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

doi:10.1038/nature09653

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.

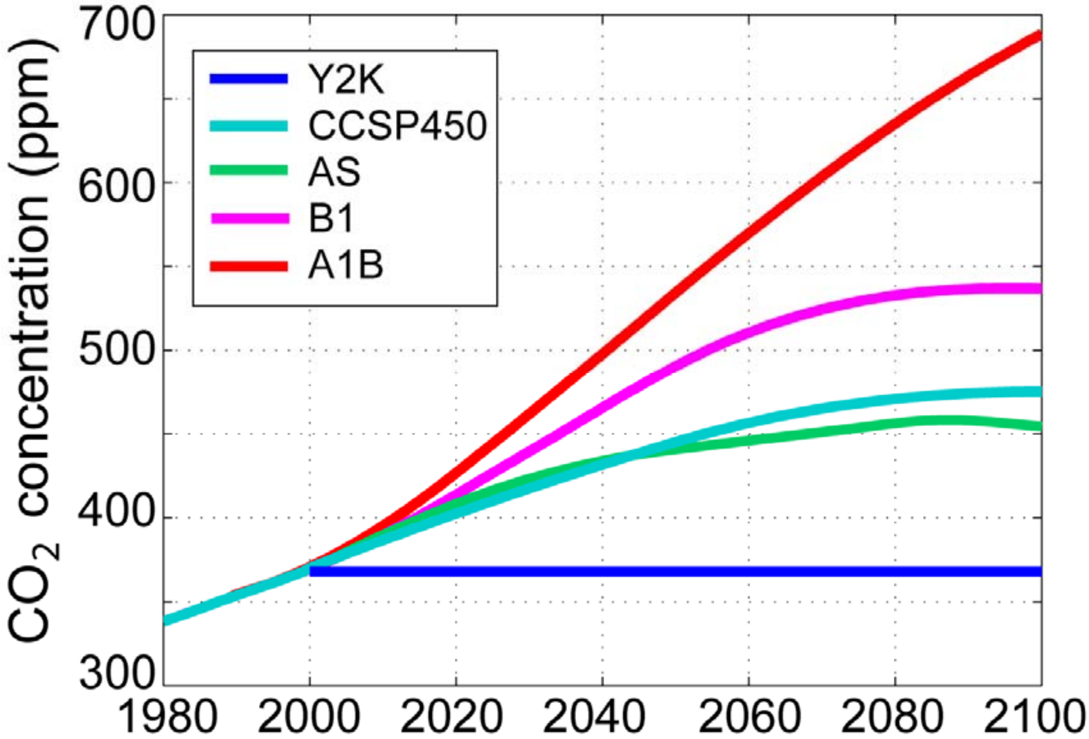
Our polar bear BN model is informed by the linear relationships we observed between GMAT and sea-ice and numerous other factors hypothesized to affect polar bear populations. The influences from sea ice, other environmental conditions, and anthropogenic stressors, collectively result in the polar bear 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.

doi:10.1038/nature09653

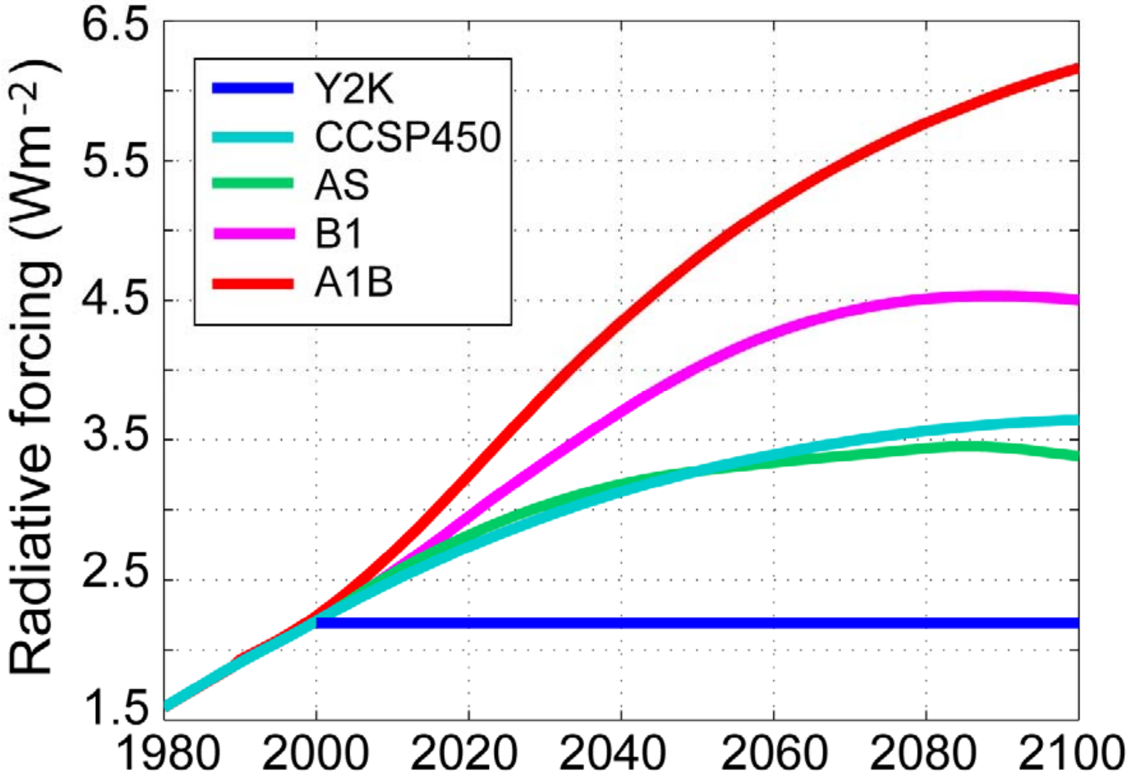
Despite quantitative shortcomings in polar bear data, which may not be filled for some time, policy-makers need information from which decisions can be made now. The BN model framework incorporates the state of current knowledge in a straightforward and transparent way and provides probabilistic predictions 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.

doi:10.1038/nature09653



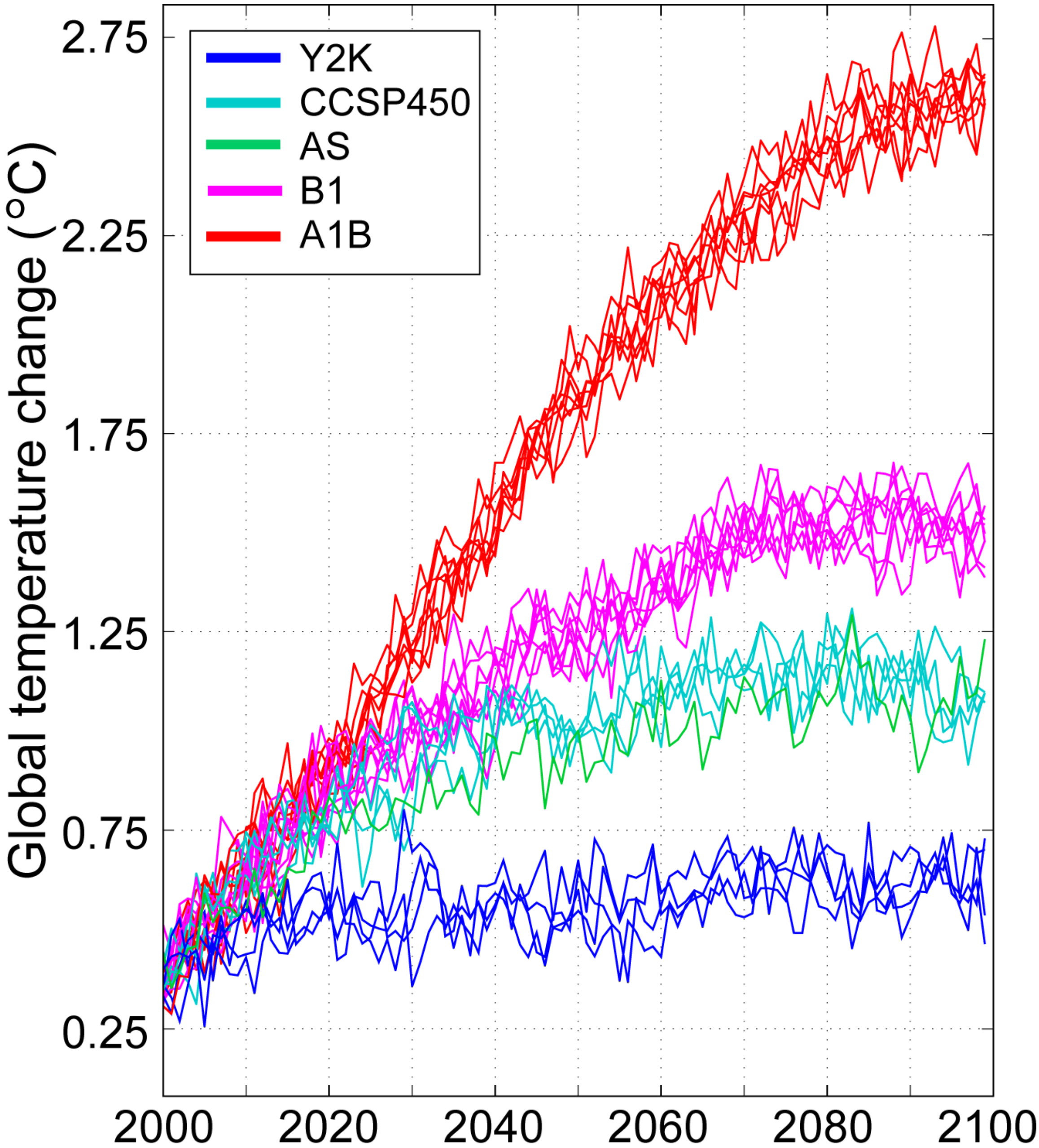
Supplementary Fig. 1. CO_2 concentration values through the 21st century for 5 greenhouse gas emissions scenarios used to reevaluate future projections of polar population status. GHG scenarios are defined in the text.

doi:10.1038/nature09653



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.

doi:10.1038/nature09653



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.

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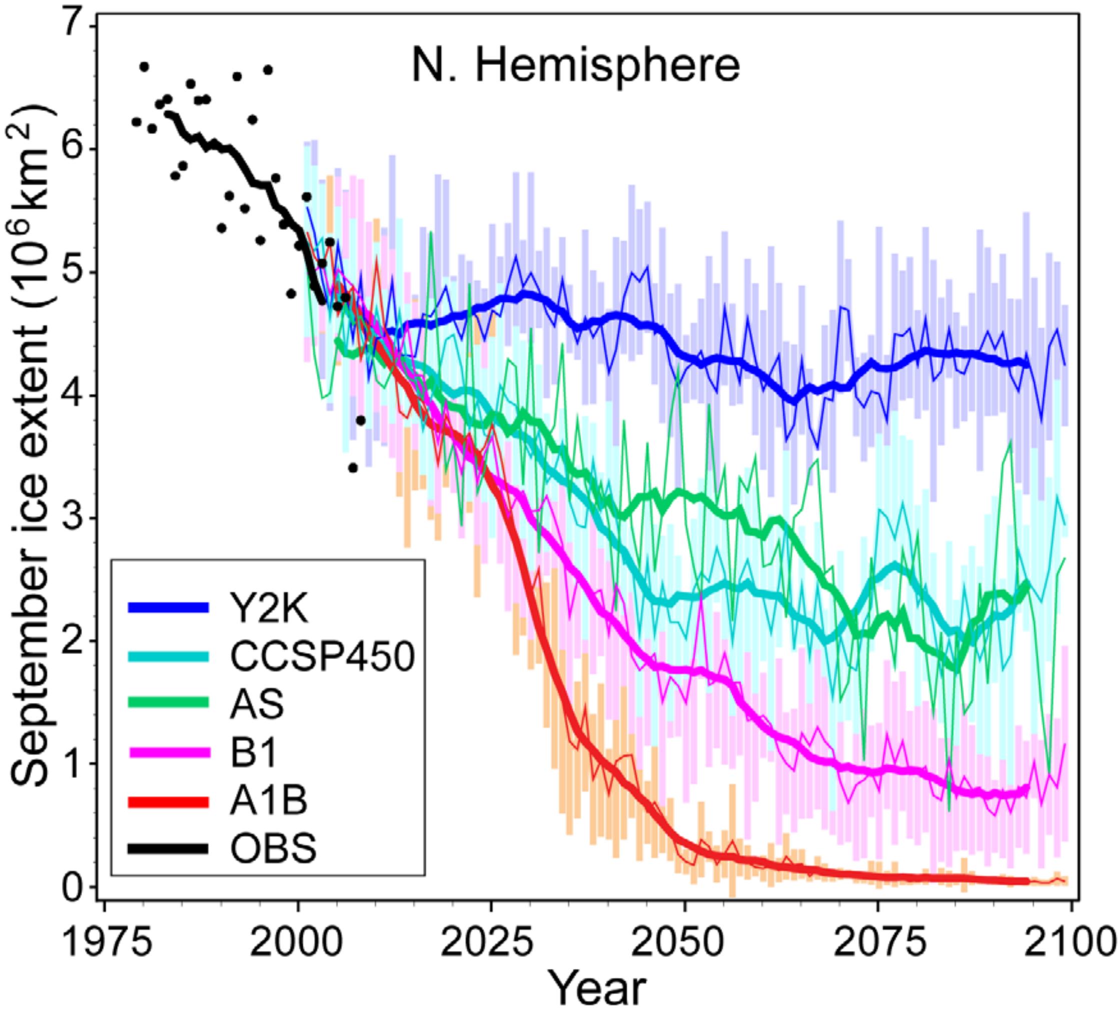
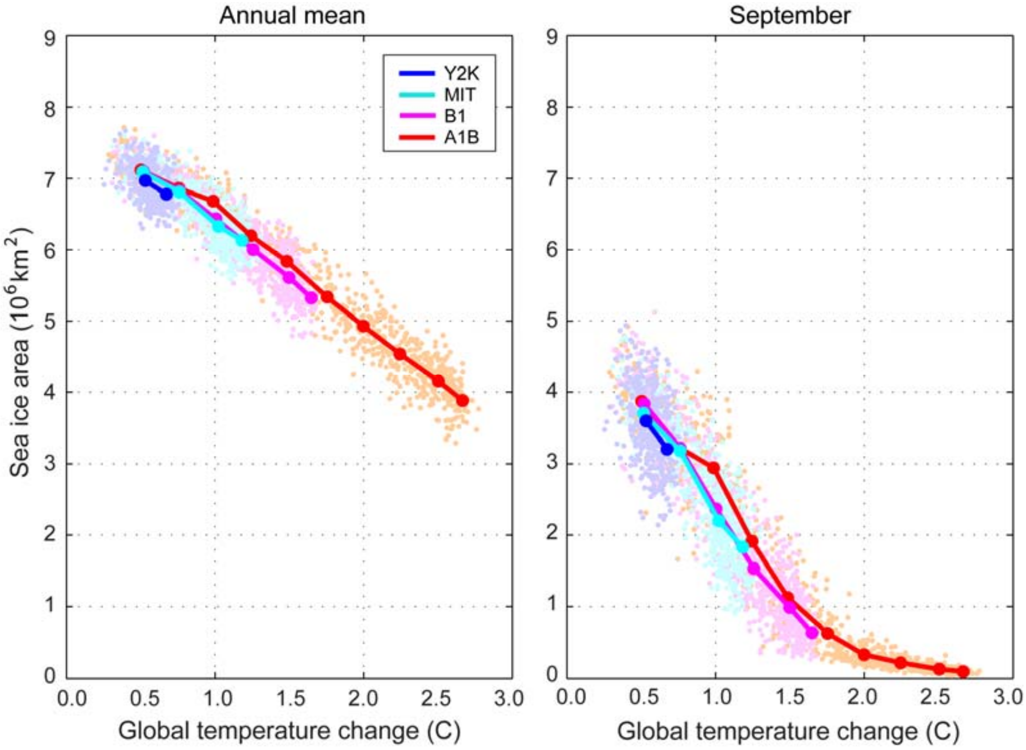


Supplementary Fig. 4. Minimal September sea-ice extent projected through the 21st century by forcing the CCSM3 general circulation model with 5 different GHG emissions scenarios. GHG scenarios are defined in the text.

doi:10.1038/nature09653



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.

doi:10.1038/nature09653

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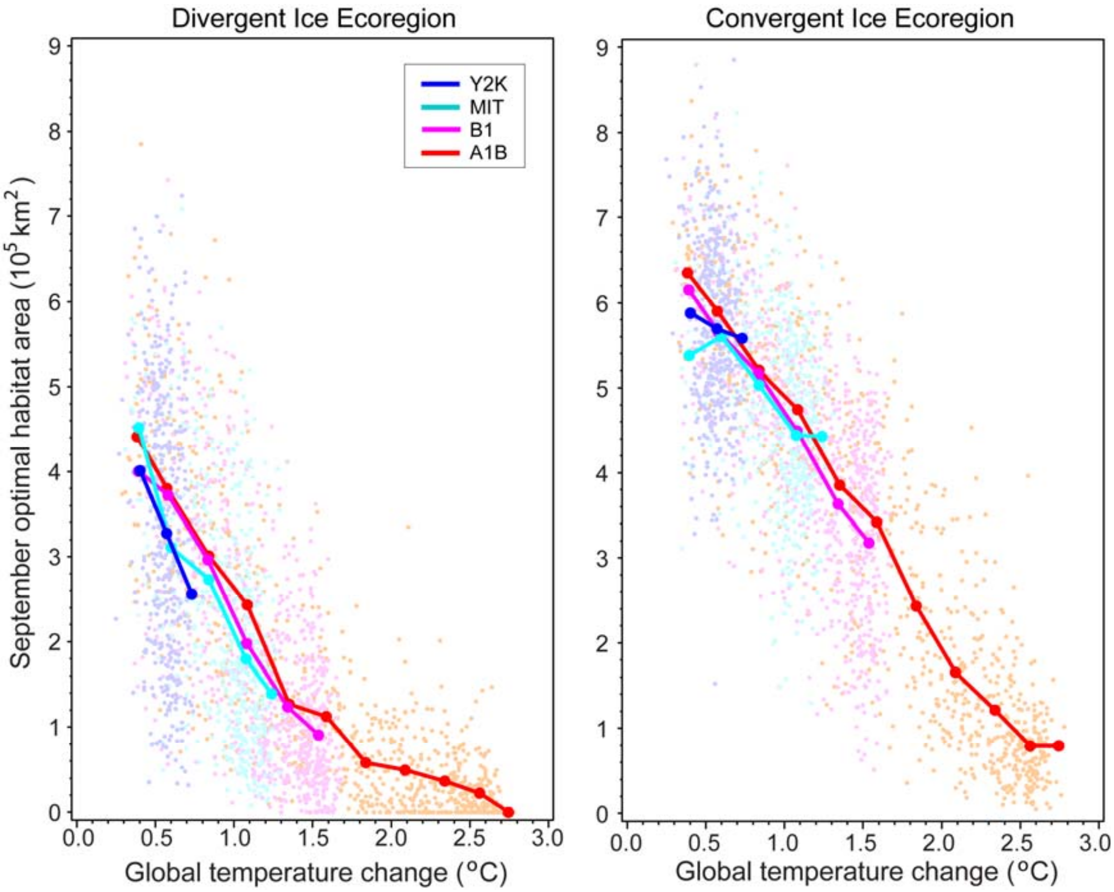

Supplementary Fig. 6. Relationship between optimal polar bear habitat, during the minimal ice period of September, in two polar basin ecoregions and change in global mean air temperature (GMAT). Note the absence of major thresholds in the pattern of change. GHG scenarios and plotting methods are defined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

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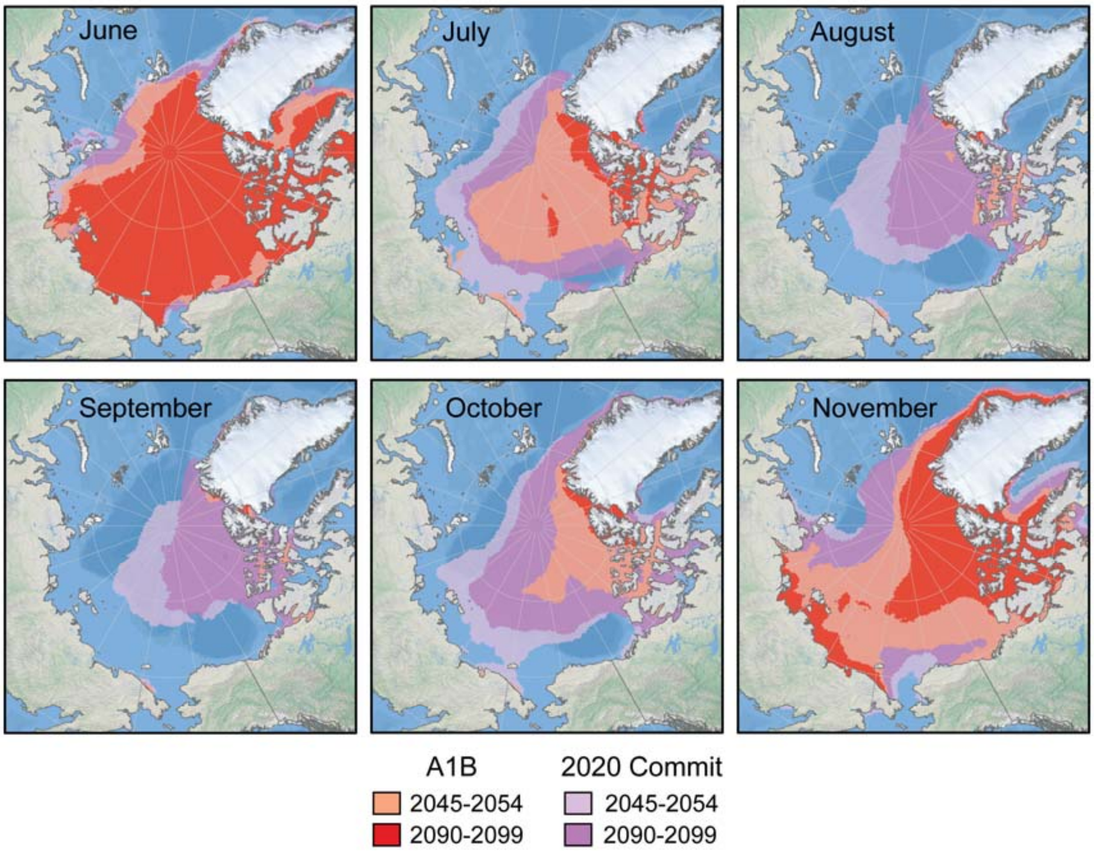
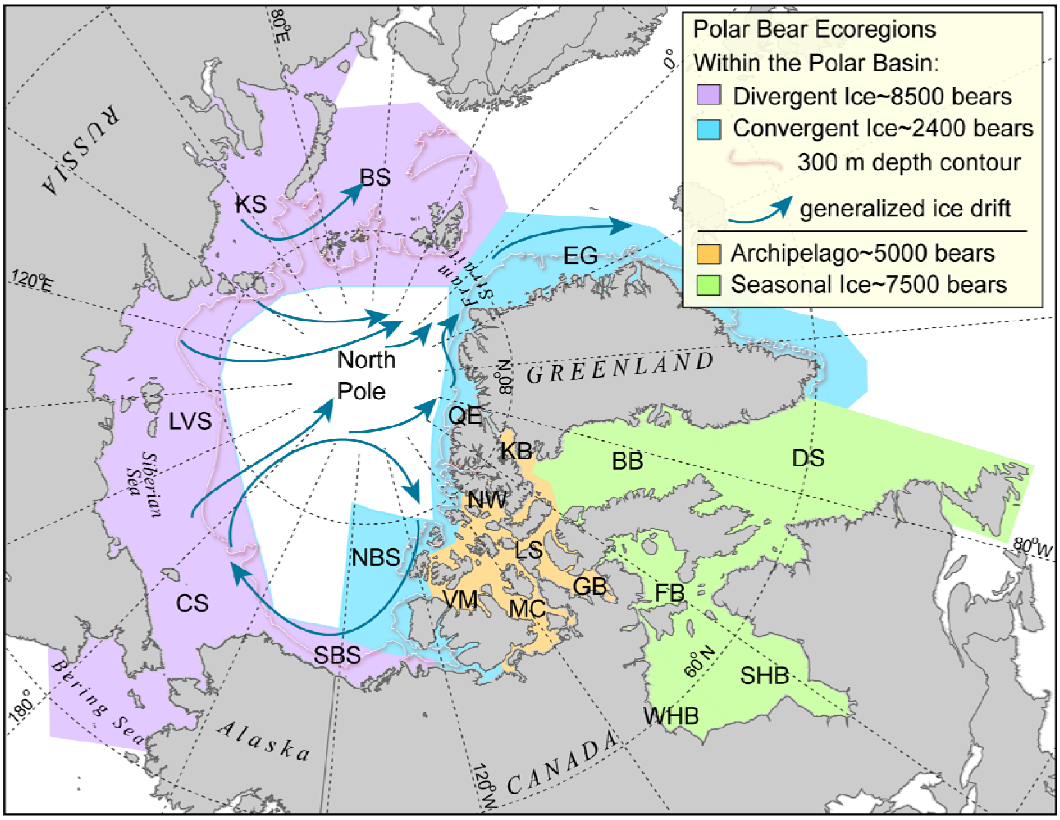


Supplementary Fig. 7. Contrasting median sea ice extents projected in CCSM3 with the A1B and the 2020 Commitment scenarios. Median sea-ice extent depicts areas where more than half of the years within each respective decade were projected to have >50% ice concentration. Projections are for the mid-21st 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.

doi:10.1038/nature09653



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).

doi:10.1038/nature09653

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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