doi:10.1038/nature09653

Greenhouse gas mitigation can reduce sea-ice loss and increase polar bear persistence

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On the basis of projected losses of their essential sea-ice habitats, a United States Geological Survey research team concluded in 2007 that two-thirds of the world's polar bears (*Ursus maritimus*) could disappear by mid-century if business-as-usual greenhouse gas emissions continue[1–3]. That projection, however, did not consider the possible benefits of greenhouse gas mitigation. A key question is whether temperature increases lead to proportional losses of sea-ice habitat, or whether sea-ice cover crosses a tipping point and irreversibly collapses when temperature reaches a critical threshold[4–6]. Such a tipping point would mean future greenhouse gas mitigation would confer no conservation benefits to polar bears. Here we show, using a general circulation model[7], that substantially more sea-ice habitat would be retained if greenhouse gas rise is mitigated. We also show, with Bayesian network model outcomes, that increased habitat retention under greenhouse gas mitigation means that polar bears could persist throughout the century in greater numbers and more areas than in the business-as-usual case[3]. Our general circulation model outcomes did not reveal thresholds leading to irreversible loss of ice[6]; instead, a linear relationship between global mean surface air temperature and sea-ice habitat substantiated the hypothesis that sea-ice thermodynamics can overcome albedo feedbacks proposed to cause sea-ice tipping points[5,6,8]. Our outcomes indicate that rapid summer ice losses in models[9] and observations[6,10] represent increased volatility of a thinning sea-ice cover, rather than tipping-point behaviour. Mitigation-driven Bayesian network outcomes show that previously predicted declines in polar bear distribution and numbers[3] are not unavoidable. Because polar bears are sentinels of the Arctic marine ecosystem[11] and trends in their sea-ice habitats foreshadow future global changes, mitigating greenhouse gas emissions to improve polar bear status would have conservation benefits throughout and beyond the Arctic[12].

Polar bears are dependent on the sea ice for access to their marine mammal prey[13,14], and occur only in Northern Hemisphere marine areas that are ice covered for long enough periods to allow sufficient foraging opportunity. Observed declines in summer sea ice have been associated with declining physical stature and condition, poorer survival and declining population size[2,15,16]. The anticipated future loss of sea-ice habitats resulting from global warming[1] was the principal driver of polar bear declines projected by the United States Geological Survey (USGS) studies[3,17]. Improved management of hunting and other human activities was found unable to materially alter this outcome (see plate 6 in ref. 3).

The USGS studies relied on general circulation model (GCM)-projected losses of Arctic sea ice based on the Special Report on Emissions Scenarios (SRES)[18] A1B 'business as usual' greenhouse gas emissions scenario. Recent emissions trends make it clear that without mitigation little departure from the 2007 polar bear projections could be expected[19]. Also, the hypothesis that the climate system contains tipping elements[4] means that habitats supporting cold-dependent species could disappear abruptly and irreversibly when a particular global mean surface air temperature (GMAT) is exceeded[6]. It has been proposed[20] that existing greenhouse gas emissions already have committed the earth to temperatures that will rise above the tipping point for loss of perennial Arctic sea ice. The perception that nothing can be done to avoid catastrophic losses and ultimate disappearance of polar bears was exemplified in 2007 when the general media proclaimed polar bears were irreversibly doomed[21].

We used projections of twenty-first century GMAT and sea-ice extent from the Community Climate System Model version 3 (CCSM3)[7] to test the hypothesis that a tipping point[4–6,8] will lead to irreversible loss of sea-ice habitats as GMAT increases. We used a Bayesian network model[3] to evaluate whether mitigating greenhouse gas rise could improve the future outlook for polar bears compared to previous projections.

CCSM3 simulations were forced with greenhouse gas concentrations from five emissions scenarios (Supplementary Table 1): SRES[18] A1B and B1; the 2000 (Y2K) climate change commitment scenario[22];

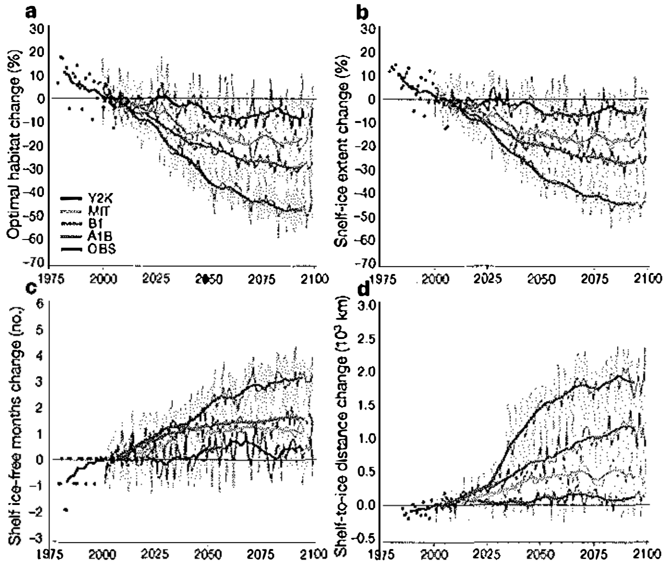

Figure 1 | Changes from the present in polar bear habitat features varied greatly among greenhouse gas scenarios. a–d, The DIV is illustrated here. Shown are changes in optimal polar bear foraging habitat (**a**), extent of sea ice over continental shelves (**b**), number of months continental shelves are ice free (**c**) and the distance from the shelf edge to the edge of the perennial pack ice as projected by CCSM3 with four greenhouse gas scenarios (defined in text) (**d**). Thin lines plot annual averages of the model runs under each greenhouse gas scenario, with error bars showing data ± 1 s.d. Bold lines are 10-year centred running averages of the annual mean values. OBS is observed passive microwave satellite data, black dots are the annual satellite observed values.

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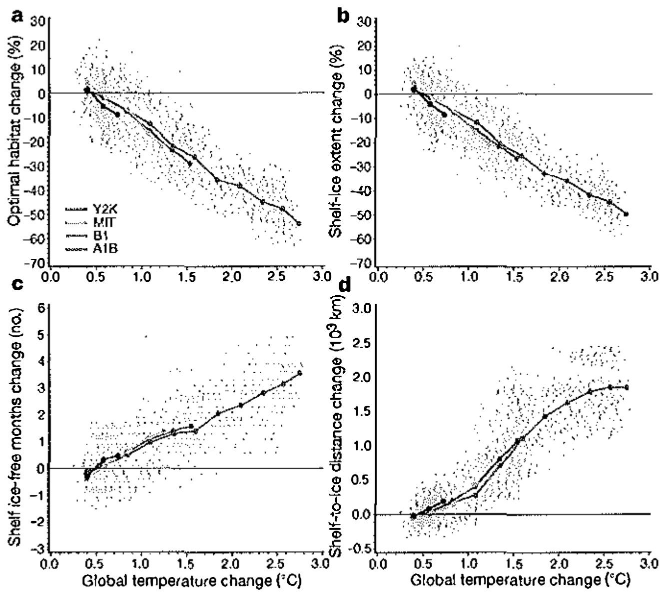

Figure 2 | **Relationship between GMAT change and change in polar bear habitat features is essentially linear.** a–d, The DIV is illustrated here. The optimal polar bear foraging habitat (a), extent of sea ice over continental shelves (b), number of months continental shelves are ice free (c) and the distance from the shelf edge to the edge of the perennial pack ice (d). Linear relationship between habitat and GMAT changes does not support the tipping-point hypothesis. Projections are from CCSM3 running four different greenhouse gas scenarios (defined in text).

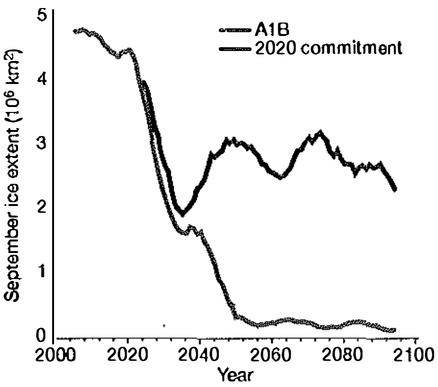

Figure 3 | **September sea-ice extent (50% concentration) recovers from a RILE in a 2020 greenhouse gas commitment realization.** In the 2020 commitment realization, which was integrated from the same initial state as the A1B reference realization, greenhouse gas concentrations followed the A1B scenario until 2020, and were fixed thereafter. RILEs occurred in both realizations during the decade of the 2020s. In contrast to the reference run (red line), the substantial sea-ice recovery in the 2020 commitment scenario (purple line) supports the concept that RILEs represent natural sea-ice variability superimposed on a secular warming-induced sea-ice decline, rather than tipping points. All lines represent 10-year running averages compiled from the annual data.

the Level 1 stabilization scenario (CCSP450) of the United States Climate Change Science Program[23]; and the alternative scenario (AS)[24]. We pooled the AS and CCSP450 realizations into a 5-run mitigation (MIT) ensemble.

Reduced radiative forcing with greenhouse gas mitigation resulted in cooler temperatures, greater sea-ice retention (Supplementary Figs 3 and 4) and less change in important polar bear habitat features (Fig. 1). Importantly, the relationship between GMAT and projected habitat change was largely linear (Fig. 2). Even in September, the month of minimum ice cover, as GMAT increased sea ice and polar-bear-habitat availability smoothly decreased—regardless of the greenhouse gas scenario (Supplementary Figs 5 and 6).

We rejected the null hypothesis that there is a tipping point[4–6,8] of perennial Arctic sea-ice collapse by our failure to find a critical temperature threshold in our GCM outcomes. Our model outcomes support the alternative hypothesis that sea-ice thermodynamics can

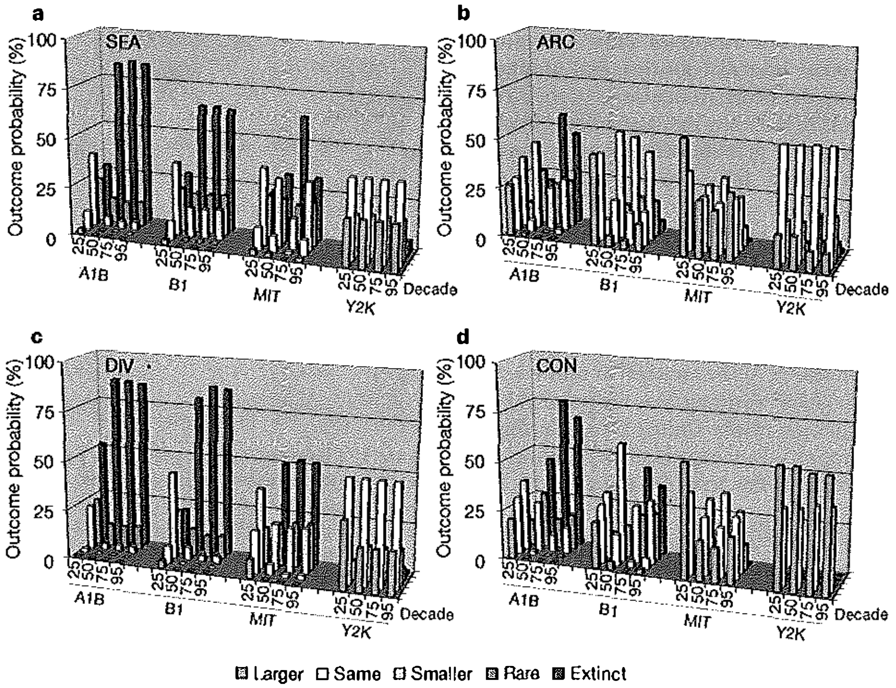

Figure 4 | **Future polar bear persistence varies among ecoregions and greenhouse gas scenarios.** Bayesian network model projected outcomes (coloured bars) are shown for each of four greenhouse gas scenarios, four future decades, and four ecoregions. Although substantial risk of extirpation continues for the SEA and DIV even with mitigation, increased levels of greenhouse gas mitigation improve the probability of future polar bear persistence in all ecoregions. In the *x*-axis legend, we refer to the decades of 2020–2029, 2045–2054, 2070–2079 and 2090–2099 as years 25, 50, 75 and 95.

dominate and reduce the destabilizing effects of the ice-albedo feedback on summer sea-ice cover[6,25,26].

To test further for evidence of tipping-point behaviour, we compared rapid ice-loss events (RILEs)[9,27] in CCSM3 realizations using A1B[18] greenhouse gas levels and levels from a 2020 commitment integration in which greenhouse gas concentrations followed A1B until 2020 and were fixed at 2020 levels thereafter. In the A1B reference run, a RILE occurred between 2020 and 2030, and September Arctic sea ice largely disappeared by mid-century (Fig. 3). If RILEs represent tipping-point behaviour, as suggested[5], the 2020 commitment run should have shown either no RILE or the same kind of permanent ice loss following a RILE as the reference run—depending on whether the climate system in that realization crossed the tipping point.

A RILE did occur in the 2020 commitment run. Instead of proceeding towards permanent ice loss as in the reference run, however, the RILE in the 2020 commitment run was followed by partial recovery and substantial retention of September sea-ice cover through the century (Fig. 3). Because the 2020 commitment run was integrated from the same 2020 initial state as the A1B reference, it experienced the same near-term natural variability, including a RILE during the 2020s. The 2020 commitment run did not proceed to an irreversible and unstoppable loss of remaining ice[6], presumably because the long-term ice loss in CCSM3 is dictated by greenhouse gas radiative forcing and consequent global warming, which are substantially lower for the 2020 commitment run than A1B. This outcome indicates that RILEs are caused by the increased volatility of a thinner and more sensitive sea-ice cover, rather than the sea ice crossing an albedo-induced threshold from which it cannot return[9,28,29].

The linear relationship between GMAT and sea-ice habitat change, and the return of sea ice after the RILE in our 2020 commitment experiment confirm that there is no tipping point[4–6,8] for summer Arctic sea ice in the CCSM3 climate model. We recognize that the absence of tipping points in a climate model does not guarantee that tipping-point behaviour will not occur in the real world. We recognize also that absence of tipping-point behaviour in one GCM does not necessarily mean that tipping points would not be present in other GCMs. Because sea-ice loss in CCSM3 is more sensitive to GMAT rise than other GCMs[30], however, it provides an appropriate and important platform to test the tipping-point hypothesis (Supplementary Information). If the most sensitive of GCMs to greenhouse gas forcing does not illustrate tipping-point behaviour, we would not expect such behaviour in other, less sensitive models.

The finding that RILEs in model outcomes result from increased volatility of an ice cover that is progressively thinning because of warming temperatures—rather than tipping-point behaviour—is consistent with recently observed summer sea-ice declines. The sea-ice loss between September 2006 and September 2007, which was roughly equal to the entire loss of September ice extent between 1979 and 2006, encouraged speculation that a tipping point might have been crossed[5]. Yet, the 2008 and 2009 minima, although well below the long-term mean, were less severe than the record set in 2007[6,10]. Major losses of summer sea ice can thus occur, both in models and in observations, without pushing the sea ice past a tipping point into a permanent state of ice-free summers[6,10,26]. Instead of tipping-point behaviour, recent observations and model outcomes illustrate great natural variability superimposed on a secular warming-induced sea-ice decline. Controlling temperature increase, therefore, is the key to preserving sea-ice habitat.

We derived Bayesian network projections, informed by CCSM3 habitat projections, for polar bear populations in four ecoregions (Supplementary Fig. 8). With A1B habitat values, polar bears were most likely to disappear from the Seasonal Ice Ecoregion (SEA) and Polar Basin Divergent Ice Ecoregion (DIV) by mid-century, and to be substantially reduced in the Archipelago Ecoregion (ARC) and the Polar Basin Convergent Ice Ecoregion (CON). With MIT habitat values, extinction probabilities were much lower in all ecoregions (Fig. 4). Contrary to the A1B case, when greenhouse gas mitigation was combined with best on-the-ground management practices (for example, controlling hunting and other interactions with humans) extinction was not the most probable outcome in any ecoregion, and future population sizes in the CON and ARC could be equivalent to or even larger than at present (Fig. 5). Greenhouse gas mitigation that keeps GMAT rise below 1.25 °C combined with traditional wildlife management could, it seems, maintain polar bear numbers at sustainable although lower-than-present levels throughout the century. (Supplementary Information).

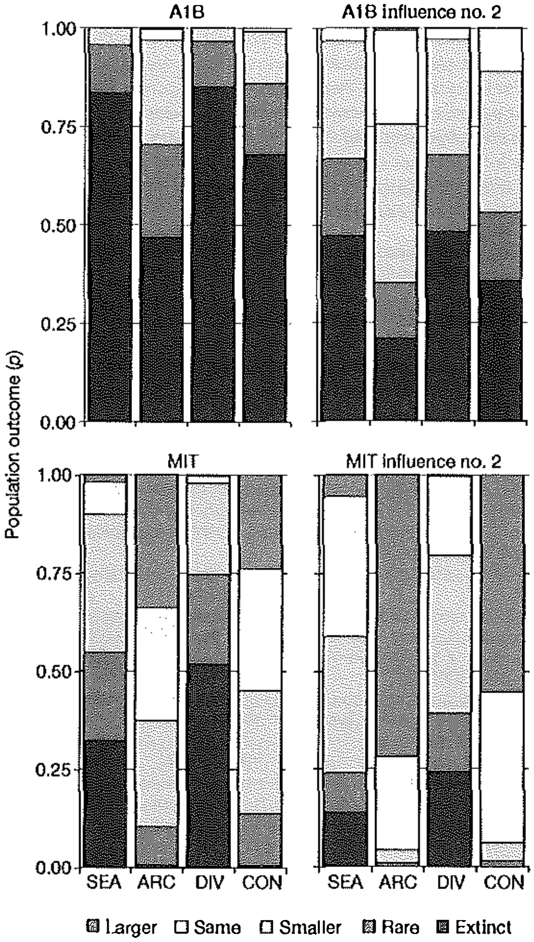

Figure 5 | Greenhouse gas mitigation and best possible wildlife management could allow polar bears to persist throughout current range. Bayesian network outcomes with habitat inputs from the MIT scenario are shown for the last decade of the twenty-first century. When temperature rise is kept at or below the MIT scenario and when on-the-ground management of harvest, bear-human interactions, oil and gas activities etc. is maximized (influence run no. 2), extinction is not the most probable outcome in any of the four ecoregions.

METHODS SUMMARY

Relationships between temperature and habitat. We evaluated relationships between GMAT change and four habitat variables important to polar bear foraging success: resource-selection-function-based optimal habitat[1]; the temporal and spatial extent of sea ice over shallow continental shelf waters[2,11,17]; and the distance ice retreated from the continental shelf. GMAT change was calculated as the difference between the mean temperature of 1980–1999 (13.67 °C), and the future temperatures projected by CCSM3 under the different greenhouse gas scenarios.

Effects of habitat alteration on polar bears. We projected the effects of habitat alteration on polar bear persistence with a Bayesian network model[3] modified to include inputs from other subject matter experts. Our Bayesian network model incorporated changes in four habitat variables projected for each of four ecoregions (Supplementary Fig. 8), with four greenhouse gas scenarios. The Bayesian network model also was informed by the broad range of other currently available information including: potential anthropogenic stressors; the established links between reduced physical stature and survival and declining sea-ice availability among polar bears in parts of their range[2,15-17]; qualitative information indicating that similar processes are underway in parts of the polar bear range where quantitative data are not yet available; the fact that polar bears ultimately are dependent on the sea ice[13,14] for consistent foraging success; and knowledge that if greenhouse-gas-induced warming continues to increase, essential polar bear sea-ice habitats ultimately will disappear[13].

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

Received 30 March; accepted 8 November 2010.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements Principal funding for this project was provided by the USGS. B.G.M. acknowledges support from the USDA Forest Service, Pacific Northwest Research Station. E.T.D. acknowledges the support of the Office of Science (BER), US Department of Energy, under grant ER64735 to the University of Maryland. E.D.'s work also was supported by the National Science Foundation (NSF) during his employment there. The findings reported here, however, are not endorsed by and do not necessarily reflect the views of the NSF. CCSM3 simulations were performed using computing resources provided by the National Center for Atmospheric Research and the Earth Simulator in Japan. D.A.B. was supported under a grant from the NSF Office of Polar Programs, award number 0908675. M. Holland provided comments regarding model design and analysis. We acknowledge the Program for Climate Model Diagnosis and Intercomparison and the World Climate Research Programme's Working Group on Coupled Modeling for their roles in making available the Coupled Model Intercomparison Project phase 3 multi-model data set (support of this data set is provided by the Office of Science, US Department of Energy). We thank W. Washington and L. Buja for running the AS and providing us with the output from the CCSP integrations. We thank D. Vongraven and S. Vavrus for comments on earlier versions of this manuscript, and we thank N. Lunn and L. Peacock for providing the peer reviews necessary for the beta version of our Bayesian network model. Any use of trade names is for descriptive purposes only and does not represent endorsement by the US government.

Author Contributions S.C.A. conceived the project, assembled the team, and led writing. E.T.D. helped refine the project and analysed habitat/GMAT and RIGEs. D.C.D. staged sea-ice data and did the spatial analysis related to sea-ice metrics. B.G.M. conducted Bayesian network model runs and compiled outcomes. G.M.D. led development of the resource selection function approach to habitat analysis. C.M.B. proposed and helped interpret the 2020 CO_2 stabilization experiments. D.A.B. set up and ran the climate model simulations. E.T.D., C.M.B. and D.A.B. led interpretation of GCM outcomes. S.C.A., B.G.M. and D.C.D. interpreted biological outcomes. E.T.D. and D.C.D. developed all graphics. All authors contributed to writing and responding to review comments.

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METHODS

GCM and scenarios. We used five emissions scenarios in our CCSM3 experiments. The Y2K scenario fixes atmospheric greenhouse gas concentrations at year 2000 levels[22]. The CCSP450[23] scenario keeps end of century total anthropogenic radiative forcing below 3.4 W m^{-2}, whereas the AS[24] does not allow anthropogenic radiative forcing to exceed 1.5 W m^{-2} above year 2000 levels. In A1B and B1, CO_2 rises to 689 p.p.m. and 537 p.p.m. by 2100 (using the CCSM3 concentration values, see Supplementary Fig. 1 and Supplementary Table 1). Greenhouse gas concentrations for the CCSP450[23] and SRES[18] scenarios were calculated from the emissions specified for these scenarios with the Model for the Assessment of Greenhouse Gas Induced Climate Change[22], a globally averaged gas-cycle/climate model. See ref. 12 for discussion of the CCSP greenhouse gas concentrations, and ref. 31 for details of the SRES[18] integrations. Greenhouse gas concentrations used in the AS are in supporting table 2 found at http://www.pnas.org/content/101/46/16109/suppl/DC1.

We obtained eight realizations each for A1B and B1, four realizations each for CCSP450 and Y2K, and one realization of the AS. Because net radiative forcing in the AS and CCSP450 were similar (Supplementary Fig. 2), and because global temperature change (Supplementary Fig. 3) and change in sea-ice extent (Supplementary Fig. 4) projected by the single AS run were very similar to members of the 4-run ensemble of CCSP450, we combined the single AS run with the 4 CCSP450 runs to create a 5-run mitigation ensemble (MIT). This left us with 4 forcing ensembles with which to compare the projected effects on the future welfare of polar bears: A1B, B1, Y2K and MIT.

GMAT change was calculated as the difference between the annual mean temperature of 1980–1999 (13.67 °C), and the future temperatures projected by CCSM3 under the different greenhouse gas scenarios we examined. We derived the 1980–1999 mean from 8 CCSM3 model runs incorporating greenhouse gas increases observed through the twentieth century (20C3M ensemble)[32].

Ecoregions. We evaluated how mitigation might affect polar bears occupying four Arctic ecoregions defined by temporal and spatial differences in observed ice melt, freeze, advection, bathymetry, proximity to land, and polar bear responses to those patterns (Supplementary Fig. 8). Each ecoregion is large, composed of several recognized subdivisions of the global polar bear population[3,33], and not entirely homogeneous. Nonetheless, they offer useful subdivisions of the worldwide polar bear distribution because areas within each tend to be more similar than they are to portions of other ecoregions.

The SEA includes Hudson Bay, Foxe Basin, Baffin Bay and Davis Strait. There, sea ice melts entirely in summer and the ~7,500 bears occurring there are forced ashore for extended periods during which they are largely food deprived. The ARC—the channels between the Canadian Arctic Islands—is presently home to ~5,000 bears and is characterized by heavy sea ice, much of which is present year round. The polar basin (the portion of the Arctic Ocean centred on the North Pole and ringed by the continental shelves of Eurasia, North America, Greenland and the Canadian Archipelago; Supplementary Fig. 8) was divided into a DIV, including the Southern Beaufort, Chukchi, East Siberian-Laptev, Kara and Barents Seas, and a CON including the east Greenland Sea, the continental shelf areas adjacent to northern Greenland and the Queen Elizabeth Islands, and the northern Beaufort Sea. Extensive formation of annual sea ice occurs in the DIV where ~8,500 bears currently occur. That ice typically is advected towards the central polar basin, out of the polar basin through Fram Strait, or against the CON. The CON is currently home to ~2,400 polar bears. Differences among ecoregions acknowledge that global warming effects on sea-ice habitats have different starting points[14] and that the nature of sea-ice changes is likely to be different.

Habitat metrics. We examined the relationship between GMAT change and four habitat variables known to be important to polar bears. First, we adopted the resource selection function (RSF) approach previously described[1] to convert GCM projections of sea-ice extent to projections of optimal polar bear habitat. RSFs are quantitative expressions of the habitats animals choose to utilize, relative to available habitats and resources[31]. Sea-ice concentrations for the observational period were estimated from monthly passive-microwave (PMW) satellite imagery[35]. Choices polar bears made from among available habitats were determined from 1985–1995 satellite radiolocations[1]. Optimal habitat was defined as any mapped pixel with an RSF value in the upper 20% of the seasonally averaged (1985–1995) RSF scores, and could be expressed as the sum of qualifying mapped pixels over any period of interest. We assessed changes in habitat availability by comparing annual sums of optimal habitat among projected time periods[1].

Estimates of optimal habitat were limited to the polar basin because only there did we have access to the radio-tracking data necessary to build RSF models. The importance of sea ice over continental shelves, however, is widely recognized as an important component of polar bear habitat[1,11]. Therefore, we derived a second habitat variable we called 'total shelf-ice habitat' from both observed and projected Arctic-wide sea-ice concentration maps. Total shelf-ice habitat was defined as the aerial cover (km^2) of all pixels with ≥50% ice concentration that were mapped over the continental shelves (<300m depth). Waters with less than 50% ice cover were denoted ice-free because available data indicate that areas with sea-ice coverage <50% may not be preferred[1,15]. Unlike optimal habitat, total shelf-ice habitat could be calculated in all ecoregions and therefore provided a means of quantifying projected changes in habitat availability throughout the range of polar bears. We compared shelf-ice habitat expressed as the annual 12-month sum of sea-ice extent over the continental shelves in each ecoregion. Because SEA and ARC are almost entirely continental shelf area, the total shelf-ice habitat in those ecoregions equated to the total annual area (sum of 12 months) of ≥50% concentration sea ice.

The third habitat variable, one of the most important variables representing seasonal changes in habitat available to polar bears[2,15-17,36], was calculated as the change from present in the number of months that ice was projected to be absent (ice-free months) from the continental shelves. An ice-free month occurred in an ecoregion when <50% of the shelf area was covered by sea ice of ≥50% concentration. Outside the polar basin this variable represented simply the ice-free season because the SEA and ARC are composed almost entirely of continental shelf.

Recognizing that the magnitude of the separation of the sea ice from preferred foraging areas also might be important, we calculated a fourth habitat variable as the change in average distance from the continental shelf to the ice pack during the month of minimum ice extent (shelf-to-ice distance). Shelf-to-ice distance was calculated, for the month of minimum ice extent, as the mean distance from every shelf pixel in either of the polar basin ecoregions to the nearest ice-covered pixel (>50% concentration) in the main body of perennial ice. We did not calculate shelf-to-ice distance in SEA and ARC because they are almost entirely comprised of continental shelf.

We plotted GMAT change against these habitat features to evaluate potential nonlinearities in the relationships. Figure 2 and Supplementary Figs 5 and 6 illustrate annual mean GMAT values (x-axis) and corresponding habitat values (y-axis) for each year of each simulation (small dots). Each scenario is shown in a different colour. Large connected dots in each plot are centred on the means, over all years, of the annual GMAT values and values of the habitat-related variables, where GMAT lies within 0.25 °C bins centred on 0.25 °C, 0.5 °C, 0.75 °C, etc., for all simulations performed for each scenario. Large dots are not in exact vertical alignment because the means of the GMAT values in each bin differ among scenarios.

Bayesian network model. The effects of future habitat alteration on probabilities of future polar bear persistence were projected with a beta version[37] of the Bayesian network model used previously[3]. The beta model was reviewed by two other polar bear experts and modified accordingly. Some conditional probabilities were modified to incorporate reviewers' suggestions and observations noted since building the original model. The beta model includes a finer division of bins for sea-ice habitat variables, but upper and lower bounds were retained to ensure that the range of possible entries in conditional probability tables was consistent with the assignments in ref. 3. The final structure (nodes and links) of the beta model is nearly identical to that of the alpha model[3].

Our beta model incorporated changes in the four habitat variables projected under different greenhouse gas scenarios. We calculated the average per cent of future changes, from the 2001–2010 decade, in annual optimal and shelf-ice habitat. Changes in the number of ice-free months and the shelf-to-ice distance were expressed as the average increases (months of ice absence and kilometres of ice retreat) at each decade.

The Bayesian network model also was informed by the broad range of other currently available information including: potential anthropogenic stressors; the established links between reduced physical stature and survival and declining sea-ice availability among polar bears in parts of their range[2,15-17,36]; available qualitative information indicating that similar processes are underway in parts of the polar bear range where quantitative data are not yet available; the fact that polar bears ultimately are dependent on the sea ice[13,14] for consistent foraging success; and that if greenhouse-gas-induced warming continues to increase, essential polar bear sea-ice habitats ultimately will disappear[13]. These additional factors were incorporated into the model as ordinal or qualitative categories or as background with which conditional probability tables were parameterized. The beta model incorporated 4 greenhouse gas scenarios and was applied to each of the four ecoregions at four future decadal time periods: 2020–2029, 2045–2054, 2070–2079 and 2090–2099. At each time period, states of these variables could represent a condition similar to present, better than present, or worse than present (see tables 3 and 4 in ref. 3).

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doi:10.1038/nature09653

Supplementary Methods

To further explore whether rapid ice loss events (RILEs) represent system volatility or tipping point behavior we tested for the presence of rapid ice gain events (RIGEs) in CCSM3 outcomes. We defined RIGE as a change comparable to the RILEs of Holland et al. (S1 S2) and Lawrence et al. (S3) but with opposite sign--ice gain rather than loss. Hence, a RIGE occurred in our model results when the derivative of the five-year running mean time series of smoothed September ice extent exceeded a gain of 0.5 million km^2 per year. The event length was determined, as defined for RILEs, by the time around the transition for which the derivative of the smoothed time series exceeded a gain of 0.15 million km^2 per year.

Supplementary Discussion:

General Circulation Model and Scenarios

CCSM3 is well suited for assessing mitigation efficacy, tipping point behavior, and responses of polar bear sea-ice habitats for four reasons. First, it produces a credible simulation of 20th century Arctic sea ice, including mean sea-ice thickness and the summer and winter spatial patterns of sea-ice concentration (S4). Second, the climate sensitivity of CCSM3 in relationship to sea-ice trends is largely concordant with the observational record (S5), and because the sea ice response in CCSM3 is more sensitive to greenhouse gas (GHG) forcings than other GCMs, it is one of only two climate models found to be capable of simulating the strong observed trend of decline in Arctic sea-ice extent over the satellite record (S6). Third, multiyear Arctic sea ice (the ice remaining in September at the end of the melt season) declines catastrophically in CCSM3 under the A1B scenario. These sea-ice declines in the CCSM3 model include abrupt steps, similar to the abrupt steps in the recent observational record (S1,S7). These abrupt steps encouraged speculation they might be evidence of tipping point behavior in summer sea-ice (S8). Fourth, CCSM3 global warming in the A1B scenario is sufficient to cause disappearance of September Arctic sea ice, and hence polar bear summer habitat, as early as 2040 (S1). This is largely concordant with forward extrapolation of the observational record of the past decade.

Projected concentrations of CO_2 (Supplementary Fig. 1) and projected radiative forcings (Supplementary Fig. 2), differed greatly among scenarios. Consequently, trajectories of GMAT change projected with the different GHG scenarios also varied (Supplementary Fig. 3). Whereas temperature gains at century's end exceeded 2.5°C in A1B realizations, they remained under 1.25 °C in MIT realizations. Reducing GHG forcing reduced the rate of decline in summer sea-ice extent (Supplementary Fig. 4) and habitat features important to polar bears (Figure 1). In all cases, however, the relationships between change in global mean surface air temperature (GMAT), sea ice extent, and sea ice habitat features, were essentially linear. These linear relationships (Figure 2, Supplementary Figs. 5, 6) do not support the hypothesis of a tipping point in summer Arctic sea ice (S9-S12).

Several factors act to reduce the sensitivity of Arctic sea ice to the sea ice-albedo feedback (SIAF) generally posited to produce a tipping point for perennial sea ice cover. Gorodetskaya and Tremblay (Figure 2 in S13) showed that the effective change in albedo between ice-covered and ice-free ocean is reduced considerably by Arctic cloud cover. Also, because sea-ice reaches its minimal extent in September, when Arctic day length is shortening, the enhancement of solar absorption due to sea-ice loss is relatively smaller than earlier in the year

(S14). Further, as day length progressively shortens following summer, the absence of sea ice is conducive to the formation of new sea ice. During freeze-up, the temperature of the unfrozen ocean surface is at or above freezing while the overlying atmosphere becomes progressively colder. Exposure of the relatively warm ocean surface to a cold atmosphere leads to strong surface-water cooling, followed by freezing and new ice growth. The stabilizing ability of new ice growth is enhanced because thin ice grows (thickens) faster than thick ice (S15). Thus, the loss of ice cover due to the sea ice albedo feedback (SIAF) in summer is partially offset by enhanced sea-ice formation in the following autumn and winter.

The ability of sea-ice thermodynamic factors to ameliorate the effects of SIAF (S14, S16) means that a substantial loss of sea-ice cover in one summer does not necessarily constitute a tipping point and does not assure a greater loss in the next summer (S17). It also means that GHG mitigation that would reduce future temperature increases can reduce future sea-ice losses. Observations of the past 3 years corroborate this conclusion. The record breaking expanse of open water that appeared in summer 2007 was followed by enhanced ice growth that autumn and winter (S18, Figure 2b in S19), and the perennial ice minima of subsequent years have been less pronounced than in summer 2007 (S19, S7).

We recognize that we cannot prove sea ice thermodynamics will overcome SIAF in the real world. However, some form of negative feedback is offsetting the positive SIAF in model results. Our results and those of the others we cite, suggest that thermodynamics are the most logical explanation. This is consistent with recent findings (S20) that September sea-ice extent becomes increasingly dependent on spring ice thickness, which in turn is dependent on GHG forced temperature increases. It is also consistent with recent analyses (S1, S2, S3) showing that rapid ice loss events (RILEs) in climate models are caused by the increasing volatility of sea-ice area as the ice thins due to warmer conditions, rather than because a SIAF driven threshold has been crossed.

The 2020 commitment scenario provided further evidence that, despite the increasing probability of RILEs in a progressively warmer Arctic, GHG mitigation can enhance persistence of sea ice habitats. Although seasonal sea-ice retreats are still projected to be much larger than at present, the 2020 commitment run retains far more sea ice throughout greater portions of the Arctic than the A1B scenario (Figure 3, Supplementary Fig. 7). In the A1B scenario, August and September sea-ice persists at the end of the century only in very small areas of the Canadian Archipelago and northern Greenland. By contrast, when GHG concentrations are fixed at 2020 levels, August and September sea-ice persists through the century in much of the central polar basin, areas north of Greenland, and throughout the Canadian Archipelago (Supplementary Fig. 7). Further, the length of time sea ice is absent from the continental shelf areas that polar bears prefer, is greatly reduced in our 2020 commitment run. By mid-century, following the A1B scenario, sea ice is absent from most of the polar basin and even the Canadian Archipelago from July through October, but ice is present throughout the summer in much larger portions of the Arctic in the 2020 commitment run (Supplementary Fig. 7). The length of time sea ice is absent, one of the habitat parameters used to inform our Bayesian network model, has been shown to be a critical factor in assessing future polar bear welfare (S21).

The presence of rapid ice gain events (RIGEs) in the CCSM3 integrations provides further evidence that RILEs do not represent tipping point behavior. Four of the eight members of the B1 ensemble included RILEs, but three of these also included RIGEs. Similarly, a RIGE occurred in one of the five members of the MIT ensemble, while two ensemble members included RILEs. If RILEs occur because the sea ice is pushed past a critical threshold to a new ice-free state (S8, S9, S17), RIGEs would not be expected in the same global warming simulations that included RILEs. The observations of RIGEs in our simulations, therefore, provides further evidence that RILEs represent natural system volatility expressed in a thinning ice environment rather than the crossing of a threshold from beyond which sea ice cannot return.

Cullather and Tremblay (S22) have shown that periods of large sea-ice decline similar to those of recent years occasionally occur in a long integration with steady pre-1990s GHG concentrations. This finding illustrates the great natural variation in sea ice conditions. In pre-1990s GHG environments, it was shown that these kinds of ice losses were fully compensated by ice gains in subsequent years (S22). Such full recovery cannot be expected in an increasing GHG environment. Yet even in the integrations with increasing GHG levels, modeled RILEs can be followed by RIGEs, just as observed record summer ice retreats are not necessarily followed by still greater retreats (S7, S17, S18, S19).

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Our integrations suggest that the reduction of polar bear habit loss from mitigation is dependent upon the level of mitigation. When CCSM3 is forced with the B1 scenario, more polar bear habitat is preserved than with the A1B scenario but less than with the MIT scenario. At the end of the century, in the B1 scenario, anthropogenic radiative forcing reaches 4.5 W/m^2 and the GMAT rise in CCSM3 is approximately 1.5° C (Supplementary Fig. 3). This results in a mean September sea-ice area remaining at the end of the century of approximately 10^6 km^2. GMAT rises only about 1.0° C in our MIT scenario and over twice the amount of September sea ice is preserved (Supplementary Fig. 4). Controlling GMAT rise, it appears, is the key to conserving polar bear habitat. Van Vuuren et al. (S23) provided additional impetus for keeping GHG forcings below the B1 level. They suggest that 4.5 W/m^2 forcing will result in a warming of 2.4° to 4.6 °C, much higher than we project with CCSM3. If the realized temperature increase is in that range, there is greater risk of losing much more polar bear habitat than we have projected under B1 forced CCSM3.

Justification for a precautionary approach also is provided by the fact that CCSM3 tends to generate more ice in Baffin Bay and Davis Strait than is reasonable (S22, S24, S25). These areas compose a large portion of the Seasonal Ice Ecoregion (SEA, Supplementary Fig. 8). This tendency of CCSM3, despite its overall good agreement with observed ice patterns, explains why our A1B CCSM3 projections for the SEA may appear a bit more favorable than those of Amstrup et al. (S26). In fact, our simulations even in the A1B scenario, project more ice in Davis Strait at the end of the century than was observed there during the decade of

1996-2006. Therefore, in all scenarios, the projections for change shown here in the SEA may be overly optimistic.

Additionally, our shelf-ice distance parameter appears to reach an unrealistic plateau at the warmest temperatures (Figure 2). This is an artifact of the ceiling placed on the distance ice can retreat from the Divergent Ice Ecoregion (DIV) by the geography of the Convergent Ice Ecoregion (CON) and not an indication that some ice persists even at the warmest temperatures. The propensity of CCSM3, contrary to the observational record, to maintain ice along the northeastern coast of Russia also appears to contribute to this lack of linearity in the change in shelf-ice distance. At high temperatures, aberrant remnants of sea ice along the Russian coast alternate among years with remnants appropriately positioned at the most distant locales in the CON, as the main bodies of perennial ice available. Nonetheless, shelf-ice distance provided an index of the seasonal retreat polar bears occupying sea-ice habitats would make from their preferred continental shelf foraging areas.

Bayesian network model—

Translating habitat savings into numbers of polar bears that might be affected is complicated by the dearth of population data across much of the polar bears' circumpolar range. That polar bears depend on sea ice for most of their life-cycle needs is well known. It is only from the surface of the sea ice that they are consistently effective at catching ringed and bearded seals, their preferred prey (S21, S27, S28). However, over most of the polar bears' range, data are insufficient to quantify the demographic links between sea ice and polar bears. More importantly, how those links might change in the future as regional differences in global warming's effects on sea ice are expressed, is not clear. The absence of quantitative data over much of the polar bears' range along with anticipated geographic differences in responses to warming-induced habitat change currently prevent range-wide population predictions based on quantitative demographic or energetic analyses. Yet, there is a great deal of quantitative information available for polar bears in some regions and considerable ability to qualitatively extrapolate from the well-known regions to the others.

We used a Bayesian network (BN) model (S29, S30) to synthesize the variety of available data and prevailing knowledge into a projection of future polar bear status in 4 major Ecoregions that encompass the global population (Supplementary Fig. 8). Because BN nodes can represent categorical, ordinal, or continuous variable states, BN models are especially useful in making projections where data are of mixed quality and availability (S31, S32) as in the polar bear case. Historically, synthetic projections made in such circumstances were derived subjectively by seasoned experts and could not be replicated. In contrast, BNs are "solved" by specifying the values of input nodes and having the model calculate posterior probabilities of the output nodes through "Bayesian learning," (S32). This approach allows a complicated assortment of different kinds of information to be objectively and transparently synthesized into probabilistic conclusions about future states.

The distribution of probabilities among outcome states in a BN model reflects the degree of uncertainty in those outcomes. When most of the probability falls into one outcome state, there is low uncertainty of predicted results. Outcome states with low but nonzero probability should not be summarily discounted, but they may be highly unlikely. On the other hand, if probabilities are more evenly spread among multiple outcome states, there is great uncertainty in any directional trend.

Our BN is not a demographic model and is not designed to estimate specific population sizes at future times. Rather, it is useful for synthesizing a variety of kinds of information into probabilistic projections of likely future outcomes. Nonetheless, these likely future outcomes can provide a general picture of relative numbers of animals that may survive at various points in the future. The BN model parameterized with habitat values generated by the A1B scenario projected 83-85% probabilities (Figure 4) that polar bears would be extinct by the end of the century in the DIV and the SEA. This corresponds with loss of ~16,000 of the approximate current world population of 24,500 (S26, S33) polar bears by the end of this century. Furthermore, extinction probabilities at the end of the century were projected to be 47% and 68% respectively for the ARC and CON suggesting high probability the current population of ~8500 bears there also would be severely reduced.

When parameterized with habitat values generated by our MIT scenario, the BN model still projected 32% and 52% of the probability falling into the extinct category at century's end for the SEA and DIV. Although there was a wider spread of probability among other outcome states, this finding recognizes that even moderate additional warming, beyond today's levels, is likely to continue to severely impact polar bears in regions where sea-ice loss already is having negative effects.

In the MIT scenario, polar bears were projected to fair better in the ARC and CON. This suggests that the more modest warming under the MIT forcings, than in other scenarios, could allow favorable conditions to persist for polar bears in the more northerly parts of their current range. Perhaps the most important observation, however, was the degree of improvement in projections when MIT forcings were combined with the assumption that the best possible on-the-ground management would be practiced. In that case, the most probable outcome was that populations in the DIV and SEA would be smaller than they are now, with extinction probabilities reduced to 14% and 24%, respectively (Figure 5), and that populations in the ARC and CON could be the same as or even larger than they are now. With the lower probability of extinction in the SEA and DIV, the end of century world-wide polar bear population could be between the current 24,500 and 8500-bears.

Our polar bear BN model is informed by the linear relationships we observed between GMAT and sea-ice and numerous other factors hypothesized to affect polar bear populations. The influences from sea ice, other environmental conditions, and anthropogenic stressors, collectively result in the polar bear outcomes projected through Bayesian learning. Although availability of sea ice in our projections declined linearly with GMAT, the relationship between the magnitude of polar bear population response and sea ice availability is not assumed to be linear. The polar bear population outcomes, nonetheless, were consistent with the direction of changes in sea ice availability in our GCM realizations.

Differences among regions, in the mechanisms by which changing sea ice will affect polar bears, are likely because different regions are at different starting points with regard to present sea ice status (S28), and because of anticipated differences in the ways sea-ice, ocean productivity, and access to seal prey, will change in different regions. For example, rather than the straightforward pattern of a progressively longer absence of annual sea ice that has been occurring in Hudson Bay (S34); the Beaufort Sea is undergoing a transition from an environment dominated by multi-year and heavy annual sea-ice to an environment characterized by thinner annual ice and limited multi-year ice. Until recently, sea ice that was too heavy for too long was a potential limiting factor for polar bears in the Beaufort Sea (S35, S36). Ultimately prolonged sea ice absence from biologically productive areas, and changes in sea ice character and associated productivity, will negatively impact polar bears throughout their range. In the shorter term, however, we expect to see a variety of impacts from sea-ice changes on polar bears, including but not limited to nutritional and energetic effects. These differences may include transient benefits to polar bears in some regions while at the same time strongly negative impacts are occurring in other regions. Given the kinds of differences apparent in the two areas where we know polar bears best (SEA and DIV), it would be naïve to think that responses of polar bears to changing sea ice would be the same throughout their range. Our BN modeling framework represents those anticipated differences among regions to the extent that they currently can be estimated.

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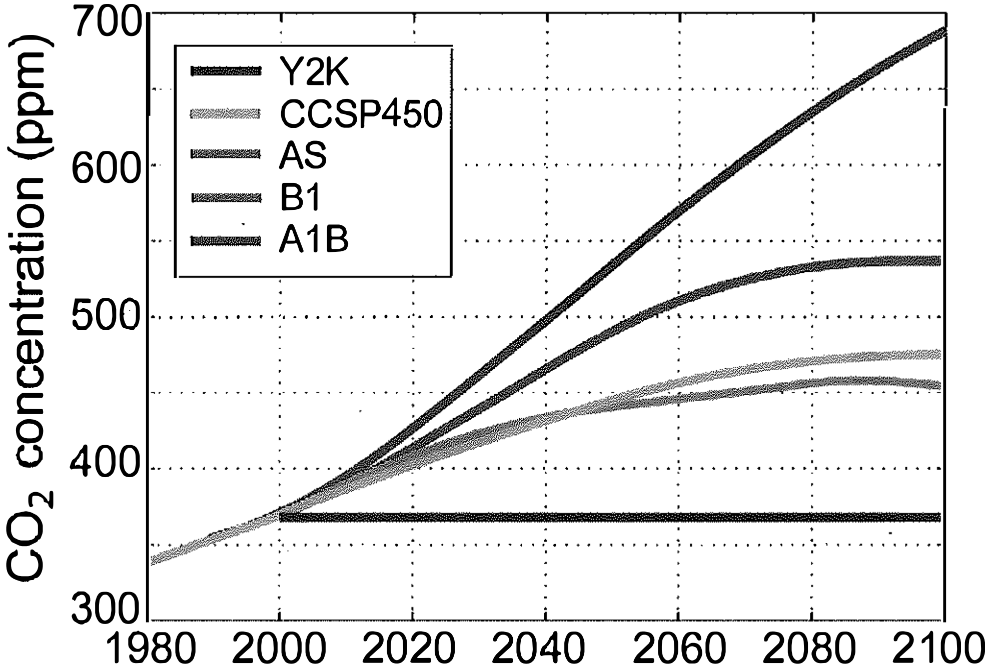
Despite quantitative shortcomings in polar bear data, which may not be filled for some time, policy-makers need information from which decisions can be made now. The BN model framework incorporates the state of current knowledge in a straightforward and transparent way and provides probabilistic predictions of outcomes based upon that knowledge. As data become available to quantify the regional mechanisms by which changing sea-ice may affect polar bear welfare and as quantitative demographic and energetic models are constructed, they can be incorporated into the BN model framework to allow more refined and quantitative projections of future polar bear welfare.



Supplementary Fig. 1. CO_2 concentration values through the 21st century for 5 greenhouse gas emissions scenarios used to reevaluate future projections of polar population status. GHG scenarios are defined in the text.

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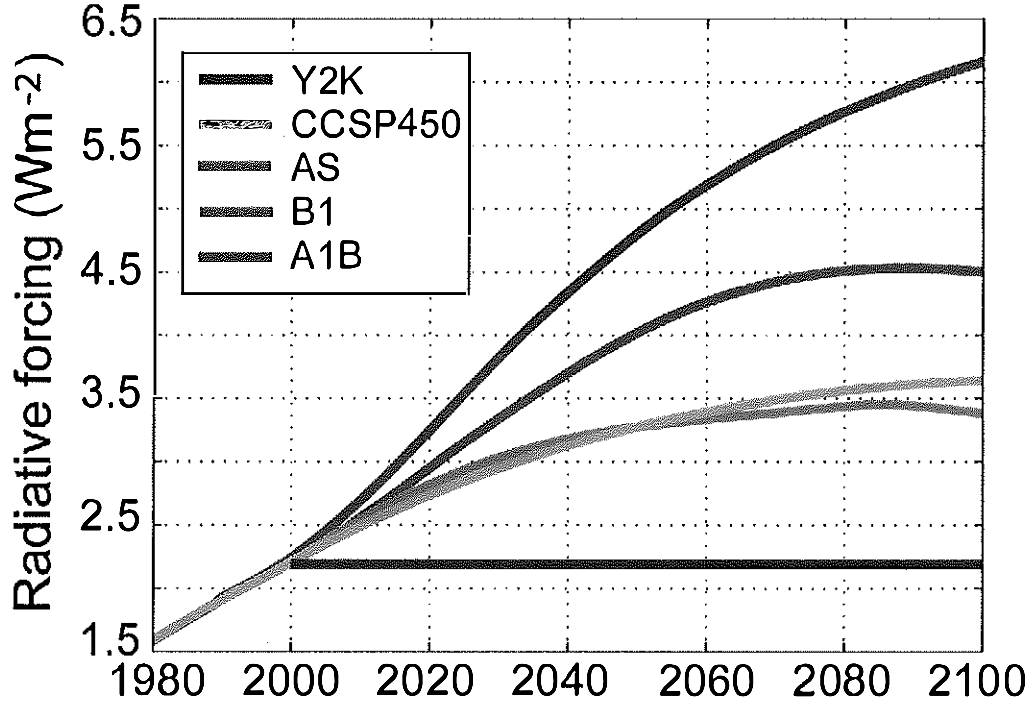

Supplementary Fig. 2. Net anthropogenic radiative forcing values through the 21st century for 5 greenhouse gas emissions scenarios used to reevaluate future projections of polar population status. GHG scenarios are defined in the text.

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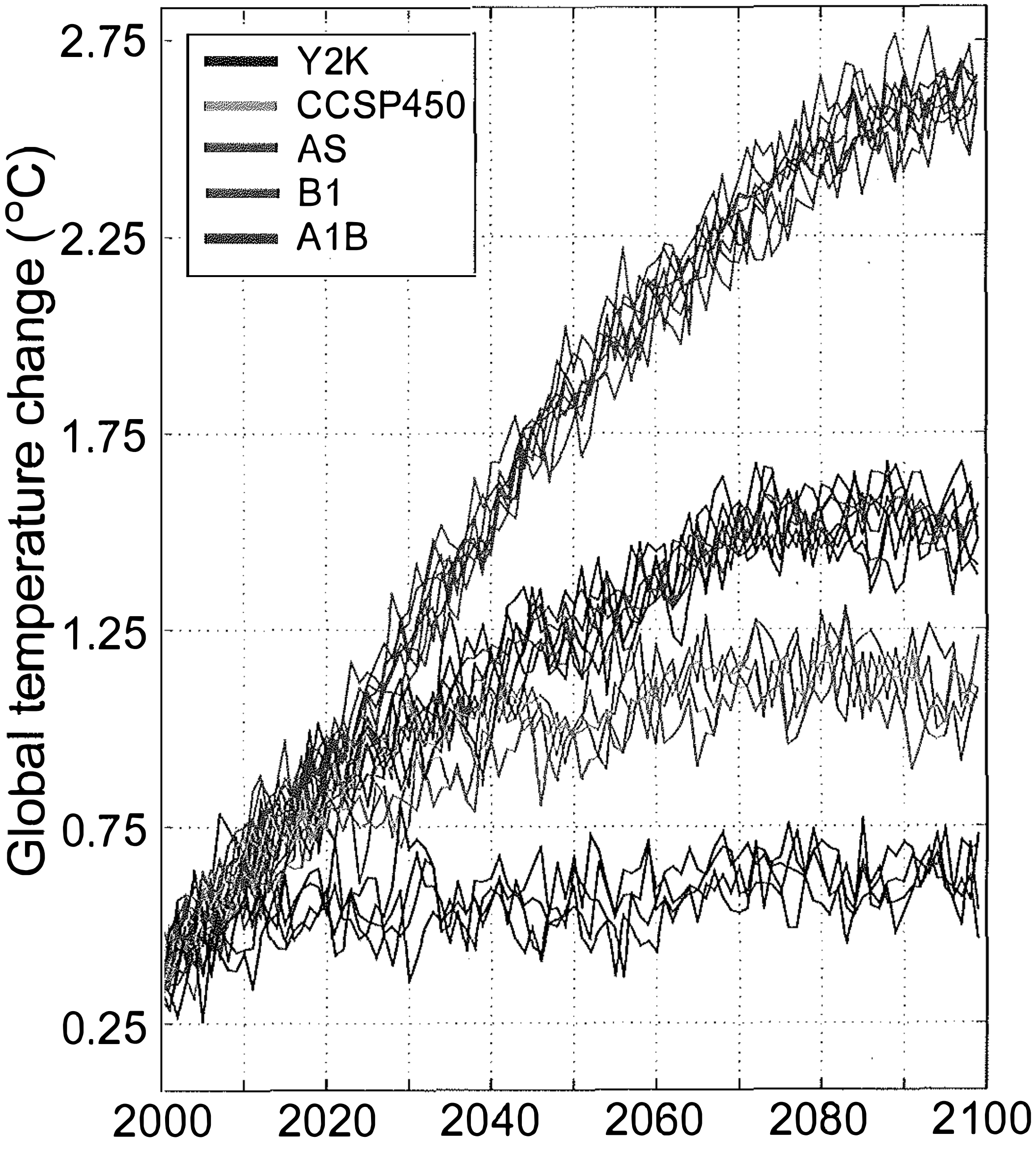
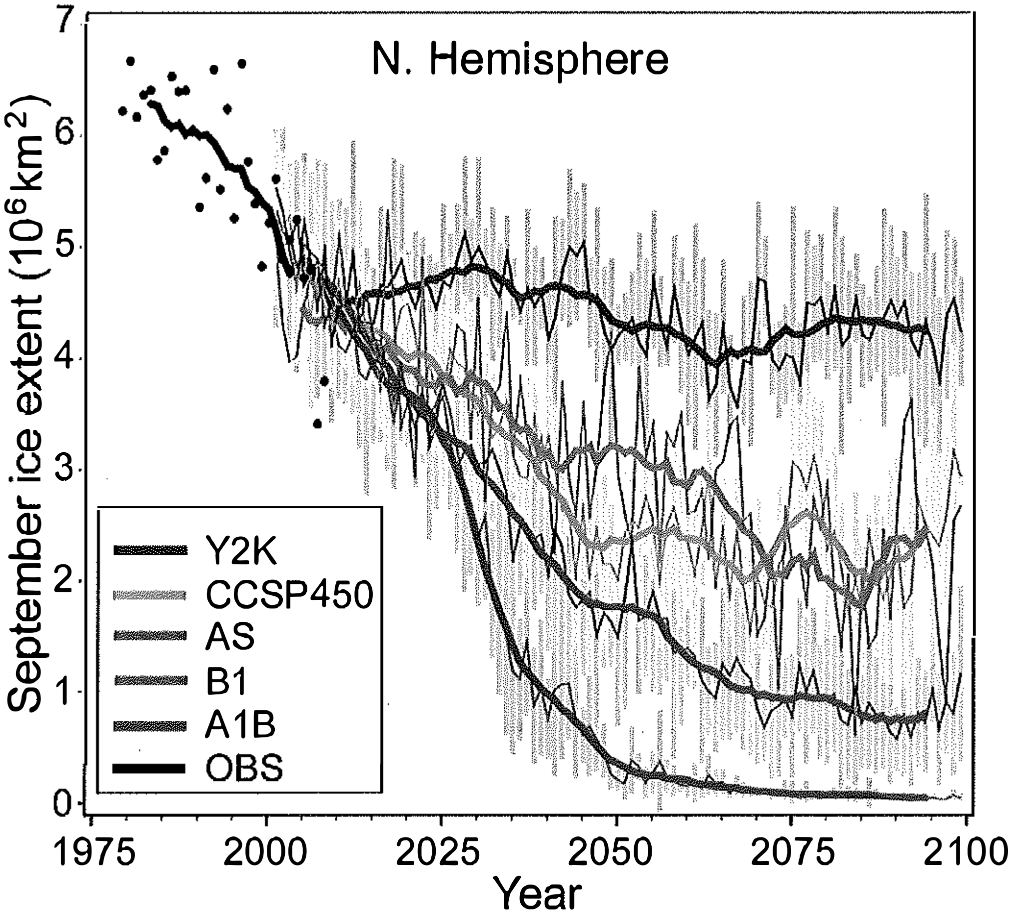


Supplementary Fig. 3. Change in global mean surface air temperature (GMAT) projected through the 21st century by forcing the CCSM3 general circulation model with 5 different GHG emissions scenarios. GHG scenarios are defined in the text.



Supplementary Fig. 4. Minimal September sea-ice extent projected through the 21st century by forcing the CCSM3 general circulation model with 5 different GHG emissions scenarios. GHG scenarios are defined in the text.

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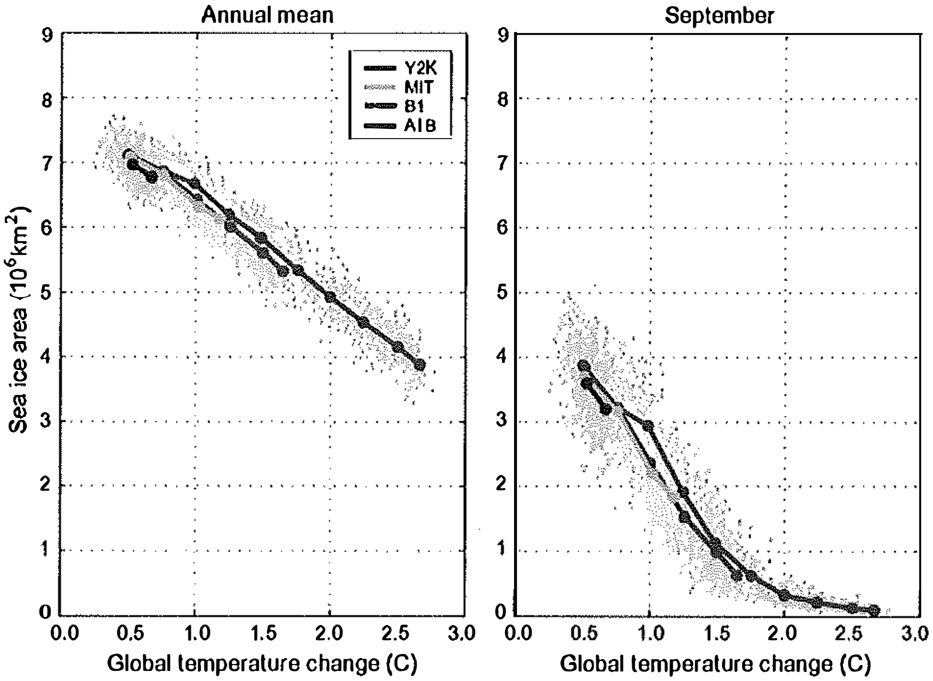
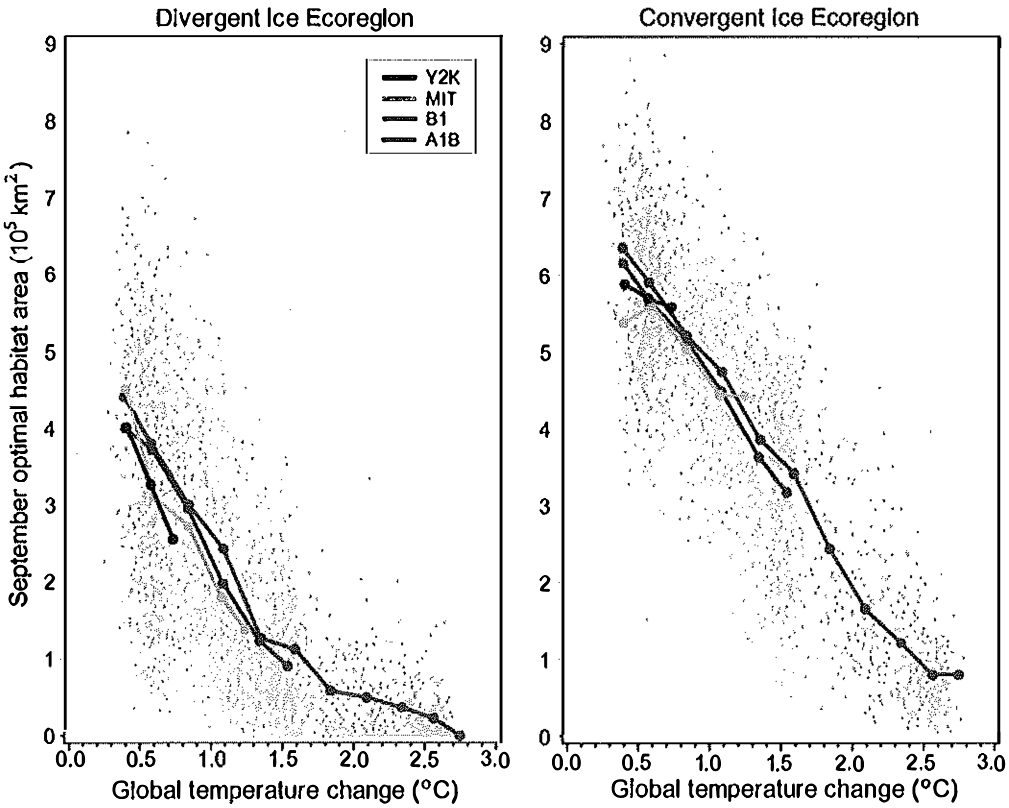
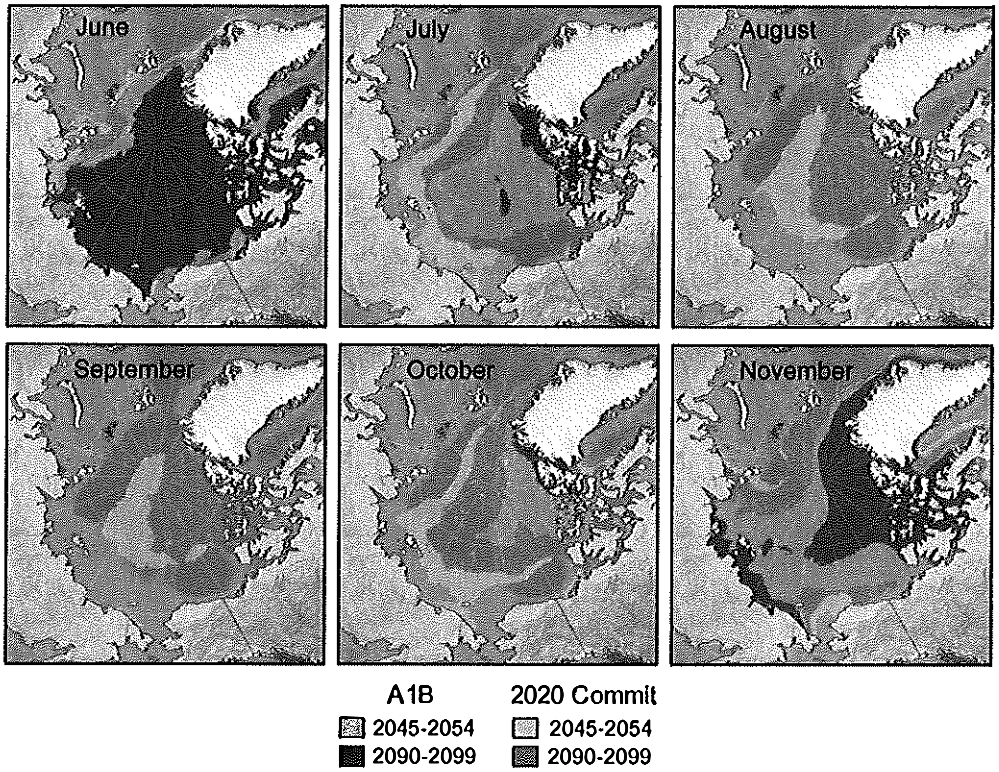


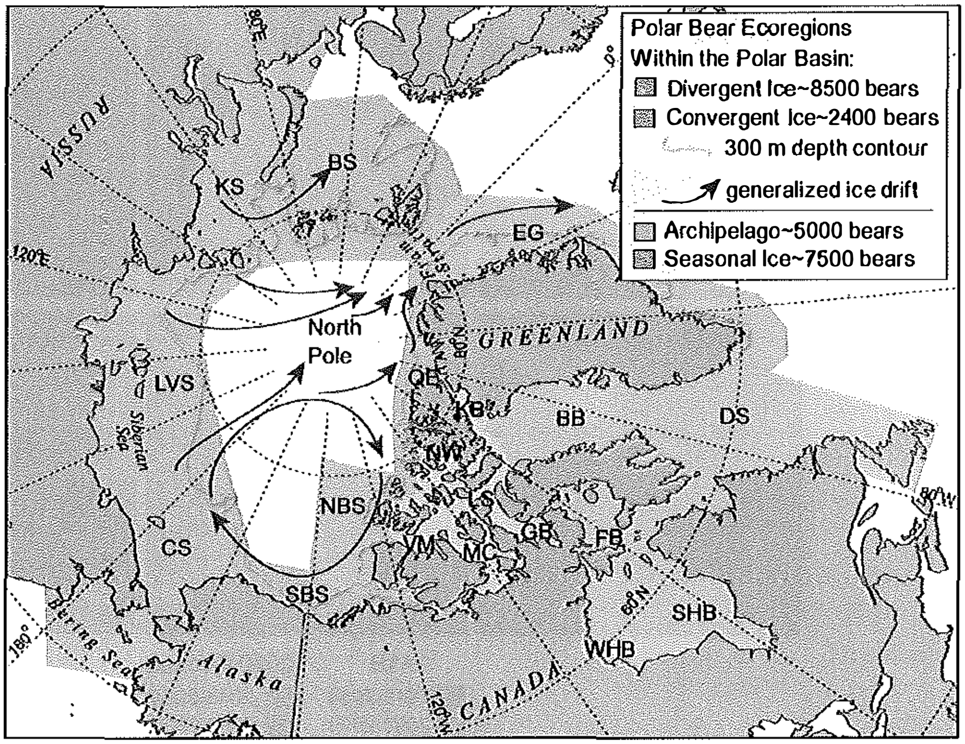
Supplementary Fig. 5. Relationship between global mean air temperature change (GMAT) and Arctic-wide sea ice area. Sea-ice area is defined as the area integral of the sea ice concentration over the Northern Hemisphere. GHG scenarios and plotting methods are defined in the text.



Supplementary Fig. 6. Relationship between optimal polar bear habitat, during the minimal ice period of September, in two polar basin ecoregions and change in global mean air temperature (GMAT). Note the absence of major thresholds in the pattern of change. GHG scenarios and plotting methods are defined in the text.



Supplementary Fig. 7. Contrasting median sea ice extents projected in CCSM3 with the A1B and the 2020 Commitment scenarios. Median sea-ice extent depicts areas where more than half of the years within each respective decade were projected to have >50% ice concentration. Projections are for the mid-21st century (2045-2054) and the late-21st century (2090-2099). In the 2020 Commitment scenario, where GHG forcings followed A1B trajectories until 2020 and were fixed thereafter, sea ice persistence far exceeded A1B in both duration and aerial extent.



Supplementary Fig. 8. Ecoregions used in analysis of the future global status of polar bears. Amstrup et al. (S6) projected that polar bears could be absent from the Divergent Ice and Seasonal Ice ecoregions by mid-century if GHG emissions continue as projected under the A1B scenario. Ecoregions include the following polar bear management units as defined by the IUCN Polar Bear Specialists' Group: The Polar Basin Divergent Ecoregion includes: Southern Beaufort Sea (SBS), Chukchi Sea (CS), Laptev Sea (LVS), Kara Sea (KS), and the Barents Sea (BS). The Polar Basin Convergent Ecoregion includes: East Greenland (EG), Queen Elizabeth (QE), Northern Beaufort Sea (NBS). The Seasonal Ice Ecoregion includes: Southern Hudson Bay (SHB), Western Hudson Bay (WHB), Foxe Basin (FB), Davis Strait (DS), and Baffin Bay (BB). The Archipelago Ecoregion includes: Gulf of Boothia (GB), M'Clintock Channel (MC), Lancaster Sound (LS), Viscount-Melville Sound (VM), Norwegian Bay (NW), and Kane Basin (KB).

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Table S1. The five greenhouse gas emissions scenarios and number of realizations used in this study. End of century GHG targets, and acronyms used in the text for each scenario also are shown.

Acronym	Scenario (# realizations)	End of Century Target
AIB	SRES A1B (8)	689ppm CO_2
B1	SRES B1 (8)	537ppm CO_2
Y2K	2000 Climate Change Commitment (4)	GHG emissions fixed at year 2000 levels (368ppm CO_2)
CCSP450	Level 1 Stabilization (4)	End of Century Radiative Forcing $<3.4W/m^2$
AS	Alternative Scenario (1)	Anthropogenic Radiative Forcing $1.5W/m^2$ above 2000 levels
MIT	Mitigation Ensemble (5), includes AS and CCSP450	

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