Chapter 25
Uncertainties in Forecasting the Response of Polar Bears to Global Climate Change

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Abstract Several sources of uncertainty affect how precisely the future status of polar bears (*Ursus maritimus*) can be forecasted. Foremost are unknowns about the future levels of global greenhouse gas emissions, which could range from an unabated increase to an aggressively mitigated reduction. Uncertainties also arise because different climate models project different amounts and rates of future warming (and sea ice loss)—even for the same emission scenario. There are also uncertainties about how global warming could affect the Arctic Ocean's food web, so even if climate models project the presence of sea ice in the future, the availability of polar bear prey is not guaranteed. Under a worst-case emission scenario in which rates of greenhouse gas emissions continue to rise unabated to century's end, the uncertainties about polar bear status center on a potential for extinction. If the species were to persist, it would likely be restricted to a high-latitude refugium in northern Canada and Greenland—assuming a food web also existed with enough accessible prey to fuel weight gains for surviving onshore during the most extreme years of summer ice melt. On the other hand, if emissions were to be aggressively mitigated at the levels proposed in the Paris Climate Agreement, healthy polar bear populations would probably continue to occupy all but the most southern areas of their contemporary summer range. While polar bears have survived previous warming phases—which indicate some resiliency to the loss of sea ice habitat—what is certain is that the present pace of warming is unprecedented and will increasingly expose polar bears to historically novel stressors.

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A. Butterworth (ed.), *Marine Mammal Welfare*, Animal Welfare 17,
DOI 10.1007/978-3-319-46994-2_25

25.1 Introduction

As discussed in the preceding chapters, polar bears (*Ursus maritimus*) have evolved preferences for sea ice habitat, which they rely on to meet a number of key life-history needs. However, global climate change, primarily caused by human activities that emit greenhouse gases, has caused the Arctic to warm at twice the rate of the rest of the planet (Overland et al. 2015). In turn, this warming has driven a multi-decadal reduction in sea ice extent that has been linked to declines in polar bear fitness and abundance in some subpopulations (e.g., Regehr et al. 2007; Rode et al. 2010; Obbard et al. 2016). As a result, continued loss of sea ice due to warming in the Arctic is considered the primary long-term threat to the persistence of polar bears (Atwood et al. 2016a).

If global greenhouse gas concentrations continue to rise unabated, most climate models project (Collins et al. 2013; Barnhart et al. 2015) that by century's end global mean surface air temperature will be ~4–5 °C above preindustrial levels and the Arctic Ocean will be ice-free in summer for as many as 5 months (Fig. 25.1, note RCP is defined below). If that occurs, polar bears could be forced ashore and food deprived (Rode et al. 2015a) for unsustainable periods across much of their current distribution, leading to widespread extirpation from many parts of their range (Amstrup et al. 2008; Robbins et al. 2012; Atwood et al. 2016a). On the other hand, with prompt and very aggressive mitigation of global emissions, most climate models project that earth's average air temperature would not rise more than 2 °C above preindustrial levels, and Arctic sea ice would persist all summer although at less than contemporary levels (Fig. 25.1). Such intervention in the current global warming trajectory, in conjunction with optimal management practices, would likely assure healthy polar bear populations could continue to occupy most of their historic range (Amstrup et al. 2010). These best- and worst-case global warming scenarios lead to distinctly different Arctic environments with distinctly different, but fairly certain, outcomes for polar bears. However, for intermediate emission

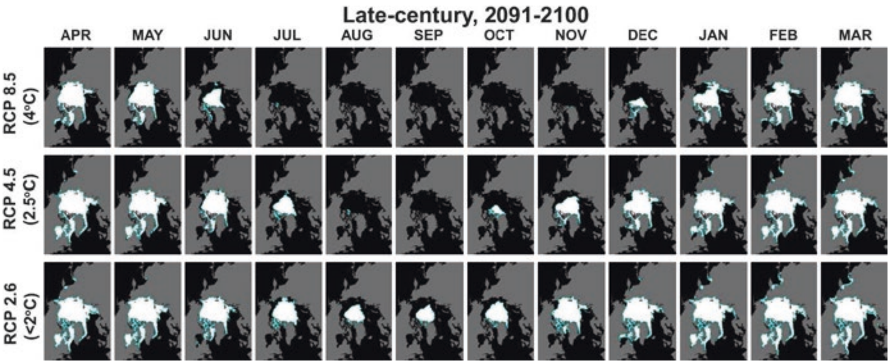

Fig. 25.1 Median monthly Arctic sea ice extent in the late twenty-first century based on projections by 13 general circulation models (GCM) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) when forced with the "worst case" RCP 8.5 greenhouse gas emission scenario (*top row*), the "best case" representative concentration pathway (RCP) 2.6 scenario (*bottom row*), and an intermediate RCP 4.5 scenario (*middle row*). Maps view the North Pole (*center*) and show sea ice (*white*), ocean (*black*), and land (*gray*). *Source:* https://alaska.usgs.gov/science/biology/habitat_dynamics/sea_ice_future.php, accessed March 2016

scenarios, while greater global warming implies greater negative impacts on polar bears, the ability to precisely forecast their status Arctic-wide becomes less certain. In the sections that follow, we describe the primary sources of uncertainty associated with forecasting future polar bear status. We also illustrate how those uncertainties manifest in an analysis that asks where polar bears will be able to spend summer onshore at the end of the twenty-first century.

25.2 Uncertain Paths to the Future: Twenty-First-Century Emission Scenarios

The biggest contributors to uncertainties about the future status of polar bears are the presently unknown choices society may make regarding GHG emission pathways. In its Fifth Assessment Report (IPCC 2013), the United Nations Intergovernmental Panel on Climate Change (IPCC) evaluated general circulation model projections of twenty-first-century climate that were based on four different emission scenarios called representative concentration pathways (RCPs) (Fig. 25.2).

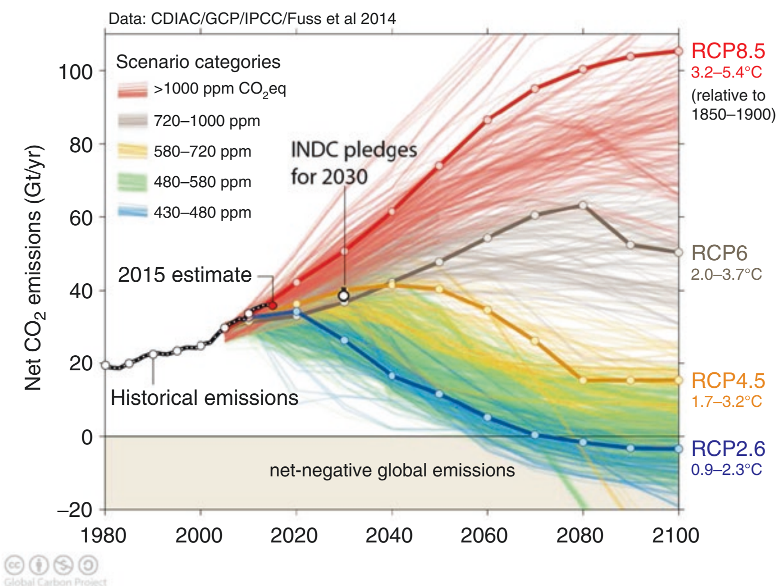

Fig. 25.2 Annual CO_2 emissions for most scenarios described by the IPCC Fifth Assessment Report Working Group 3 (*pale lines*) and four representative concentration pathways (RCPs) used for evaluating model projections of future climate changes by Working Group 1 (*bold lines*). Individual scenarios are grouped into five categories based on atmospheric concentrations of CO_2 equivalents in 2100. Historical CO_2 emissions are shown (*black*) with an estimated value for 2015 (*red dot*). Ranges of temperature increase for each RCP (*right*) refer to average warming in 2081–2100 relative to 1850–1900 (IPCC 2013). Emissions in 2030 are shown (*white dot*) assuming all countries meet their pledged (*nonbinding*) intended nationally determined contributions (INDCs) that were submitted under the Paris Climate Agreement in 2015. *Source: Global Carbon Project (http://www.globalcarbonproject.org), accessed March 2016*

RCPs are named by the approximate level of radiative forcing (above preindustrial levels) attained near the end of the century, expressed in units of watts per meter squared (W/m^2). The "warmest" scenario, RCP 8.5, represents a worst-case outcome of abandoning attempts to curtail global warming. It portrays a world with fast population growth (12 billion by 2100), little technological advancement, widespread poverty and slow economic growth, and high energy use (mostly from coal) and high emissions (van Vuuren et al. 2011). Models from this scenario project that by century's end average global temperature rise will climb upward of 4–5 °C (above preindustrial levels) and the Arctic Ocean will be ice-free for ~5 months during summer (Fig. 25.1).

The RCP 2.6 scenario represents a best-case outcome and portrays a world that keeps average global warming below 2 °C by promptly and aggressively reducing GHG emissions, even to the point of achieving negative emission rates (i.e., removing CO_2 from the atmosphere) by late-century. The aims of the Paris Climate Agreement, as adopted by 195 countries in 2015 (United Nations 2015), would be largely met if the RCP 2.6 was to be realized. At century's end under the RCP 2.6 scenario, most models project that summer sea ice will persist in the Arctic Ocean in all months (Fig. 25.1). Achieving an emission pathway like RCP 2.6 would require unprecedented global commitments and technological advances (Tollefson 2015; Smith et al. 2015).

The RCP 8.5 and RCP 2.6 scenarios reasonably establish upper and lower limits to all probable twenty-first-century emission pathways and upper and lower limits to the persistence of sea ice. Without question, the closer the future adheres to the RCP 2.6 scenario and its projection of sea ice availability in all months of the year, the better the prognosis for polar bears. With time, the real twenty-first-century emission pathway will play out, and the spread of plausible pathways for the remainder of the century will narrow. But today, the spread of possible emission scenarios remains broad and so too does the spread of possible outcomes for sea ice and polar bears.

25.3 Model Uncertainties

When forced with the same emission scenario, different models project somewhat different environmental outcomes, which in turn affect projections of polar bear status. It is unknown how much the earth's surface would warm if CO_2 concentration in the atmosphere were to double over the preindustrial era (termed the earth's climate sensitivity). Contemporary climate models differ in their estimates of the resultant warming, ranging between 2 and 4.5 °C (Knutti and Hegerl 2008). Similarly, different climate models project different estimates of when and by how much the sea ice will melt for any given level of greenhouse gas forcing. The uncertainties introduced by different model outputs are, however, expected and informative. Global climate models have been developed by various institutions worldwide where scientists have applied different strategies for approximating physical processes that occur at spatial and temporal resolutions beyond those of the model framework (Knutti 2008). For example, approximating the sub-grid-scale behaviors of clouds is among some of the most challenging and sensitive parameterizations. Since no best way exists to prescribe sub-grid-scale processes, and for other reasons, the spread of outcomes obtained from an ensemble of models reflects uncertainties attributable to the state of the art in global climate modeling.

25.4 Natural Climate Variability

The total amount of uncertainty in climate projections stems from three primary sources (Fig. 25.3): (1) differences between emission scenarios (i.e., RCP scenario spread), (2) differences between models (i.e., model spread), and (3) natural climate variability (i.e., internal variability). The relative contributions of these three sources change as a function of lead time (i.e., the length of time the forecast spans). Natural climate variability contributes a fairly constant level of uncertainty over all lead times, so it dominates uncertainty in short-term projections. Uncertainties associated with emissions and models increase with longer lead times. When projecting to mid-century, uncertainties owing to the spread among the RCP emission scenarios and the spread among contemporary models increase, and the amount of uncertainty

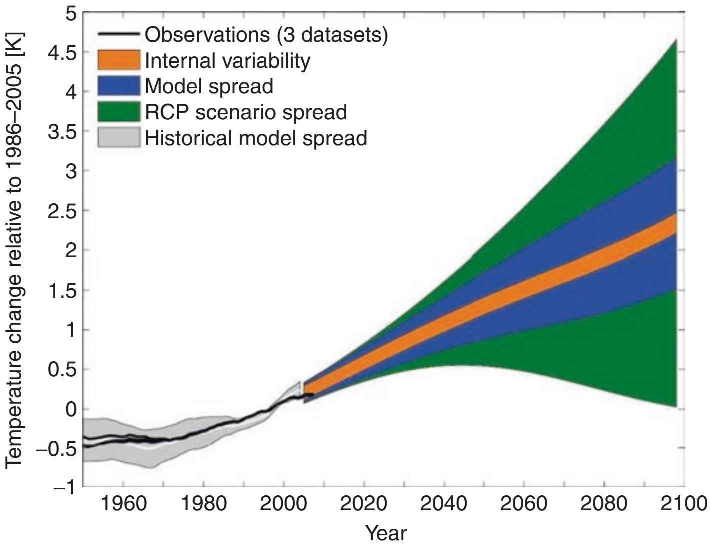

Fig. 25.3 Sources of uncertainty in climate projections as a function of lead time based on an analysis of CMIP5 results. Projections of global mean decadal mean surface air temperature to 2100 together with a quantification of the uncertainty arising from internal variability (*orange*), model spread (*blue*), and RCP scenario spread (*green*). *Reproduced from* Fig. 11.8 *in* Kirtman et al. (2013)

due to natural climate variability becomes proportionally less. During the second half of the century, the amount of uncertainty from today's broad spread of possible emission scenarios increasingly dominates over the uncertainties due to models. By the end of the century, the amount of uncertainty owing to the different emission scenarios is several times greater than that due to model spread, and uncertainty due to natural climate variability is inconsequential by comparison.

25.5 Forecasting Future Summer Habitat

How emissions and model uncertainties influence forecasts of polar bear status can be evaluated by asking: at the end of the twenty-first century, where can polar bears come ashore during summer without risk of undue stress from prolonged food deprivation? In some polar bear subpopulations, the longer open-water season (and thus the period of food deprivation) already has been linked to declines in fitness (Stirling et al. 1999; Obbard et al. 2016; Rode et al. 2010) and survival (Regehr et al. 2007, 2010). Moreover, energy budget models suggest that an open-water period lasting >150 days could result in a significant risk of reproductive failure and starvation (Molnár et al. 2010, 2014; Robbins et al. 2012), although that threshold likely has geographic dependencies due to variations in ocean productivity and prey accessibility that locally influence the nutritional condition of bears prior to their arrival on shore. Additionally, polar bears may develop a broader capacity to exploit alternative foods while on land, which could buffer the effects of food deprivation associated with an extended stay on land (Gormezano and Rockwell 2015).

To answer the question posed above, global climate model projections of future monthly sea ice extent from six climate models, each forced with three emission scenarios (RCP 2.6, RCP 4.5, and RCP 8.5), were analyzed to locate land where the minimum distance to sea ice did not exceed 200 km for ≥5 months during summer in every year, 2091–2100. The 200 km threshold was applied because adult polar bears are capable of swimming long distances (Pagano et al. 2012). Results of the analysis (Fig. 25.4) showed that with increasing levels of CO_2 emissions (i.e., increasing RCP), coastal areas where the summer ice-free period was projected to be no more than 4 months in duration occurred in fewer areas and were corroborated by fewer models. At the century's end under the RCP 8.5 emission pathway, only half of the models indicated that coastal areas in northern Canada and Greenland will have an ice-free period ≤4 months, while the other half indicated that all coasts will be unsuitable for sustaining polar bear populations because the entire Arctic Ocean will be ice-free for 5 months or more, at least in some years.

The three RCP scenarios lead to very different outcomes for polar bears. Under the RCP 8.5 scenario, the model spread raised uncertainty about whether polar bears will face extinction by the century's end or if they might persist in a refugium in northern Canada and Greenland. The RCP 2.6 and RCP 4.5 scenarios projected

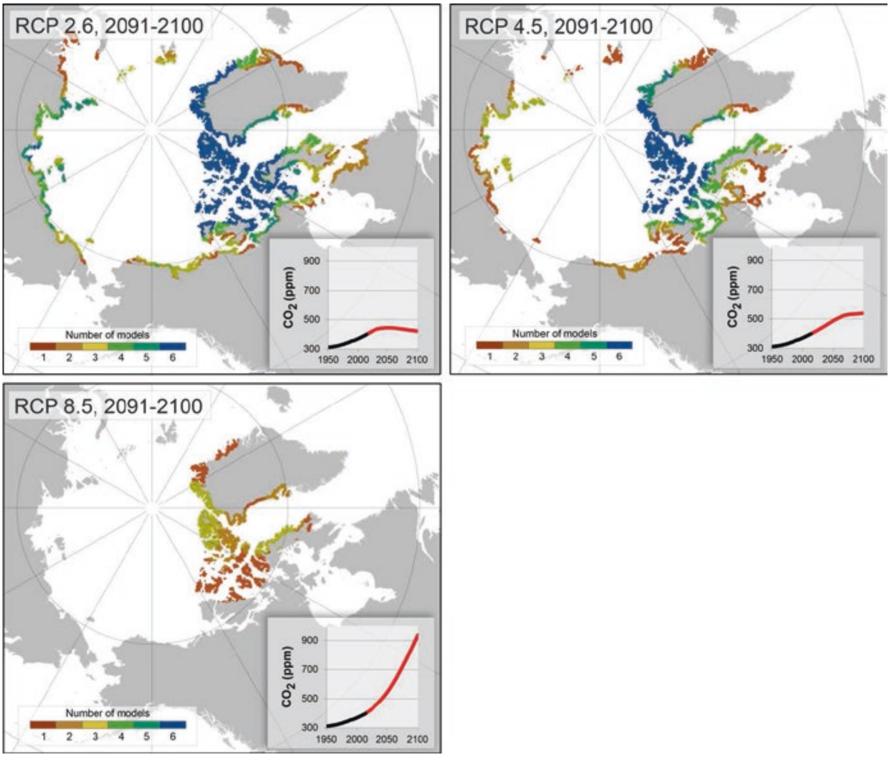

Fig. 25.4 Coastal areas where the summer ice-free period within 200 km of shore is projected to be 4 months or less in duration in each year, 2091–2100, as projected by six global climate models forced with three greenhouse gas emission scenarios (RCP 2.6, 4.5, and 8.5). Color shading along the coastline denotes the number of models in agreement. Inset shows the historic rise in atmospheric CO_2 concentration from 1950–2014 (*black line*) and the scenario-specific change from 2015–2100 (*red line*). (Six CMIP5 models included: CCSM4, CESM-CAM5, GFDL-CM3, HadGEM2-AO, HadGEM2-ES, and MPI-ESM-MR.)

very different outcomes compared to RCP 8.5, illustrating how the differences between emission scenarios inflate uncertainties in projections with long lead times (i.e., late-century). Under both the RCP 2.6 and RCP 4.5 scenarios, complete agreement among model projections in northern Canada and Greenland provided higher confidence that polar bears will be able to use those areas during summer at the century's end without being stranded onshore for ≥5 months (Fig. 25.4). Furthermore, under the RCP 2.6 scenario, a majority of models identified potential summer areas along the northern coast of Eurasia—but only half the models did so under the RCP 4.5 scenario. Hence, model uncertainties under RCP 4.5 introduced greater doubt about whether the Eurasian coast could support polar bears during summer by late-century, compared to the RCP 2.6 scenario.

25.6 Ecological and Behavioral Uncertainties

Future sea ice will only have value to polar bears before they come ashore if prey are sufficiently available to allow the bears to accumulate fat at levels comparable to present-day bears that routinely summer onshore (e.g., Hudson Bay, Canada). Can we assume that prey availability will accompany climate model projections of sea ice availability? Large uncertainties accompany that assumption, including the extent to which changes in primary production and nutrient cycling may influence food webs (Arrigo et al. 2008; Tremblay et al. 2015); however, we feel it reasonable to expect that greater changes to the food web are more likely for scenarios with greater warming. So while global climate models provide insights into how the earth's physical environment may change, how those changes could affect complex biological systems such as marine food webs is presently unclear (Hoegh-Guldberg and Bruno 2010; Schofield et al. 2010). Assuming changes are not severe, we can speculate how seals might redistribute as the Arctic sea ice ecosystem shrinks northward (Moore and Huntington 2008). For example, ringed (*Pusa hispida*) and bearded (*Erignathus barbatus*) seals, the primary prey of contemporary polar bears and the most ice-dependent seals in the Arctic, could be expected to shift northward with warming to occupy ice over continental shelf waters (Harwood et al. 2015) that has adequate stability and snow cover for birthing, weaning, and molting. Such a northward shift would likely be restricted to North America and Greenland because the deep basin of the Arctic Ocean would restrict a northward expansion in the Eurasian Arctic. Subarctic seals, such as spotted (*Phoca largha*), ribbon (*Histriophoca fasciata*), harp (*Pagophilus groenlandicus*), and hooded seals (*Cystophora cristata*), could expand their ranges northward into areas vacated by ringed and bearded seals. The net effects of these changes are unknown: many subarctic seals are adapted to extended bouts of pelagic behavior which may make them less available to polar bears, while some range shifts could introduce new prey that, if also available for capture, could improve conditions for polar bears (Peacock et al. 2013).

The faster the rate of ice loss, the more polar bears will be challenged by their low reproductive rate and long generation time and the likelihood that individual behaviors (such as where to spend the summer) are learned and possibly deep-rooted. As more summer ice melts in the future, more polar bears will likely come ashore (Rode et al. 2015b; Atwood et al. 2016b). If the future Arctic Ocean melts entirely in summer, then all polar bears will come ashore somewhere. Polar bears already possess a feast-and-famine lifestyle, in that they rely on fat reserves accumulated in spring to subsidize their energy requirements during the rest of the year when seals are less available for capture. The interplay between the amount of time spent onshore, the amount of fat reserves accumulated upon arrival, and the amount of available terrestrial food subsidies (Gormezano and Rockwell 2015; Rode et al. 2015a) will determine where oversummering is—and is not—possible. Some polar bears will perish when attempting to summer in marginal areas during years with extremely poor conditions, resulting in population-level selection pressure against the use of those areas in future summers. Under scenarios with greater warming and longer ice-free periods (e.g., Fig. 25.4), polar bear extirpation events will likely be more common and widespread because the overall rate of change will be faster, marginal areas will be more extensive, and extreme years will be more frequent.

25.7 Conclusions

We have described several sources of uncertainty that affect how precisely we can forecast the impacts of global warming on polar bear welfare. Under a worst-case emission scenario like RCP 8.5, it is uncertain if polar bears could survive as a species, and if they were able to persist, it would likely be in a high-latitude refugium in northern Canada and Greenland—assuming a food web also existed with enough accessible seals to fuel weight gains for surviving onshore during the most extreme years of summer ice melt. In all likelihood, such a refugium would be fragile and vulnerable, and ensuring its viability might be of little concern to a world grappling with more urgent ecological and humanitarian problems (Schneider 2009). On the other hand, if emissions could be aggressively mitigated like the RCP 2.6 scenario, healthy polar bear populations might continue to occupy all but the most southern areas of their contemporary summer range, while habitats in northern Canada and Greenland might even improve (Durner et al. 2009). The future for polar bears is yet to be determined, and many sources of uncertainty preclude our ability to precisely forecast their future status. The response of individual polar bear populations to a changing Arctic will likely vary based on the severity of future warming and the regional processes that regulate sea ice dynamics and biological productivity (Amstrup et al. 2008; Rode et al. 2014). Additionally, the extent of behavioral plasticity that polar bears possess may determine how well they respond to alterations in ecosystem structuring and to increasing human presence as the Arctic becomes more attractive to economic interests. However, time for ensuring the future of polar bears is running out. While polar bears have survived previous warming phases—which indicate some resiliency to the loss of sea ice habitat—what is certain is that the present pace of warming is unprecedented and will increasingly expose polar bears to historically novel stressors. The sooner global warming and sea ice loss are stopped, the better the long-term prognosis for the species.

References

Amstrup SC, Marcot BG, Douglas DC (2008) A Bayesian network modeling approach to forecasting the 21st century worldwide status of polar bears. In: DeWeaver ET, Bitz CM, Tremblay LB (eds) Arctic Sea ice decline: observations, projections, mechanisms, and implications, American Geophysical Union Geophysical Monograph No. 180, Washington, pp 213–268

Amstrup SC, DeWeaver ET, Douglas DC et al (2010) Greenhouse gas mitigation can reduce sea ice loss and increase polar bear persistence. Nature 468:955–960

Arrigo KR, van Dijken G, Pabi S (2008) Impact of a shrinking Arctic ice cover on marine primary production. Geophys Res Lett 35:L19603. doi:10.1029/2008GL035028

Atwood TC, Marcot BG, Douglas DC et al (2016a) Forecasting the relative influence of environmental and anthropogenic stressors on polar bears. Ecosphere 7(6):e01370. doi:10.1002/ecs2.1370

Atwood TC, Peacock E, McKinney M et al (2016b) Rapid environmental change drives increased land use by an Arctic marine predator. PLoS ONE 11(6):e0155932. doi: 10.1371/journal.pone.0155932

Barnhart KR, Miller CR, Overeem I et al (2015) Mapping the future expansion of Arctic open water. Nat Clim Chang 6:280–285

Collins M, Knutti R, Arblaster J et al (2013) Long-term climate change: projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Doschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, pp 1029–1136

Durner GM, Douglas DC, Nielson RM et al (2009) Predicting 21st-century polar bear habitat distribution from global climate models. Ecol Monogr 79:25–58

Gormezano LJ, Rockwell RF (2015) The energetic value of land-based foods in Western Hudson Bay and their potential to alleviate energy deficits of starving adult male polar pears. PLoS One 10:e0128520. doi:10.1371/journal.pone.0128520

Harwood LA, Smith TG, George JC et al (2015) Change in the Beaufort Sea ecosystem: diverging trends in body condition and/or production in five marine vertebrate species. Prog Oceanogr 136:263–273

Hoegh-Guldberg O, Bruno JF (2010) The impact of climate change on the world's marine ecosystems. Science 328:1523–1528

Intergovernmental Panel on Climate Change (IPCC) (2013) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK

Kirtman B, Power SB, Adedoyin JA et al (2013) Near-term climate change: projections and predictability. In: Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, pp 953–1028

Knutti R (2008) Should we believe model predictions of future climate change? Philos Trans R Soc A 366:4647–4664

Knutti R, Hegerl GC (2008) The equilibrium sensitivity of the Earth's temperature to radiation changes. Nat Geosci 1:735–743

Molnár PK, Derocher AE, Thiemann GW et al (2010) Predicting survival, reproduction and abundance of polar bears under climate change. Biol Conserv 143:1612–1622

Molnár PK, Derocher AE, Thiemann GW (2014) Corrigendum to "predicting survival, reproduction and abundance of polar bears under climate change" [Biol Conserv 143 (2010) 1612−1622]. Biol Conserv 177:230–231. doi:10.1016/j.biocon.2014.07.001

Moore SE, Huntington HP (2008) Arctic marine mammals and climate change: impacts and resilience. Ecol Appl 18(sp2):S157–S165. doi:10.1890/06-0571.1

Obbard ME, Cattet MRL, Howe EJ et al (2016) Trends in body condition in polar bears (*Ursus maritimus*) from the Southern Hudson Bay subpopulation in relation to changes in sea ice. Arct Sci 2:15–32

Overland J, Hanna E, Hanssen-Bauer I et al (2015) Surface air temperature. In: Jeffries MO, Richter-Menge J, Overland JE (eds) Arctic Report Card 2015, pp 10–16. http://www.arctic.noaa.gov/reportcard. Accessed 23 Nov 2016

Pagano AM, Durner GM, Amstrup SC et al (2012) Long-distance swimming by polar bears (Ursus maritimus) of the southern Beaufort Sea during years of extensive open water. Can J Zool 90:663–676

Peacock E, Taylor MK, Laake J et al (2013) Population ecology of polar bears in Davis Strait, Canada and Greenland. J Wildl Manag 77:463–476

Regehr EV, Lunn NJ, Amstrup SC et al (2007) Effects of earlier sea ice breakup on survival and population size of polar bears in western Hudson Bay. J Wildl Manag 71:2673–2683

Regehr EV, Hunter CM, Caswell H et al (2010) Survival and breeding of polar bears in the southern Beaufort Sea in relation to sea ice. J Anim Ecol 79:117–127

Robbins CT, Lopez-Alfaro C, Rode KD et al (2012) Hibernation and seasonal fasting in bears: the energetic costs and consequences for polar bears. J Mammal 93:1493–1503

Rode KD, Amstrup SC, Regehr EV (2010) Reduced body size and cub recruitment in polar bears associated with sea ice decline. Ecol Appl 20:768–782

Rode KD, Regehr EV, Douglas DC et al (2014) Variation in the response of an Arctic top predator experiencing habitat loss: feeding and reproductive ecology of two polar bear populations. Glob Chang Biol 20:76–88

Rode KD, Robbins CT, Nelson L et al (2015a) Can polar bears use terrestrial foods to offset lost ice-based hunting opportunities? Front Ecol Environ 13:138–145

Rode KD, Wilson RR, Regehr EV et al (2015b) Increased land use by Chukchi Sea polar bears in relation to changing sea ice conditions. PLoS One 10:e0142213. doi:10.1371/journal.pone.0142213

Schneider S (2009) The worst-case scenario. Nature 458:1004–1005

Schofield O, Ducklow HW, Martinson DG et al (2010) How do polar marine ecosystems respond to rapid climate change? Science 328:1520–1523

Smith P, Davis SJ, Creutzig F et al (2015) Biophysical and economic limits to negative CO_2 emissions. Nat Clim Chang 6:42–50

Stirling I, Lunn NJ, Iacozza J (1999) Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. Arctic 52:294–306

Tollefson J (2015) Is the 2°C world a fantasy? Nature 527:436–438

Tremblay J-É, Anderson LG, Matrai P et al (2015) Global and regional drivers of nutrient supply, primary production and CO_2 drawdown in the changing Arctic Ocean. Prog Oceanogr 139:171–196

United Nations (2015) Adoption of the Paris Agreement, draft. Framework Convention on Climate Change, FCCC/CP/2015/L.9. https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf. Accessed 23 Nov 2016

van Vuuren DP, Edmonds J, Kainuma M et al (2011) The representative concentration pathways: an overview. Clim Chang 109:5–31