widely repeated. However, many species may be more flexible, having broad distribution ranges from low to high latitudes, as in the case of the Knot and the Sanderling (see Figures 15 and 17).

- **Adaptation to new habitats**
  Geese in particular have shown a considerable ability to adapt to new situations. The Barnacle Goose, for example, has established large colonies outside the Arctic, in the Baltic Sea area (Ganter *et al*. 1999). Similarly, the White-fronted Goose was observed breeding in the northern limits of the Taiga in semi-open habitats along small river valleys in 1999 (Syroechkovski jr., pers. com.). The high Arctic breeding Brent Geese also demonstrate an adaptive mechanism. These geese have established a nomadic breeding pattern in high Arctic breeding grounds to avoid overgrazing and unsuitable snow conditions and they move from season to season to suitable sites with favourable food and nesting conditions. In this way they enable the sparse and slow growing vegetation to recover while breeding and feeding a few kilometers away (Boyd & Maltby 1979). While such behaviour clearly shows an adaptive strategy, it also illustrates that population densities may indeed be limited by area of available habitat.

  Most of the Calidrid waders will not be able to adapt to shrubby or tree like habitats and cannot expand into other habitats, except for a few areas gained by retreating glaciers. They will thus be forced to develop new strategies for survival in the remaining tundra habitats. Most of the geese and waders do not show any kind of flexible response and might not be able to adapt to the new conditions. Those species, not directly affected by the changing habitat, are pushed further to the edge. In particular, those breeding in the far north, do not have any choice other than to compete with the northwards shifting individuals of the same and of other species. But some birds such as the Temminck's Stint (*Calidris temminckii*) and the Long-billed Dowitcher will most likely be able to adapt, as has been recently observed in semi-natural pastures along the northern edge of the boreal zone in Siberia. These species might possibly benefit from a change in vegetation.

MITIGATION

The impacts of climate change and the changes in habitat may be dramatic for certain species, yet a more holistic understanding is required before any mitigation actions can be recommended.

The northward migration of forest may provide an important additional CO_2 sink and compensation for forest areas lost further south. According to White *et al*. (2000) land areas above 50ºN (about 23% of the vegetated global land area) are currently accumulating about 0.4 PgC/yr (about 30% of the estimated global terrestrial sink). This sink could double to 0.8-1.0 PgC/yr by the second half of the next century and persist undiminished until 2100. The halving of the tundra will contribute 30% to the carbon sink by the 2090s (White *et al*. in press). Countering these affects, the northwards extension of forest will reduce the albedo and contribute further to global warming (Foley *et al*. 1994). After 2050, due to a saturating effect, forests might release more CO_2 rather than sequestrate (Cramer *et al*. in prep.), leading to an even warmer climate.

The increased forest area might also provide important habitats for boreal species, many of which may suffer losses on their southern boundary, or as a result of forecasted and observed increases in fire occurrences (Oechel & Vourlitis 1996).

If it is concluded that the tundra environment is critically important and that efforts should be made to maintain existing areas as far as possible, one potential measure of active management might be to control and selectively increase or encourage grazing in the more threatened areas of tundra.

In the Eurasian Arctic, there are large numbers of domestic reindeer and horses grazing in large areas of Arctic biomes and keeping them open. In many cases, the densities of grazing animals are too high and actually have a negative impact on the tundra vegetation. However, local increases in the number of reindeer might inhibit forest invasion in certain areas. One other, less well documented animal, is the Yakutian horse, a race highly adapted and capable of enduring temperature differences of up to 100^{0}C over the year and feeding on sparse vegetation over frozen ground for more than 8 months per

year without significant human support. In northern Yakutia, where these horses are widely kept, the vegetation has been kept open or actively converted into open landscapes on a large scale. Such habitats can suit some Calidrid wader species. During an expedition in 1999 into the Abiiski region in the middle Indigirka basin in NE Yakutia, Temminck's Stint, Ruff (*Philomachus pugnax*), Red-necked Phalarope (*Phalaropus lobatus*) and others like Ross's Gulls were found breeding in such areas (Lugert & Zöckler 2000). It remains to be demonstrated whether similar habitats suitable for Calidrid waders might be generated or maintained when horses are introduced on a less intensive scale to tundra areas on the edges of forests.

A large-scale study of different management schemes using horses or reindeer could be undertaken to test appropriate measures in combating the impact of global warming on Arctic water birds.

THE RELEVANCE OF THE IMPACT ON THE BIRDS WINTERING IN THE U.K.

Ten of the 25 analysed species occur in the U.K. in winter (Table 6). They breed as far West as NE Canada (Knot) and as far East as the Taimyr Peninsula (Brent Goose, Knot and Curlew Sandpiper). Four species and one subspecies, the Greenland White-fronted Goose, winter in the U.K. in internationally important numbers. The U.K is taking over particular responsibility for these species, which is documented by special species protection plans and the designation of RAMSAR sites.

The analysis of the direct impact of climate variables shows that the Greenland White-fronted Goose is likely to face severe summer cooling with serious implications for the species' breeding success. Due to its restricted breeding range in West Greenland and wintering only in the British Isles, the species is very vulnerable and needs specific attention. In similar terms this also refers to other species breeding in the same area, where summer cooling is predicted in the next 50 years, such as Sanderling and Knot. But, these species breed in a much larger area and are facing different weather patterns not analysed in this report.

The change of habitat as an indirect impact of a changing climate demonstrates the implications for a number of species breeding in the Arctic, but only Dunlin and Little Stint, which winter in relevant numbers in the U.K are likely to face a level of habitat change of significance (Table 6).

All the other species analysed in the report, which winter in internationally important numbers in the U.K., such as Brent Goose, Knot Pink-footed Geese and Barnacle Geese are not affected significantly according to this study.

5. CONCLUSION

Climate change scenarios indicate the potential for widespread changes in populations of Arctic breeding water birds. The level of the impact varies from species to species, and will be affected by both the direct effects of changes in the climate and indirect effects of changes in habitat.

In summary, the gentle warming with earlier snowmelt and increasing temperatures during the Arctic summer will favour reproductive success for most populations. One focus of future research should be water bird populations in West Greenland and Northeast Canada where cooling rather than warming is predicted. The example of the Greenland White-fronted Goose in this region provides evidence for concern. Any changes are likely to be within the adaptive capacity of most species. However, increases in extreme weather events or simply the greater variation in the weather between seasons could severely test the ability of some species to adapt.

Additionally, habitat changes may limit the species' range considerably. They may occur relatively slowly. For most of the considered species there will be enough time for adaptation. However, concern remains for those species which already have restricted ranges or specialised habitat requirements, and especially those species listed as globally threatened (Table 6). In particular, attention needs to focus on the Red-breasted Goose, the Spoon-billed Sandpiper and the Emperor Goose, and the further development of all other populations in relation to a changing climate, still needs to be followed.

This study can only serve as a first approximation. It provides a baseline upon which further analyses can be built upon, utilising improved and updated GCMs, improved distribution data and a better understanding of the species' response and flexibility to a changing climate. Further studies should include more species and information from different populations. In addition, it would be valuable to incorporate other factors inside and outside the Arctic. In particular, studies should consider in more detail, the impact of precipitation and snow cover as better data become available on a circumpolar scale. Of particular importance will be the incorporation of the potential sea level rise and increasing river runoff data, due to warming and higher precipitation. This may particularly threaten river deltas and lowland and coastal wetlands which are the main breeding areas for many water birds. Of even greater concern, however, is the potential impact of sea level rise at major migratory stopover sites for Arctic water birds, mainly outside the Arctic region. Several initiatives already investigate the impact on selected sites, such as along the East coast of North America (Galbraith pers. com.) and coastal wetlands in Great Britain (Rehfish and St. Josef pers. com). For the U.K., estimates of a sea level rise by 2050 range between 13cm and 74cm according to the low or high scenarios (Hulme & Jenkins 1998). These need to be integrated into a single study with a global coverage. On the basis of improved impact assessments, it may be possible to make further detailed proposals for response and mitigation measures.

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