Journal of Applied Ecology

British Ecological Society

Journal of Applied Ecology 2008, **45**, 1649–1659 doi: 10.1111/j.1365-2664.2008.01552.x

Using expert knowledge to assess uncertainties in future polar bear populations under climate change

Saffron J. O'Neill[1,2]*, Tim J. Osborn[2], Mike Hulme[1], Irene Lorenzoni[1] and Andrew R. Watkinson[1]

[1]*Tyndall Centre for Climate Change Research and School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK; and* [2]*Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK*

Summary

1. Polar bear *Ursus maritimus* population dynamics under conditions of climate change has become a controversial topic. A survey of expert opinion based on modelled sea-ice data was performed in order to quantify the trends and variance surrounding possible impacts of climate change on polar bear populations.

2. Polar bears have become an iconic species in the communication of climate change. Negative impacts of climatic warming on polar bears have been suggested, but cannot be fully quantified as no Arctic-wide models yet exist to analyse the relationship between polar bear population dynamics and climate change.

3. Ten polar bear experts participated in an expert opinion survey in early 2007, quantifying the trends and variance surrounding possible impacts of climate change on polar bear populations. The experts were provided with maps and time-series of sea-ice extent and duration to 2050, simulated under a mid-range emissions scenario. Expert projections of future polar bear habitat range and population size across the Arctic, and for population size in five regions, were obtained. Experts were asked to define 'best conservation practice', and to re-evaluate the total Arctic population projection if this best practice was implemented.

4. Most experts project a substantial decline in polar bear range and population size across the Arctic and in population size across each region. Expert best estimates for total Arctic polar bear population size lie from no change to a 70% decrease by 2050 relative to today; with half the experts projecting at least a 30% decrease. The median best estimates show the Barents Sea, Hudson Bay and the Chukchi Sea populations experiencing the greatest population decline under this scenario. There is much uncertainty both within and between expert responses, especially in little-researched regions such as the Chukchi Sea.

5. *Synthesis and applications*. Based on projected changes in sea-ice extent, experts suggest that polar bear populations will undergo significant declines by 2050, even implementing best management practices, under the scenario of climatic warming outlined here. The expert survey approach could be applied to a wide range of species for which there is a lack of available data and considerable uncertainty surrounding all aspects of the problem that prevent quantification with more formal modelling approaches.

Key-words: Delphi technique, evidence-based conservation, expert opinion, population change, sea-ice, *Ursus maritimus*

Introduction

Polar bears *Ursus maritimus* Phipps are frequently used as an iconic species in the communication of climate change by the media (e.g. Pearce 2006). Popular articles regularly suggest a rapid and alarming decline in polar bear populations under climate change. Conversely, Bjørn Lomborg argues that polar bears are not the climate 'canaries in the cage' they are portrayed to be: '*once you look at the supporting data the narrative falls apart*' (Lomborg 2007). What is not clear from these

*Correspondence author. E-mail: s.o-neill@uea.ac.uk

© 2008 The Authors. Journal compilation © 2008 British Ecological Society

various narratives, however, is how representative they are of the range of views held by the expert community. Current scientific knowledge indicates that most populations of polar bears are either stable or increasing, and that the likely extent of the population declines under climatic warming is uncertain (Stirling & Derocher 1993; Stirling & Parkinson 2006). Only in certain regions such as in western Hudson Bay have population declines been hypothesized to be linked to climate change thus far (Stirling & Parkinson 2006). In this study, we investigate these narratives with reference to a particular climate future. In considering the potential impact of climate change on polar bear populations, there are two critical issues: the relationship between the extent of sea-ice and polar bear ecology (Derocher, Lunn & Stirling 2004), and the available modelling techniques to make projections into the future (Sutherland 2006).

SEA-ICE AND RELATIONSHIP WITH POLAR BEAR ECOLOGY

Climatic warming is predicted to impact on the timing of sea-ice break-up and formation as well as its distribution in the Arctic. All models used in the Arctic Climate Impact Assessment predict a decrease in Arctic sea-ice extent and sea-ice thickness over the 21st century (ACIA 2005). A rapid acceleration in Arctic warming has also been detected in recent satellite data (Comiso 2003) with the annual mean and summer minimum ice extent declining respectively from 1978–1979 at a rate of 2·7% and 7·4% per decade (IPCC 2007b, p. 339).

A continuing decrease in sea-ice distribution and thickness can be expected to impact negatively on polar bears, as the sea-ice provides a platform for travel and hunting (Derocher *et al*. 2004). Polar bears are especially abundant on the near shore seasonal sea-ice over the continental shelf where biological productivity is highest. It is these sea-ice habitats that are, in particular, projected to be impacted by climatic warming. With climate warming, freezing of the ocean occurs later in the year and open water occurs earlier in the year, so that bears may have to fast on land or offshore on multi-year ice until the sea-ice provides suitable habitat. The ice surface may also become increasingly fractured.

The specialized nature of polar bears, coupled with the rapid changes projected for the Arctic, puts them at risk (Derocher *et al*. 2004). Changes in the sea-ice distribution, characteristics and length of the ice-free season could have 'profound impacts' on bears (Stirling & Derocher 1993). However, the only published probabilistic statement that relates to polar bear populations is that from the Intergovernmental Panel on Climate Change (IPCC) Working Group II, which states that *'polar bears will face a high risk of extinction with warming of 2·8 °C above pre-industrial'* (Box 4·3, IPCC 2007a, p. 231).

POPULATION MODELLING TECHNIQUES

A range of modelling techniques are available to predict the impacts of environmental change on species distribution and abundance (see Sutherland 2006). Phenomenological models and, in particular stochastic population viability analysis (PVA), have been used most extensively to determine the likelihood of a decline in polar bear subpopulations in the future (Aars, Lunn & Derocher 2006). However, the projection of polar bear population dynamics under climate warming is an ecologically complex issue involving many unknown variables, and is associated with considerable uncertainty. In these cases, the range of conventional modelling techniques and approaches such as extrapolation, PVA and climate envelope modelling, may not be satisfactory (Sutherland 2006). The required data may not be available (for example, reliable estimates of parameters such as abundance are not available for the Barents Sea population) and the time-scales for climate change are too long for such approaches to be reliably applied.

With a lack of available data and considerable uncertainty surrounding all aspects of the problem, expert judgement is perhaps the only available method for assessing future risks (Sutherland 2006). Informal expert judgment based on limited scientific data is used in management decisions (Gregory *et al*. 2006), and public opinion is shaped by the media often interviewing just one or two scientists (e.g. Garfield 2007). Both of these situations utilize unquantified expert judgments from the research community. Expert surveys, however, represent an opportunity to use a systematic, quantitative process involving multiple contributors to thoroughly investigate the trends, variance and consensus (or lack of it) in current expert opinion: in this case, on future polar bear population dynamics under a specified climate future.

EXPERT OPINION SURVEYS

Expert judgement is not intended to be a substitute for scientific research (Morgan & Henrion 1990), but to define the current knowledge and range of uncertainty surrounding a given response. Expert opinion surveys are systematic, quantitative and involve multiple experts. Such approaches are of value for management decisions where uncertainty is high and where there is a lack of empirical data to assess uncertainty. It can make knowledge available that may not otherwise be easily accessible (van der Sluijs *et al*. 2004), illustrate the current pool of expert knowledge (Akcakaya *et al*. 2000), reveal areas of greater or lesser agreement and help drive future applied research.

Expert opinion is increasingly used as a method for assessing evidence and uncertainty. Examples of such studies examine aerosol forcing (Morgan 2006), the possibility of West Antarctic ice sheet collapse (Vaughan & Spouge 2002), the impact of livestock grazing on birds (Martin *et al*. 2005), the risk of herbicide-tolerant oilseed crops (von Krauss, Casman & Small 2004) and forest ecosystem change (Morgan, Pitelka & Shevliakova 2001). The aim of this study is to provide a formal assessment of the current expert opinion on the future of polar bear populations under a defined scenario of climate warming in the context of the frequent claims for strong negative impacts in the media and elsewhere.

Increasing uncertainty →

	Source of uncertainty	Input used in this study
Upstream uncertainty	Emissions scenario	One scenario used to a stated time period, fulfilling the following criteria at the time of survey protocol development: • Mid-range emissions scenario • Timeframe far enough into future to show significant anthropogenic changes in climate • Timeframe fulfils IUCN red list criteria for projecting climate change impacts on biodiversity of being three generations long (Akçakaya *et al.* 2006) (SRES A1B, 2050)
Upstream uncertainty	Global climate representation	Carbon cycle uncertainties Atmospheric composition uncertainties Mult-model mean used of 16 CMIP3 GCMs,fulfilling the following criteria at the time of survey protocol development: • Historic and C21st periods available • SRES A1B data available • Monthly sea-ice concentration data (BCCR-BCM2·0, CGCM3·1(T47), CGCM3·1(T63), CNRM-CM3, CSIRO-Mk3·0, GISS-AOM, GISS-1 ER, INM-CM3·0, IPSL-CM4, MIROC3·2(hires), MIROC3·2(medres), ECHO-G, ECHAM5/MPI-OM, MRI-CGCM2·3·2, CCSM3, and UKMO-HadCM3)
Upstream uncertainty	Regional climate representation (e.g. downscaling)	GCM data extracted for areas detailed in Figure 2. Downscaling or impact models not incorporated.
Downstream uncertainty	Expert uncertainty projections of population dynamics in response to sea-ice projections	Expert knowledge, information, literature, models, advice, beliefs and gut feeling (5–95% uncertainty range requested)

Fig. 1. Quantifying the impact of uncertainties associated with transplanting the effect of environmental change onto environmental processes.

Materials and method

Members of the International Union for the Conservation of Nature (IUCN) Species Survival Commission Polar Bear Specialist Group (PBSG) were approached to take part in the expert survey. Experts were not asked to contribute views on climate change, but for their judgements on polar bear population dynamics under a specified climate future. The survey was designed to gather responses on eight issues (see Supporting Information Appendix S1). Experts were asked to identify three main threats facing polar bear populations over the next 50 years. The body of the survey then obtained responses about the direction of change in polar bear populations and the associated uncertainties. Experts were asked to provide responses as a percentage change in range and population across the Arctic as a whole and in five specific regions. Lastly, experts were asked for their definition of 'best conservation practice' and its potential impact on population change across the Arctic. Participants were also asked to assess their own expertise in both climate science and polar bear population dynamics.

SEA-ICE SUPPORTING MATERIAL

Experts were asked to provide their responses with reference to supporting material on sea-ice change. In all cases, sea-ice projections were presented under the Special Report on Emissions Scenario (SRES) A1B anthropogenic emissions scenario (Nakicenovic *et al.* 2000) for the 2050s. The sea-ice information used to construct the maps and time series was diagnosed from the large data base of Global Climate Models (GCM) from phase 3 of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP3; http://www-pcmdi.llnl.gov). This data base of model simulations has been used extensively in the IPCC Fourth Assessment Report (IPCC 2007b). Figure 1 details the inputs used in this study and the associated up- and downstream uncertainties.

The time period was selected as 2050 because it is far enough into the future to show significant anthropogenic changes in climate, but also fulfils the IUCN Red List criteria for projecting climate change impacts on biodiversity over a three-generation period (Akçakaya *et al.* 2006). The justification for using SRES A1B is threefold. First, the greatest number of CMIP3 GCMs projected sea-ice under SRES A1B compared to other scenarios at the time of the study. Second, SRES A1B presents a mid-range emissions scenario (Nakicenovic *et al.* 2000). Last, we did not want to overwhelm the experts with many different plots of sea-ice under different scenarios. It is noted that 'for projected short-term warming [...] warming is similar across different scenarios, compared to later in the century where the choice of scenario significantly affects the projections' (IPCC, 2007b: p. 809).

The first set of supporting material comprised two maps of projected sea-ice cover change for March and September (Fig. 2a), the months of maximum and minimum Arctic sea-ice extent,

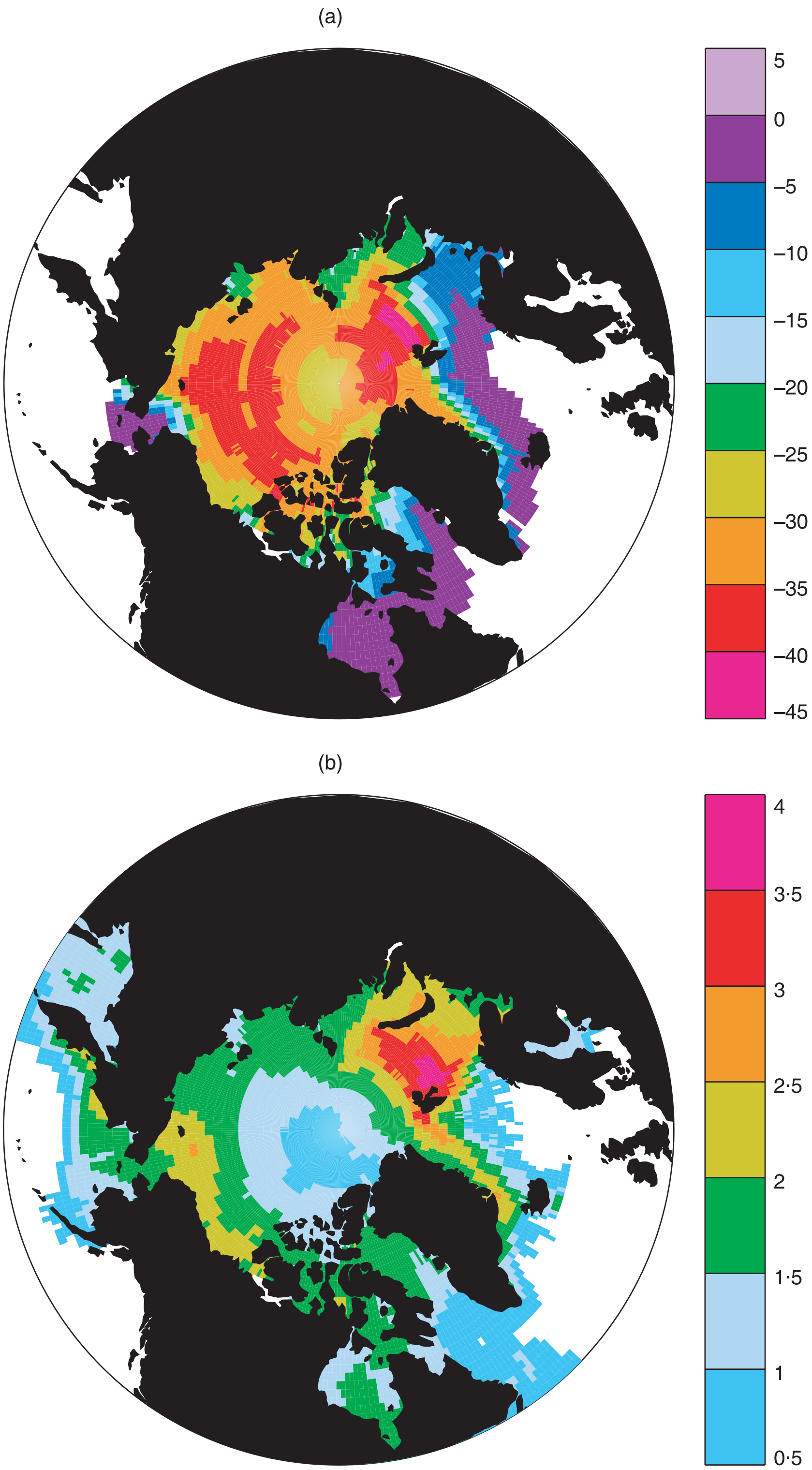

Fig. 2. (a) Projected change in sea-ice extent for September, indicated by the percentage of sea-ice cover for each grid cell. Negative values indicate a decrease in sea-ice. (b) Projected change in the average length of the 'ice-free season', indicated by the number of consecutive months with less than 50% sea-ice concentration. Projections are the change from the mean over 1961–1990 to the mean over 2040–2069 (representing the 2050s) under the SRES emissions scenario A1B. Changes were diagnosed from simulations with 16 climate models and then averaged to form a multi-model mean.

respectively: a map of the change in the length of the 'ice-free season' (Fig. 2b); and a map defining the regions under consideration (Fig. 3). The 'ice-free' season was defined for each grid cell of the climate model's sea-ice component, as the maximum run for which monthly mean sea-ice concentration remained below 50%, a threshold chosen as polar bears are known to abandon sea-ice under such conditions (following Etkin 1991). A multi-model mean of 16 GCMs was used for the sea-ice maps. Despite wide differences in sea-ice projections between GCMs, the multi-model mean of sea-ice extent is in reasonable agreement with observations (IPCC 2007b), although it is also noted that sea-ice projections at particular locations (e.g. Davis Strait) are still problematic.

The second set of supporting material was of sea-ice time series. Polar bears are long-lived species: while 1 or 2 years with reduced sea-ice extent may impact survival, reproduction or body condition during those particular years, such small-scale variation would be

Fig. 3. Geographic locations of the five regions.

unlikely to have an effect in the long run on overall population dynamics. Thus, we embedded five time-series of projected changes to 2050 for each of the five specific regions to incorporate plausible inter-annual variability into the survey (Fig. 4). The ECHAM5/MPI-OM GCM (Max Plank Institute for Meteorology, Hamburg) was chosen to provide the regional time-series on the basis of three criteria: (i) its close simulation of the present-day annual cycle of Arctic ice extent; (ii) its close simulation of the multi-model mean of the change in Arctic ice extent (i.e. the model is not an outlier); and (iii) its relatively high horizontal resolution (1·5° latitude and longitude) of the sea-ice component. The regions were defined to be as closely aligned, as the GCM grid allowed, to specific populations as described by the PBSG (2006).

THE QUESTIONNAIRE PROTOCOL

Participants were given 3 weeks during January 2007 to complete the first iteration of the questionnaire. Experts were asked to give responses using a box-plot question format, based on an expert survey instrument devised by Morgan *et al*. (2006). The survey was iteratively refined, and was piloted with four researchers specializing in population ecology. No major changes were made to the protocol after piloting.

The box-plot questions requested participants to provide the 5% upper and lower confidence bounds first, rather than the best estimate. This was to minimize 'anchoring and readjustment' (Morgan *et al*. 2001) whereby participants first provide their best estimate, and then draw outer bounds narrowly around this best estimate, rather than first imagining the range that their uncertainty estimate may fall between.

There is a general tendency towards overconfidence when providing estimates for probability distributions (Morgan *et al*. 2001). The distributions given tend to be too narrow, and do not encompass the true range of uncertainty that may exist. Even if calibration questions are used in a survey to demonstrate this overconfidence, or if participants are thoroughly briefed on the relevant psychological literature, participants may continue to be overconfident in their predictions (Morgan *et al*. 2001). Given the time constraints and the lack of evidence that either of these approaches were particularly successful, an attempt to de-bias the responses was made by briefly explaining the routine bias towards overconfidence before the survey began. After the experts had given upper and lower 5% confidence bounds for the first box-plot question, they were again reminded of the tendency towards overconfidence, and asked to reconsider their responses and adjust them if they considered their previous response range too narrow.

Absolute population totals, especially in some of the regions examined, are quite uncertain. For this reason, we asked participants to give their responses as a percentage change in range or population relative to today, rather than in hectares or absolute numbers of bears. Five confidence bounds were requested:

E1 lower confidence bound (corresponding to the 5% confidence bound)
E2 mid-lower confidence bound (corresponding to the 25% confidence bound)
E3 best estimate (corresponding to the 50% confidence bound)
E4 mid-higher confidence bound (corresponding to the 75% confidence bound)
E5 upper confidence bound (corresponding to the 95% confidence bound)

Absolute lower and upper bounds were not requested as polar bear population dynamics are contingent upon so many other factors apart from climate change. We, therefore, sought experts to quantify only 'reasonably extreme' outcomes, rather than 'absolutely extreme' ones.

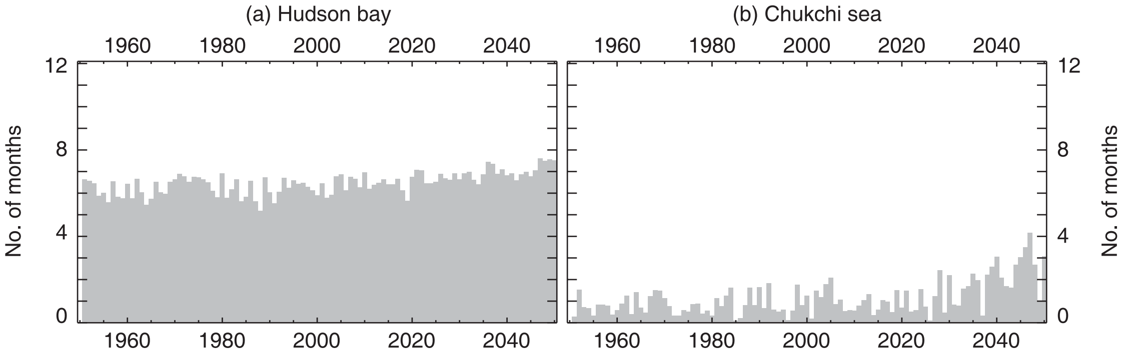

Fig. 4. Time series indicating inter-annual variability and long-term changes in the length (in number of consecutive months with less than 50% sea-ice concentration) of the 'ice-free season' averaged over (a) Hudson Bay, and (b) Chukchi Sea from 1950 to 2050 under SRES emissions scenario A1B, as simulated by the ECHAM5/MPI-OM climate model.

© 2008 The Authors. Journal compilation © 2008 British Ecological Society, *Journal of Applied Ecology*, **45**, 1649–1659

PARTICIPANT SELECTION

Considered selection of expert participants is important in any such exercise, because the choice of participants will invariably affect the results. In this case, a pre-defined group of experts was available through the PBSG. Experts were offered an honorarium of £50 to be donated to a polar bear charity if they participated. Recruitment was via email with an endorsement by the PBSG Chairman to 17 permanent members or researchers closely affiliated to the work of the PBSG. Eleven experts (see Supporting Information Table S1) agreed to participate (with one later withdrawing due to time commitments); two experts did not respond, and four experts declined. Reasons for non-participation were time constraints, or because of a self-stated lack of expertise.

None of the experts expressed doubts regarding the validity of using expert judgement, which contrasts with other studies (e.g. Vaughan & Spouge 2002). It could be hypothesized that this is because expert judgement has played a significant if informal role to date in the ecological field (Sutherland 2006), and thus, ecologists may feel more comfortable than do experts from other disciplines with combining judgement and intuition with scientific information.

THE DELPHI METHOD

The Delphi method is a technique for combining expert judgements in a risk analysis. Participants do not meet, and interaction is through exchange of anonymous assessments (Morgan & Henrion 1990). It was not our aim to reach consensus on each of the eight questions posed. Rather the Delphi method was being used so that participants could view their responses to each specific scenario anonymously against others in the research community, allowing the chance to reflect both on the information given and other expert responses.

Once the first round of responses had been received from all participants, results were collated. Each expert was allocated a participant number so they could identify the box-plot of their individual response for each question against those of the group (as for Figs 5–7, but without the median value box-plot). The collated results were then sent back to the experts and everyone was asked to view their answers in the light of those of the group as a whole, and reply via an online form if they wished to reassess any of their responses. Only one expert chose to do this; others stated that they were satisfied with their contributions and did not wish to change them. The results were again collated and re-sent to the expert group for a third round. None of the experts chose to change their responses in the third round, and thus, the survey was closed.

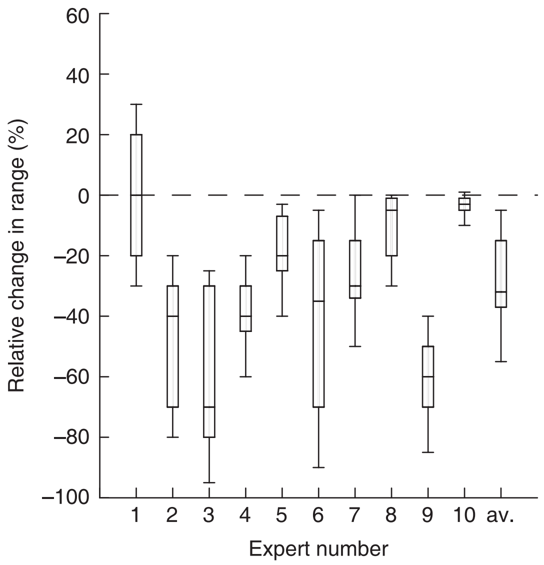

Fig. 5. Projected change in polar bear range relative to 2007 under current management practice. Projections were undertaken for SRES emissions scenario A1B to 2050. Each 'box-plot' represents the views of an individual expert; the error bars indicate the expert's 5% and 95% confidence bounds, the box spans the 25% and 75% confidence bounds, and the central line the expert's 'best estimate'. An average box plot of all the expert views is given on the right.

COMBINING JUDGEMENTS

Combining expert judgements is not straightforward, since the percentage of experts holding a given view is not proportional to the

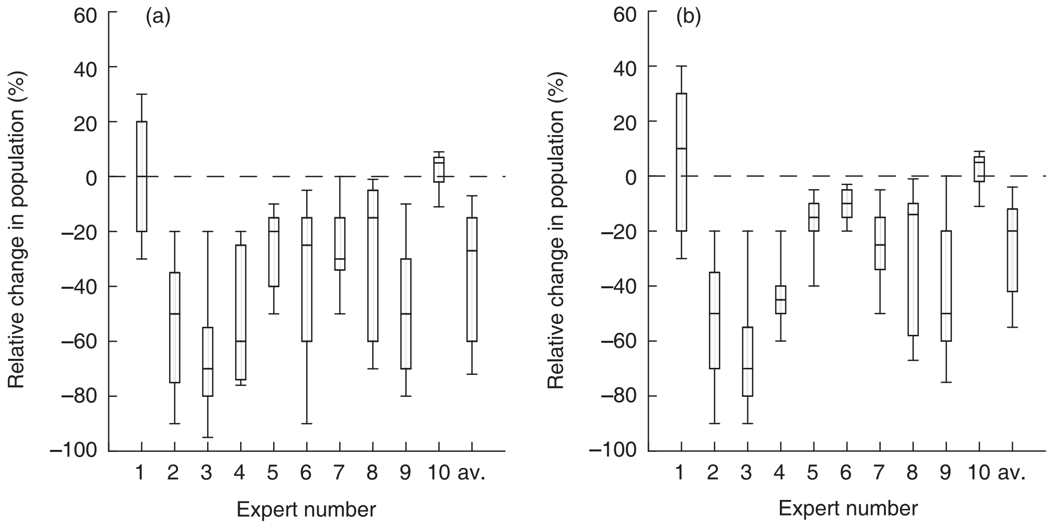

Fig. 6. Projected change in total polar bear population relative to today under (a) current management practice, and (b) expert-defined 'best management practice'. See legend of Fig. 4 for further details.

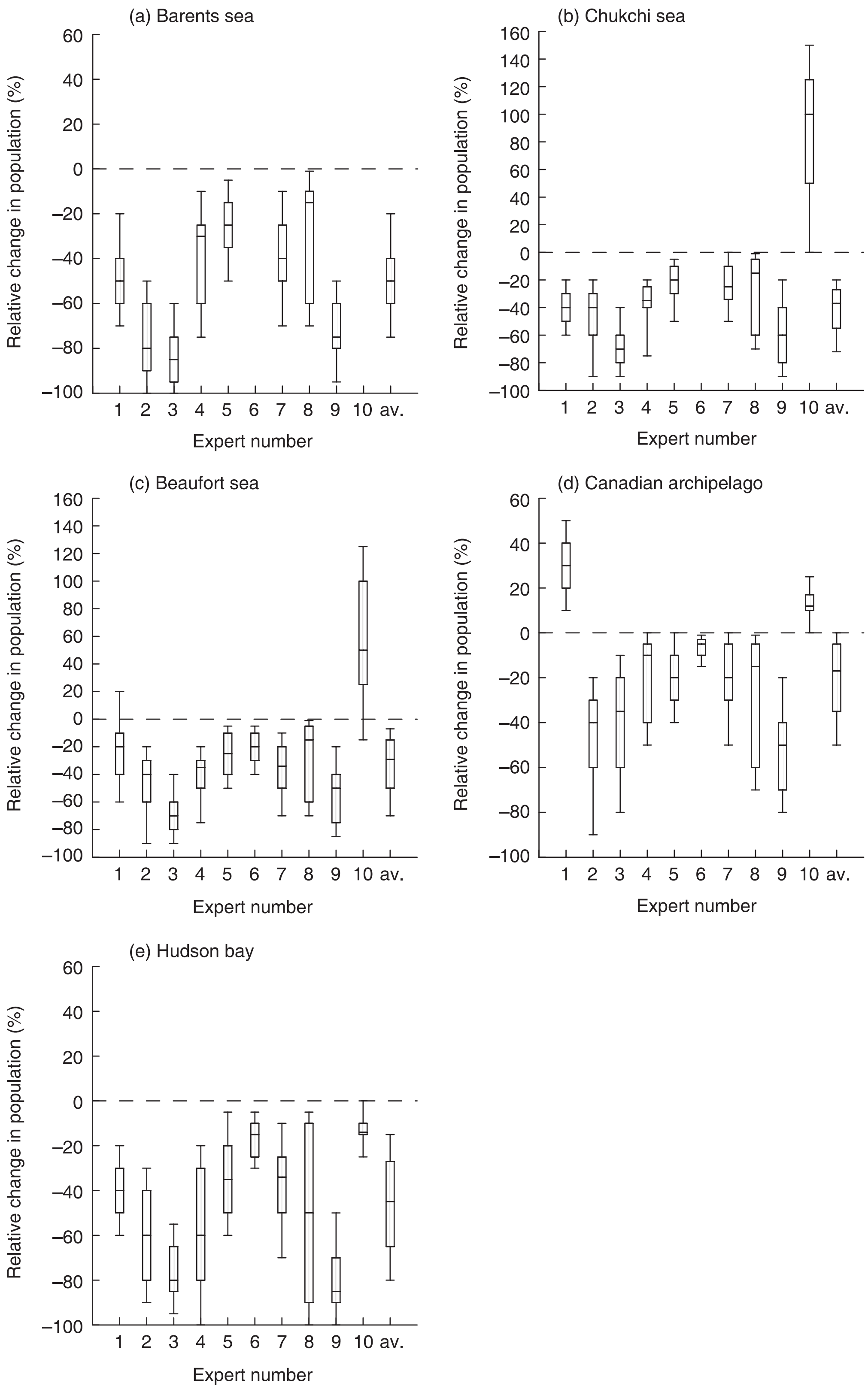

Fig. 7. Projected change in polar bear population in five regions, relative to today under current management practice. See legend of Fig. 4 for further details.

probability of that view being correct (Keith 1996). A number of methods for combining judgements exist, ranging from complex statistical methods (e.g. see Garthwaite, Kadane & O'Hagan 2005) to simple aggregation methods. Clemen & Winkler (1999) state that simpler aggregation methods (e.g. mean, median) generally perform better than more complex methods. Thus, the simple aggregation methods used here provide a useful overview of the current state of expert opinion and associated uncertainties.

It is our aim in aggregating the results to display the diversity and commonalities of opinions on polar bear population dynamics. We, therefore, present the collated results as individual expert box plots (Figs 5–7), which demonstrate the trends, uncertainty and variance in opinion. The final box plot is the median value from all expert responses. The mean is not used in order to avoid the skew that can be introduced by a minority of individual views.

Results

The majority of participants ranked themselves as a 'top expert' in polar bear life-cycle dynamics. All participants considered they had less expertise in climate, with all experts stating either 'some' or 'little' knowledge of climate modelling. There was no discernable trend between responses and the experts' assessments of their expertise.

The three main threats to polar bear populations over the next 50 years were viewed as climate change, hunting and pollution. Many of the specific concerns listed could also be linked to climate change, for example, the future availability of permafrost for maternal denning. Other salient concerns included the increasing frequency of human–polar bear interactions due to climatic warming, perhaps leading to an increase in 'defence kills'.

POPULATION AND HABITAT OVER THE ARCTIC

The experts indicated a negative trend in polar bear range across the Arctic as a whole by 2050 (Fig. 5). The median best estimate for range change was a 33% decline, relative to 2007. Individual expert best estimates lie from no change to a 70% decrease, with half the experts projecting at least a 30% decline. There was a large amount of uncertainty surrounding the projections of polar bear range, evidenced by expert responses between the absolute upper and lower confidence bounds spanning 125%. Although responses from experts 1 and 10 are significantly different to the main body of expert responses, their responses do overlap at least part of the range of experts 2–8.

In considering where there was most likely to be a change in range, experts specifically named Hudson Bay, the Beaufort Sea, Baffin Bay, the Davis Straight, the Barents Sea, the Chukchi Sea and the Laptev Sea. Of these, the Barents Sea was mentioned by six experts, and the Chukchi Sea by four. Five experts either specifically named Hudson Bay, or discussed range changes in more southerly populations.

Projections on changes in total polar bear population size were very similar to projections regarding changes in total habitat area (Fig. 6a). Experts identified a potential negative trend in polar bear population across the Arctic, with a median best estimate of a 28% decrease, relative to 2007. Eight of the 10 best estimates were a 20% decrease or more in polar bear population size. As with estimations of polar bear range, there exists a large amount of uncertainty surrounding projections of population: expert 1 projected an upper confidence bound of a 30% increase in population size relative to today. In contrast, expert 3 suggested a lower confidence bound as a 95% decrease in population: an overall uncertainty range of 125%. Changes in population size were considered to be most likely in the same areas as those experiencing changes in range, with the Barents and Chukchi Seas both named by five experts, and Hudson Bay and the Beaufort Sea named by four experts.

REGIONAL DATA

For each of the five regions (Fig. 2), the median best estimate from all expert responses shows a projected decrease in population (Fig. 7). This projected decrease is greatest in Hudson Bay and the Beaufort Sea, and smallest in the Canadian Archipelago.

Experts 6 and 10 declined to give responses for population change in the Barents Sea, stating a lack of knowledge of polar bear dynamics in these regions. Although little literature exists on Russian polar bear dynamics, the remaining participants gave responses for population change in the Barents Sea (Fig. 7a). Of the eight experts, all projected a decrease in population for the Barents Sea, with a median best estimate of a 63% decline in population relative to the 2007 population. The range of responses given was the narrowest from any of the questions asked, but still spanned 99% between the upper and lower confidence bounds.

Expert 6 also declined to give responses for the Chukchi Sea for the same reasons as detailed above. The median best estimate for the Chukchi Sea region is a decrease of 38%, relative to 2007 population levels (Fig. 7b). Although there is a general consensus in the expert opinion of population decrease, expert 10 considered that the Arctic basin and southern populations will be impacted more severely during the time-scale presented than those farther north. Consequently, this region has the greatest range (250%) between the upper and lower confidence bounds.

All experts gave projections for the Beaufort Sea, with estimates (Fig. 7c) similar to the Chukchi Sea region. Again, expert 10 provided a very different estimate. The median best estimate for the region is a 30% population decrease by 2050 compared to 2007 levels.

Eight experts project a decrease in population in the Canadian Archipelago (Fig. 7d), while experts 1 and 10 both project an increase. The reasoning behind expert 10's views is stated above, whereas expert 1 considered a loss in population likely to occur in Russian regions around Svalbard and Novaja Semlja rather than in the Canadian Arctic. The median best estimate for the Canadian Archipelago is an 18% decrease in population, the smallest population decrease of any of the regions.

Lastly, the experts all projected a population decrease for Hudson Bay by 2050, relative to the population in 2007. This was the only situation where responses were gathered from all 10 participants, and where all responses showed a decrease in population. The median best estimate is a 45% decline in population relative to 2007 levels.

POSSIBLE STRATEGIES FOR 'BEST MANAGEMENT'

Experts were asked to reassess their projections regarding changes in total polar bear population size across the Arctic under their own definition of 'best management practice' rather than current practices. Nine experts considered a precautionary approach to hunting was needed, with some stating hunting should be eliminated altogether. Some experts questioned the current situation of a 'sustainable harvest' as not practical, as detailed population data on which to base sustainable harvest estimates is only available for a few specific populations. This uncertainty is likely to worsen in a warming climate and with associated changes in sea-ice. Only three experts mentioned the issue of climate stabilization as being important in polar bear conservation. The statement from expert 8: '*it (climate stabilization) is unlikely to happen at a significant level within this time frame*' may be insightful here. Regardless, if no action is taken to abate climatic warming within this time period, there will be an even greater climate commitment beyond 2050, with increasing longer-term impacts upon polar bear populations.

One expert stressed that, with climatic warming, bears may increasingly be crowded on land and come into more frequent contact with human settlements. Education could be key in reducing 'nuisance kills', or kills in defence of lives or property (expert 7). Lastly, several experts stated the importance of intensive monitoring and research into polar bear populations and the relationship of these populations to climate change, with facilitation of co-management initiatives between both scientific and traditional knowledge.

Most experts considered that under scenario A1B, considerable population loss by 2050 is inevitable, regardless of management technique (Fig. 6). For half of the participants, responses to each confidence bound E1 to E5 changed no more than 5%. However, the responses from experts 4–6 were impacted rather more by implementing best management, with at least one response E1–E5 changed by 20% or more. In the case of expert 6, implementing best management practice raised the lower confidence bound by 70%: from a 90% decrease to a 20% decrease in the total Arctic polar bear population. Changes in expert responses were evenly spread over the confidence bounds E1 to E5, with no more pronounced change in either the upper or lower confidence bounds.

Discussion

The expert responses suggest polar bear population and range will undergo significant declines by 2050 under SRES A1B. The median best estimates show the Barents Sea, Hudson Bay and the Chukchi Sea projected to suffer the greatest impact with median decline projections of 63%, 45% and 38% respectively. However, although there is consensus over a likely future decline, there is a great deal of variance in the expert responses (especially in relation to the Chukchi Sea), and also in the uncertainty expressed by the experts. The narrowest variance occurs in the responses to the Barents Sea population, although this will almost certainly have been impacted by two experts declining to give responses for this region.

The expression of uncertainty in this study has a number of components (Fig. 1). First, 'downstream uncertainty' exists due to the variability between experts' projections (i.e. some experts' experiences – whether guided by knowledge, literature or belief – led them to project larger polar bear population declines than other experts). This component of uncertainty also includes the willingness of experts to express their uncertainty. It is illustrated by the variation of expert responses in each box plot, and the 5% and 95% confidence intervals of each expert. The wide uncertainty bounds stated in most cases gives reassurance that the experts were not overconfident in their projections. They were willing to describe their current uncertainty, although it is apparent that in some cases, overconfidence may still exist.

Second, 'upstream uncertainty' exists because the 'future' to which experts give their responses is necessarily uncertain. Attempts were made to band the impact of the 'upstream uncertainty' component. We specifically requested participant views on polar bear ecology under the provided scenario and time-scale, and not their opinions on climate change generally. When asked to reflect on their responses, nine experts referred to the sea-ice information. However, expert 10 reflected that his responses '*do not assume the ice scenarios will actually occur*'. Thus, caution should be used when viewing expert 10's results, as the responses provided may not be based on the sea-ice scenario provided.

Media reporting of polar bear risk under climate change has increased as polar bears have become more widely used as a climate icon (e.g. Slocum 2004). Both the more optimistic projections such as those expressed by experts 1 and 10 (e.g. Langan & Leonard 2007) and the more pessimistic projections such as those expressed by expert 3 (e.g. Zabarenko 2007) are apparent in such media representations. This expert survey represents an attempt to reveal the variation of expert judgement about polar bears under a specified climate future. Expert surveys may also be of use in other ecological circumstances where uncertainty is high and other methodologies such as PVA are inappropriate. In contrast to current informal methods of decision making, an expert survey uses a systematic and thorough methodological tool which captures the subjective, yet quantitatively expressed, range of uncertainties surrounding an issue.

Due to a lack of quantitative population data for all polar bear populations, expert opinion is currently the only means available to investigate the impacts of climate change on polar bears in a wider Arctic setting, or in regions where detailed population studies do not exist. Population modelling is possible, and future work in this area is ongoing. Expert opinion cannot be used to replace rigorous scientific projections that would be based on population models combined with data.

However, these responses provide a hitherto unseen view of the state of expert opinion as it stands today. The uncertainties associated with the responses emphasize the need for further research into the impacts of climate change upon polar bear population dynamics.

The Fourth Assessment Report of the IPCC states 'polar bears will face a high risk of extinction with warming of 2·8 °C above pre-industrial' (Box 4·3, IPCC 2007a). This statement of population risk was agreed upon among the authors of Working Group II, Chapter 4 (IPCC 2007a) based on the available literature and on modelled sea-ice decline, in itself forming a process of expert assessment. The research reported here has sought to provide a more in-depth and transparent analysis of the current state of expert knowledge.

There is a considerable difference between the statement of the IPCC ('high risk of extinction') and that from the expert survey participants ('median expert judgement of 28% decline in total population'). They are not directly comparable, however, partly because the sea-ice scenarios on which they are based are different. The IPCC statement assumes that global warming of 2·8 °C causes a 62% loss of summer sea-ice extent (a multi-model mean, with individual simulations within the range 40–100%; Table 4·1, IPCC 2007a), relative to pre-industrial conditions. No time frame was given over which the sea-ice retreat would take place. In the study reported here, experts were asked for projections based on a 47% loss of summer sea-ice extent, relative to 1961–1990 conditions, by the 2050s. These were diagnosed from model simulations under the A1B scenario, under which the multi-model ensemble global temperature rise from pre-industrial to 2050 was 1·9 °C (Table II.4, IPCC 2001). The observed temperature rise of 0·4 °C from pre-industrial to 1961–1990 leaves a projected future rise of 1·5 °C from 1961–1990 to 2050. If ice retreat is linearly related to global temperature change (probably a poor assumption), then the 47% loss of summer ice relative to 1961–1990 would be equivalent to a 60% ($= 47\% \times 1{\cdot}9/1{\cdot}5$) loss relative to pre-industrial. This suggests that the scenario used in this expert survey is, in fact, very similar to that used as the basis for the IPCC statement, and thus, the reason for the differences must lie elsewhere. In particular, we urge caution in interpreting the extrapolated statement from the expert survey; it is based on the median of the experts' mean values and thus does not demonstrate the full range of expert projections, and there is considerable uncertainty and regional variation.

Best management practice does not greatly impact on projections of future polar bear populations, with the projected median decline decreasing from 28 to 20% under this scenario. It is clear from the suggestions given for 'best management practice' that no expert considers current management across the Arctic of polar bear populations as optimal; a number of methods, and in particular the reduction of hunting, could be used to help conserve populations. It has been suggested for a range of habitats that the resilience of communities and taxa to climate change could be increased if other stresses are reduced (IPCC 2007a). Lomborg (2007) suggests that if we wish to conserve stable populations of polar bears, dealing with polar bear hunting may be a '*smarter and more viable strategy*' than curbing greenhouse gas emissions. However, the rather small differences between the projections of the experts under current and optimal management suggest that the scope for this in the case of polar bears is limited. The expert survey data implies that climate change is the primary driver of change in future polar bear populations. Global mitigation efforts are, therefore, a key element in any future conservation strategy.

Acknowledgements

This study forms part of the lead author's PhD into using icons for communicating climate change. We thank Péter Molnár for his comments; PBSG Chairman Andrew Derocher and the expert participants; James Risbey for reviewing the protocol; the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the CMIP3 model output; the WCRP's Working Group on Coupled Modelling (WGCM) for organizing the model data analysis activity. The WCRP CMIP3 multi-model data set is supported by the Office of Science, US Department of Energy. Thanks to Xiangdong Zhang for seasonal sea-ice data, to Simon Busby and James Screen for plotting several figures and to the reviewers for comments on the manuscript. Saffron O'Neill was supported by the School of Environmental Sciences, UEA.

References

Aars, J., Lunn, N.J. & Derocher, A.E. (2006) *Polar Bears: Proceedings of the 14th Working Meeting of the IUCN/SSC Polar Bear Specialist Group*, 20–24 June 2006, Seattle, Washington, USA. International Union for the Conservation of Nature, Gland, Switzerland.

ACIA. (2005) *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, UK.

Akcakaya, H.R., Ferson, S., Burgman, M.A., Keith, D.A., Mace, G.M. & Todd, C.R. (2000) Making consistent IUCN classifications under uncertainty. *Conservation Biology*, **14**, 1001–1013.

Akçakaya, H.R., Butchart, S.H., Mace, G.A., Stuarts, S.N. & Hilton-Taylor, C. (2006) Use and misuse of the IUCN Red List criteria in projecting climate change impacts on biodiversity. *Global Change Biology*, **12**, 2037–43.

Clemen, R.T. & Winkler, R.L. (1999) Combining probability distributions from experts in risk analysis. *Risk Analysis*, **19**, 187–203.

Comiso, J.C. (2003) Warming trends in the Arctic from clear-sky satellite observations. *Journal of Climate*, **16**, 3498–510.

Derocher, A.E., Lunn, N.J. & Stirling, I. (2004) Polar bears in a warming climate. *Integrative and Comparative Biology*, **44**, 163–76.

Etkin, D.A. (1991) Break-up in Hudson Bay: its sensitivity to air temperatures and implications for climate warming. *Climatological Bulletin*, **25**, 21–34.

Garfield, S. (2007) Can polar bears save the world? *The Observer Magazine*, 4 March 2007.

Garthwaite, P.H., Kadane, J.B. & O'Hagan, A. (2005) Statistical methods for eliciting probability distributions. *Journal of the American Statistical Association*, **100**, 680–701.

Gregory, R., Failing, L., Ohlson, D. & McDaniels, T.L. (2006) Some pitfalls of an overemphasis on science in environmental risk management decisions. *Journal of Risk Research*, **9**, 717–35.

IPCC (2001) Climate change 2001: the scientific basis. *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (eds J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell & C.A. Johnson), p. 824. Cambridge University Press, Cambridge, UK.

IPCC (2007a) Climate change 2007: impacts, adaptation and vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson), pp. 211–272. Cambridge University Press, Cambridge, UK.

IPCC (2007b) Climate change 2007: the physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor & H.L. Miller), 996 pp. Cambridge University Press, Cambridge, UK.

Keith, D.W. (1996) When is it appropriate to combine expert judgments? *Climatic Change*, **33**, 139–43.

von Krauss, M.P.K., Casman, E.A. & Small, M.J. (2004) Elicitation of expert judgements of uncertainty in the risk assessment of herbicide-tolerant oilseed crops. *Risk Analysis*, **24**, 1515–1527.

Langan, F. & Leonard, T. (2007) Polar bears 'thriving as the Arctic warms up'. *The Telegraph*, 9 March 2007.

Lomborg, B. (2007) *Cool It: The Sceptical Environmentalist's Guide to Global Warming*. Cyan, London.

Martin, T.G., Kuhnert, P.M., Mengerensen, K. & Possingham, H.P. (2005) The power of expert opinion in ecological models using Bayesian methods: impact of grazing on birds. *Ecological Applications*, **15**, 266–280.

Morgan, G.M., Adams, P.J. & Keith, D.W. (2006) Elicitation of expert judgements of aerosol forcing. *Climatic Change*, **75**, 195–214.

Morgan, G.M., Pitelka, L.F. & Shevliakova, E. (2001) Elicitation of expert judgments of climate change impacts on forest ecosystems. *Climatic Change*, **49**, 279–307.

Morgan, M. G. & Henrion, M. (1990) *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press, New York.

Nakicenovic, N., Davidson, O., Davis, G., Grubler, A., Kram, T., Lebre La Rovere, E., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R. & Dadi, Z. (2000) *IPCC Special Report, Emissions Scenarios: Technical Summary. A Special Report of IPCC Working Group III*. Cambridge University Press, Cambridge, UK.

PBSG (2006) IUCN Polar Bear Specialist Group [online]. http://pbsg.npolar.no/ (accessed 29 Oct 2007).

Pearce, F. (2006) RIP: the Arctic polar bear breathes its last. *The Independent on Sunday*, 5 November 2006.

Slocum, R. (2004) Polar bears and energy-efficient lightbulbs: strategies to bring climate change home. *Environment and Planning D*, **22**, 413–438.

van der Sluijs, J.P., Janssen, P.H.M., Peterson, A.C., Kloprogge, P., Risbey, J.S., Tuinstra, W. & Ravetz, J.R. (2004) *RIVM/MNP Guidance for Uncertainty Assessment and Communication*. (RIVM/MNP Guidance for Uncertainty Assessment and Communication Series, 4). Utrecht University.

Stirling, I. & Derocher, A.E. (1993) Possible impacts of climatic warming on polar bears. *Arctic*, **46**, 240–245.

Stirling, I. & Parkinson, C.L. (2006) Possible effects of climate warming on selected populations of polar bears (*Ursus maritimus*) in the Canadian Arctic. *Arctic*, **59**, 261–275.

Sutherland, W.J. (2006) Predicting the ecological consequences of environmental change: a review of the methods. *Journal of Applied Ecology*, **43**, 599–616.

Vaughan, D.G. & Spouge, J.R. (2002) Risk estimation of collapse of the West Antarctic Ice Sheet. *Climatic Change*, **52**, 65–91.

Zabarenko, D. (2007) Most polar bears could be lost by 2050: report [online] http://www.reuters.com/article/scienceNews/idUSN0721298620070907 (accessed 29 Oct 2007)

Received 2 May 2008; accepted 4 August 2008
Handling Editor: E. J. Milner-Gulland

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Expert opinion survey protocol

Table S1. Experts whose judgements are reported in this study

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

© 2008 The Authors. Journal compilation © 2008 British Ecological Society, *Journal of Applied Ecology*, **45**, 1649–1659