



**USGS Science Strategy to Support U.S. Fish and Wildlife Service Polar Bear Listing Decision**

# **Predicting Movements of Female Polar Bears between Summer Sea Ice Foraging Habitats and Terrestrial Denning Habitats of Alaska in the 21<sup>st</sup> Century: Proposed Methodology and Pilot Assessment**

By Scott Bergen<sup>1</sup>, George M. Durner<sup>2</sup>, David C. Douglas<sup>3</sup>, and Steven C. Amstrup<sup>2</sup>

Administrative Report

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## Abbreviations, Acronyms, and Symbols

Abbreviations, Acronyms, and Symbols	Meaning
AR-4	IPCC Fourth Assessment Report
GCM	General circulation model
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources
PMW	Passive microwave
RSF	Resource selection function
SRES	IPCC Special Report on Emission Scenarios
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

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## Abstract

Polar bears (*Ursus maritimus*) require the relative warmth and stability afforded by snow dens for successful reproduction. Pregnant bears must travel from foraging habitats on the sea ice to land in autumn to establish winter dens. Data of sea ice extent and composition from satellite-acquired passive microwave (PMW) imagery show a reduction in summer sea ice extent throughout the Arctic from 1979-2006. Additionally, General Circulation Models (GCM) predict that Arctic sea ice extent will continue to diminish throughout the 21<sup>st</sup> century. Greater energetic demands will be placed on pregnant polar bears in the future if they travel greater distances from summer forage habitats to traditional denning habitats on land. We developed an approach for estimating how much these distances may change by modeling autumn movement paths of polar bears using the observational PMW record of sea ice distribution and sea ice projections of 5 GCMs during the 21<sup>st</sup> century. Over the 1979-2006 PMW record, polar bears returning to Alaska to den have experienced an annual increase in travel of > 6 km/year—an increase of >168 km over the 28 year period. Based on GCM sea ice projections during 2001-2060, the average increase in the distance required to reach traditional Alaskan denning regions was estimated to increase > 16 km/year. Distances traveled, and therefore, energetic demands, will likely vary among the different circumpolar sub-populations of polar bears.

## Introduction

The U.S. Fish and Wildlife Service (USFWS) proposed listing the polar bear (*Ursus maritimus*) as a threatened species under the Endangered Species Act in January, 2007. To help inform their final decision, they requested that the U.S. Geological Survey (USGS) conduct additional analyses about polar bear populations and their sea ice habitats. Between February and August 2007, USGS and collaborators developed nine reports targeting specific questions considered especially informative to the final decision. As one of the nine reports, this report addresses the impacts of predicted 21<sup>st</sup> century changes in sea ice on the energetics of pregnant polar bears as they travel from summer sea ice foraging habitats to traditional maternal den habitat.

Polar bears give birth to young in dens of snow and ice during mid-winter (Amstrup and Gardner 1994). Maternal dens are built adjacent to landscape or sea ice features that capture and accumulate wind-blown snow (Durner et al. 2003). Polar bears demonstrate substrate and regional fidelity for denning (Ramsay and Stirling 1990, Amstrup and Gardner 1994). In the southern Beaufort Sea, a greater proportion of dens of radio-marked female polar bears are occurring on land (Fischbach et al. 2007). Polar bear survival is dependent on the sea ice as a platform from which they capture seals (Amstrup 2003). Therefore, most pregnant polar bears must transit between pelagic foraging

habitats and terrestrial denning habitats.

Autumn sea ice development is an important determinant of the distribution of polar bear terrestrial dens (Stirling and Andriashek 1992). Maternal denning occurs at greater frequency on land near persistent summer sea ice, or waters that develop sea ice early in the autumn (Stirling and Andriashek 1992). Also, body condition is an important prerequisite to successful den tenure; pregnant bears with low lipid stores will be less likely to leave the den with healthy young in the spring (Atkinson and Ramsay 1995). Polar bears are capable of sustained rates of movement  $> 4$  km/hr (Amstrup et al. 2000) and may travel an average of 5000 km/year (Garner et al. 1990). To conserve body stores, however, pregnant bears may reduce activity levels up to 2 months prior to denning (Messier et al. 1994). Therefore, it may be hypothesized that denning success is inversely related to the distance a pregnant polar bear is required to travel to reach denning habitat.

In the past 2 decades the Arctic has experienced longer summer melt seasons (Belchansky et al. 2004) and reduced summer ice extent (Stroeve et al. 2005). Sea ice projections by most General Circulation Models (GCM) predict continued reductions in summer sea ice extent throughout the 21<sup>st</sup> century (Holland et al. 2006, Zhang and Walsh 2006). Thus, pregnant polar bears will likely incur greater energetic expense in reaching traditional denning regions if sea ice loss continues along the projected trajectory. This could negatively affect individual fitness, denning success, and ultimately sub-populations of polar bears (Aars et al. 2006).

To help understand the effects of a changing Arctic on pregnant polar bears, we propose, and provide an example of, an approach to estimate the distances polar bears would be required to travel between late-summer sea ice (foraging habitats) and a traditional denning region in northern Alaska. We compare distance estimates derived from the satellite

observational passive microwave (PMW) sea ice record, 1979-2005, and sea ice projections from 5 GCMs, 1979-2060. We use a single hypothetical polar bear in the Beaufort Sea and a single den location in northern Alaska to estimate a total annual distance traveled for each year and each sea ice data source.

## Methods

We used monthly estimates of polar bear habitat distribution in the pelagic Arctic that were developed and described by Durner et al. (2007). Durner et al. (2007) estimated resource selection functions (RSF) from PMW monthly grids of average sea ice concentration ( $25 \times 25$  km pixel size), ocean depth, and satellite radio locations of female polar bears (Amstrup et al. 2000). An RSF is defined as a function that is proportional to the probability of use (Manly et al. 2002). RSFs may be extrapolated by a Geographic Information System (GIS) to understand and compare the spatial and temporal distribution of habitat.

Durner et al. (2007) extrapolated the observational derived RSF to 10 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR-4) fully-coupled GCMs for 1975-2100. These 10 models were selected based on the criteria defined by DeWeaver (2007). GCMs were run under the 20<sup>th</sup> century experiment (forced by observed natural and anthropogenic environmental factors) and the 21<sup>st</sup> century 'business as usual' greenhouse gas forcing scenario (Special Report on Emission Scenarios SRES-A1B; Solomon et al. 2007).

In this report, we used RSF extrapolations from 5 of the 10 GCMs during 1975-2060 (Table 1). Reporting time constraints precluded us from analyzing the full suite of GCMs in DeWeaver (2007), other denning areas, and the latter decades of the 21<sup>st</sup> century. Our objective was to estimate the distance that a polar bear was required to travel from good summer sea ice habitat to a traditional denning locale in

Alaska. We defined “good” sea ice habitat within each monthly RSF map as pixels that possessed two criteria: 1) the estimated sea ice concentrations were  $\geq 50\%$ ; and 2) the RSF-values (Durner et al. 2007) were in the upper 50% of the total RSF-valued habitat area in the polar basin (Figure 1). That is to say, the polar bear was restricted to travel within the better half of the total RSF-valued sea ice habitat area.

Hypothetical polar bears were designated as members of the southern Beaufort Sea IUCN management unit (Aars et al. 2006). As we outlined in the Introduction, we constrained our analysis in this pilot assessment to a single den habitat location in the northeast corner of Alaska, and this den location was held constant for all analyses (Figure 1). The den habitat location was within a region of high denning frequency (Amstrup and Gardner 1994). A polar bear’s starting location was defined in September as the pixel that was: 1) within good habitat, 2) occupying the largest contiguous region of sea ice, and 3) nearest to the den habitat location.

We forced movements of bears toward the den habitat location in monthly time steps using a cost-path approach (ESRI, Redlands, CA). A “cost” surface was generated for each RSF map by partitioning the good habitat pixels into 10 equal area zones (the highest RSF-valued zone was attributed the least cost). Each month, two concurrent measurements (path distances) were made: no-cost and least-cost (Figure 2). No cost movements only required the path to travel over ice that was  $>50\%$  sea ice concentration, without regard to the RSF habitat quality (i.e. the RSF cost-surface was flat). In contrast, least cost movements sought an optimized path that strove to follow higher RSF-valued habitat while simultaneously minimizing distance. In both cases, paths were not permitted to cross over land. At the end of each month, no cost and least cost distances respectively were summed. The ending location was used to define the starting location for the subsequent month’s calculations, until the ending location

reached the denning location.

Maps of good polar bear habitat and cost-surfaces were created for each monthly RSF, September-December, for all PMW (1979-2006) and GCM (1979-2060) data. We calculated an annual distance sum from each of the PMW and 5 GCMs for each year (1979-2060) from their respective monthly distances. If the starting point in September was adjacent to the den habitat location, then the distance for September (and the annual sum distance) was zero. Similarly, if the October starting point (i.e., the September ending point) was adjacent to the den habitat location, distances for October to December were set to zero and the annual sum was simply the accumulated September distance.

We characterized trends in PMW (1979-2006) and GCM (1979-2060) distance estimates graphically and with linear regression. To reduce the noise from inter-annual variation, we calculated 10-year running means throughout the PMW and GCM history from 1988-2060. Running means were also calculated for 1985, 1986 and 1987 and included 7, 8 and 9 years, respectively. Graphical assessment of averaged distance trends allowed a convenient visual comparison between PMW and GCMs.

## Results

Because our analyses focused on terrestrial denning habitat in northern Alaska, all modeled movement paths occurred in the Beaufort Sea (Figure 3). Because the 5 GCM monthly estimates of sea ice extent and composition were independently derived, starting points and paths varied within any particular month. By the mid-21<sup>st</sup> century, most September starting points occurred in the high-latitude Canadian Arctic between Prince Patrick Island and Ellesmere Island, while some occurred in the deep waters of the Arctic Basin (Figure 3).

The observational PMW sea ice record suggests that polar bears have been required to travel increasing distances between summer sea ice habitats and northeast Alaska denning

habitats during 1985-2006 (Figure 4). Interannual variation among the annual distance estimates was high, ranging from 0 km in 1983 to 675 km in 2006. Linear regression slopes of the 1979-2006 annual distance estimates were 6.6 km/year for no cost movement paths and 8.0 km/year for the least cost paths (Table 2). The 10-year running average distance was relatively flat from 1985-1992, followed by a distinct and steady increase thereafter. Linear trend of the 10-year averages shows an estimated 8.0 km/year increase in the no cost distance (from 225 km in 1985 to 400 km in 2006) and a 7.7 km/year increase in the least cost distance (from 290 km in 1985 to 460 km in 2006).

Least cost and no cost average distance trends based on the CCSM3 GCM were generally similar to PMW trends but showed greater inter-annual variation (Figure 5a). Distances based on CCSM3 projections were sometimes twice those of PMW (i.e., 1992-1993 and 1999 and 2000). Between 1985 and 2060, no cost distances between ice and denning habitats increased from 279 km to 2325 km (26.9 km/year; Figure 5b). During the same period, least cost distances increased from 306 km to 2950 km (34.8 km/year; Figure 5b). These rates were similar to regression slopes of the annual 1979-2060 CCSM3 estimates for both no cost (24.3 km/year) and least cost distance (32.5 km/year; Table 2).

The CGCM3-T47 no cost 10-year running mean closely tracked PMW least cost and no cost estimates from 1985 to 2002, after which predicted distances from CGCM3 were approximately 125 km less than the PMW estimates (Figure 6a). Least cost distances predicted with CGCM3 were often > 100 km greater than PMW estimates between 1987 and 1997, but were in close agreement with no cost estimates between 2003 and 2006 (Figure 6a). During 1979-2060 (Figure 6b), CGCM3 no cost distance estimates increased 4.2 km/year (Table 2) while least cost distances increased at a slightly higher rate of 4.9 km/year.

Smoothed distance estimates from the

GFDL-GM2 model were approximately 250 km greater than those observed by PMW throughout 1985-2006 (Figure 7a). Both GFDL-GM2 and PMW, however, showed similar rates of increase. Over the full record of GFDL-CM2 data used here (1979-2060; Fig 7b), annual no cost distances increased 3.0 km/year (Table 2) and least cost distances increased 4.5 km/year.

The HadGEM1 model also showed increasing trends similar to the PMW data (Figure 8a), however, HadGEM1 consistently underestimated distances by ~100 km throughout most of the PMW record. From 1979 to 2060 (Figure 8b), no cost distances predicted with HadGEM1 data increased 19.5 km/year (Table 2), while least cost distances increased 25.4 km/year.

Distance estimates based on the CNRM-CM3 model were most dissimilar to the PMW distances (Figure 9a). CNRM-CM3 distances were consistently greater than PMW derived distances by > 500 km throughout most of the PMW record. From 1979 to 2060 (Figure 9a), annual no cost distances based on the CNRM-CM3 model increased 20.0 km/year (Table 2), and the least cost distances increased 28.5 km/year.

The 5 GCMs showed considerable variability (uncertainty) among their estimates of the distances between projected summer ice habitats and terrestrial den habitat in northeast Alaska (Figs. 5-9), but all models indicated an increasing trend during 1979-2060 (Table 2). The multi-model averages (Figure 10a and 10b) generated estimates that were reasonably aligned with the PMW observed record during the period of overlap (Figure 4). Near the end of the observational record, the 10-year running multi-model average distances exceeded that of the PMW results by about 100 km and 200 km for the no cost and least cost paths, respectively. Based on linear regression of the multi-model averages (Table 2), the 10-year running mean no cost distance increased by 15.8 km/year, and the least cost distance increased 18.2 km/year. Nevertheless, visual inspection of Figure 10



clearly suggests the likelihood of a non-linear trend, with distance rates accelerating around the year 2030.

## Discussion

Regardless of variation among GCMs in their point estimates of the distances between summer sea ice habitat and terrestrial denning habitat in northeast Alaska, all GCMs projected an increasing trend throughout the first half of the 21<sup>st</sup> century. Our results suggest that pregnant polar bears could face increased travel distances from summer foraging habitats on the sea ice to terrestrial denning habitats in northeast Alaska from 385 km in 1985 to a multi-model average projection of 1487 km in 2060 (Figure 10a). Assuming non-stop travel and an average movement rate of 1.62 km/hr (October mean movement rate; Table 2 in Amstrup et al. 2000), it would take a bear 10 and 38 days to traverse these distances. If bears attempted to follow the best sea ice habitat while traveling, distances would be ~25% greater (Figure 10b).

Distance estimates derived from PMW data provided an empirical baseline to compare to those derived from the modeled 20<sup>th</sup> century sea ice simulations and 21<sup>st</sup> century projections. In terms of absolute distances, the GCM estimates were often different from PMW estimates. However, the smoothed multi-model average distance (Figure 10a) showed reasonable concordance with the smoothed PMW results (Figure 4), corroborating the robustness of an ensemble mean for extracting the underlying signal from multiple GCM outputs (DeWeaver 2007, Randall et al. 2007).

All total distance estimates were within theoretical possibilities based on movement data from radio-collared polar bears (Amstrup et al. 2000). Rates of increase in the distances between sea ice and denning habitats were consistently greater for least cost paths (i.e., following good ice habitat) than for no cost paths. Nevertheless, least cost path distances were generally similar to no cost distances

(~25% greater) because most GCMs predicted remnant summer sea ice in the high-latitude Canadian Arctic and good ice habitats were common during freeze-up along the southward corridor to our denning habitat in northeast Alaska. However, we anticipate larger disparities between no cost and least cost paths from the Canadian Arctic to the high-density denning areas on Wrangel Island because no cost paths will typically cross the very large and very deep polar basin where good ice habitats are rarely predicted (Durner et al. 2007).

Our least cost models forced bears to preferentially occupy higher RSF-valued ice habitats, but this does not necessarily place bears over the continental shelf where prey densities are likely to be greatest (Derocher et al. 2004) or near coastal shear zones and polynyas where seals are most accessible (Stirling 1997). While polar bears are capable of long-distance movements, their walking efficiency is lower than what is predicted by models (Hurst et al. 1982). Polar bears that are forced to travel great distances may therefore experience high energy demands and few opportunities to hunt for seals. This in turn would impose unprecedented demands on lipid stores of pregnant polar bears.

Our results establish a foundation for estimating actual energetic costs that female polar bears may face if sea ice continues to retreat. It can be expected that impacts of climate warming will be expressed differently among the several sub-populations of polar bears in the Arctic. This study focused on polar bears using denning habitat in northern Alaska. Several other denning regions, including Wrangel Island, have been identified in the Arctic Basin (Harrington 1968). Most of these denning regions are much further from areas where summer ice is predicted to persist in the future. Polar bears returning to other denning locales such as Wrangel Island will likely have to travel greater distances than those reported here.

## Conclusions

We developed an approach to use observed sea ice distributions (1979-2006) and GCM sea ice projections (1975-2060) to estimate minimum distances that pregnant polar bears would be required to travel between summer sea ice habitats and a terrestrial den location in northeast Alaska. In this pilot assessment, calculations were made with and without the constraint of least cost movement paths, which required bears to optimally follow high-quality ice habitats. Although variation among the 5 GCMs we analyzed was considerable, smoothed multi-model average distances aligned reasonably well with those derived from the observational record. Assuming robustness of the 5-model ensemble mean as applied to our one denning location, we summarize the main results of this study as:

- Based on observed sea ice distributions during 1979-2006, the minimum distance that polar bears have been required to travel from ice habitats to denning habitats in northeast Alaska has increased at an average linear rate 6–8 km/year, and this long-term rate almost doubled after 1992.
- Based on 21<sup>st</sup> century projected sea ice distributions by 5 GCMs, the minimum distance that polar bears will be required to travel from ice habitats to denning habitats in northeast Alaska will increase almost 3-fold, reaching upwards of 1,500 – 2,000 km by 2060, with pronounced increases commencing around the year 2030.

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## References Cited

- Aars, J., N.J. Lunn, and A.E. Derocher. (Editors). 2006. Polar Bears: Proceedings of the 14th Working Meeting of the IUCN/SSC Polar Bear Specialist Group, 20-24 June 2005, Seattle, Washington, Occasional Paper 32.
- Amstrup, S.A. 2003. Polar bear, *Ursus maritimus*. Pages 587-610 in G.A. Feldhamer, B.C. Thompson, and J.A. Chapman (Editors). Wild Mammals of North America: Biology, Management, and Conservation. Johns Hopkins University Press, Baltimore, Maryland, 2nd edition.
- \_\_\_\_\_, G.M. Durner, I. Stirling, N. Lunn, and F. Messier. 2000. Movements and distribution of polar bears in the Beaufort Sea. *Canadian Journal of Zoology* 78:948-966.
- \_\_\_\_\_, and C. Gardner. 1994. Polar bear maternity denning in the Beaufort Sea. *Journal of Wildlife Management* 58:1-10.
- Atkinson, S.N., and M.A. Ramsay. 1995. Effects of prolonged fasting of the body composition and reproductive success of female polar bears (*Ursus maritimus*). *Functional Ecology* 9:559-567.
- Belchansky, G.I., D.C. Douglas, and N.G. Platonov. 2004. Duration of the Arctic sea ice melt season: Regional and interannual variability, 1979-2001. *Journal of Climate* 17:67-80.
- Derocher, A.E., N.J. Lunn, and I. Stirling. 2004. Polar bears in a warming climate. *Integrative and Comparative Biology* 44:163-176.
- DeWeaver, E. 2007. Uncertainty in Climate Model Projections of Arctic Sea Ice Decline: An Evaluation Relevant to Polar Bears. USGS Alaska Science Center, Anchorage, Administrative Report.
- Durner, G.M., S.C. Amstrup, and A.S. Fischbach. 2003. Habitat characteristics of polar bear terrestrial maternal den sites in northern Alaska. *Arctic* 56:55-62.
- \_\_\_\_\_, D.C. Douglas, R.M. Nielson, S.C. Amstrup, and T.L. McDonald. 2007. Predicting the Future Distribution of Polar Bear Habitat in the Polar Basin from Resource Selection Functions Applied to 21<sup>st</sup> Century General Circulation Model Projections of Sea Ice. USGS Alaska Science Center, Anchorage, Administrative Report.
- Fischbach, A.S., S.C. Amstrup, and D.C. Douglas. 2007. Landward and eastward shift of Alaskan polar bear denning associated with recent sea ice changes. *Polar Biology*: in press.
- Garner, G.W., S.T. Knick, and D.C. Douglas. 1990. Seasonal movements of adult female polar bears in the Bering and Chukchi Seas. *International Conference on Bear Research and Management* 8:216-226.
- Harrington, C.R. 1968. Denning habits of the polar bear (*Ursus maritimus* Phipps). *Canadian Wildlife Service, Ottawa, Report Series* 5.
- Holland, M.M., C.M. Bitz, and B. Tremblay. 2006. Future reductions in the summer Arctic sea ice. *Geophysical Research Letters*. 33:L23503.
- Hurst, R.J., M.L. Leonard, P.D. Watts, P. Berkerton, and N.A. Ørtsland. 1982. Polar bear locomotion: body temperature and energetic cost. *Canadian Journal of Zoology* 60:40-44.
- Manly, B.F.J., L.L. McDonald, D.L. Thomas, T.L. McDonald, and W.P. Erickson. 2002. *Resource Selection by Animal Statistical Design and Analysis for Field Studies*. Kluwer Academic Publishers, Dordrecht, Netherlands, 2<sup>nd</sup> edition.

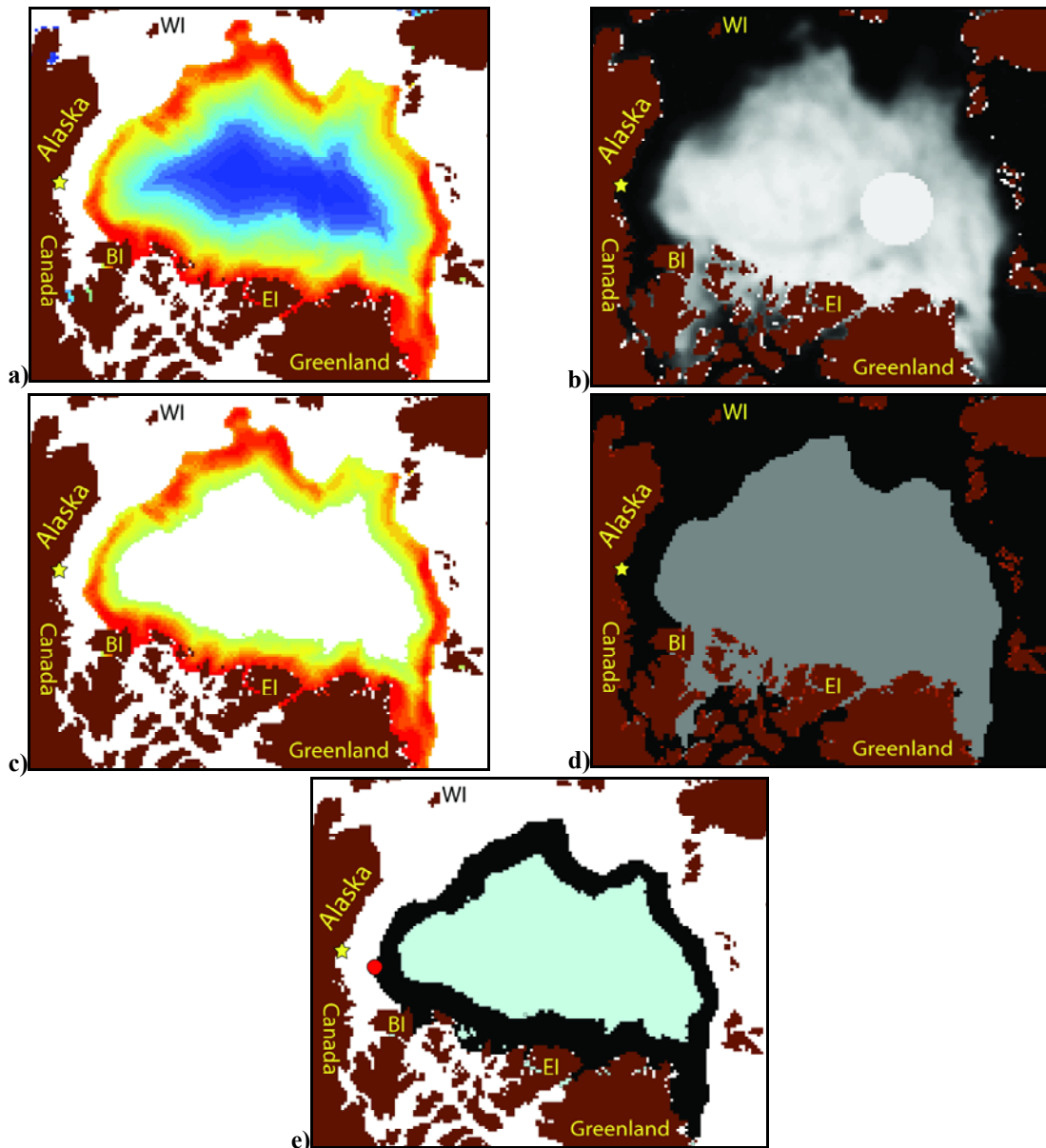
- Messier, F., M.K. Taylor, and M.A. Ramsay. 1994. Denning ecology of polar bears in the Canadian Arctic archipelago. *Journal of Mammalogy* 75:420-430.
- Ramsay, M.A., and I. Stirling. 1990. Fidelity of female polar bears to winter-den sites. *Journal of Mammalogy* 71:233-236.
- Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, and K.E. Taylor. 2007. Climate models and their evaluation. In S. Solomon, D. Qin, M. Manning, and H.L. Miller (Editors). In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the IPCC*. Cambridge University Press, United Kingdom. Available from <http://www.ipcc.ch/>.
- Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (Editors). 2007. Summary for policymakers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, United Kingdom. Available from <http://www.ipcc.ch/>.
- Stirling, I. 1997. Importance of polynyas, ice edges, and leads to marine mammals and birds. *Journal of Marine Systems* 10:9-21.
- \_\_\_\_\_, and D. Andriashek. 1992. Terrestrial maternity denning of polar bears in the eastern Beaufort Sea area. *Arctic* 45:363-366.
- Stroeve, J.C., M.C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, and K. Knowles. 2005. Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. *Geophysical Research Letters* 32:L04501.
- Zhang, X., and J.E. Walsh. 2006. Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 model simulations. *Journal of Climate* 19:1730-1747.

**Table 1.** Five IPCC AR-4 GCMs whose sea ice simulations and derivative polar bear RSF habitat models were used to estimate distances traveled by pregnant polar bears: IPCC model ID, country of origin, abbreviation used in this paper, approximate native grid resolution (degrees), forcing scenario, and the number of model runs. For details see DeWeaver (2007) and Durner et al. (2007).

<b>MODEL ID</b>	<b>Country</b>	<b>Acronym (this paper)</b>	<b>Grid Res. (lat x lon)</b>	<b>Forcing Scenario</b>	<b>Runs (n)</b>
ncar_ccsm3_0	USA	CCSM3	1.0 x 1.0	20c3m	1
cccma_cgcm3_1	Canada	CGCM3 T47	3.8 x 3.8	SRES A1B	1
cnrm_cm3	France	CNRM CM3	1.0 x 2.0	20c3m	1
gfdl_cm2_0	USA	GFDL CM2	0.9 x 1.0	SRES A1B	1
ukmo_hadgem1	UK	HadGEM1	0.8 x 1.0	20c3m	1
				SRES A1B	1

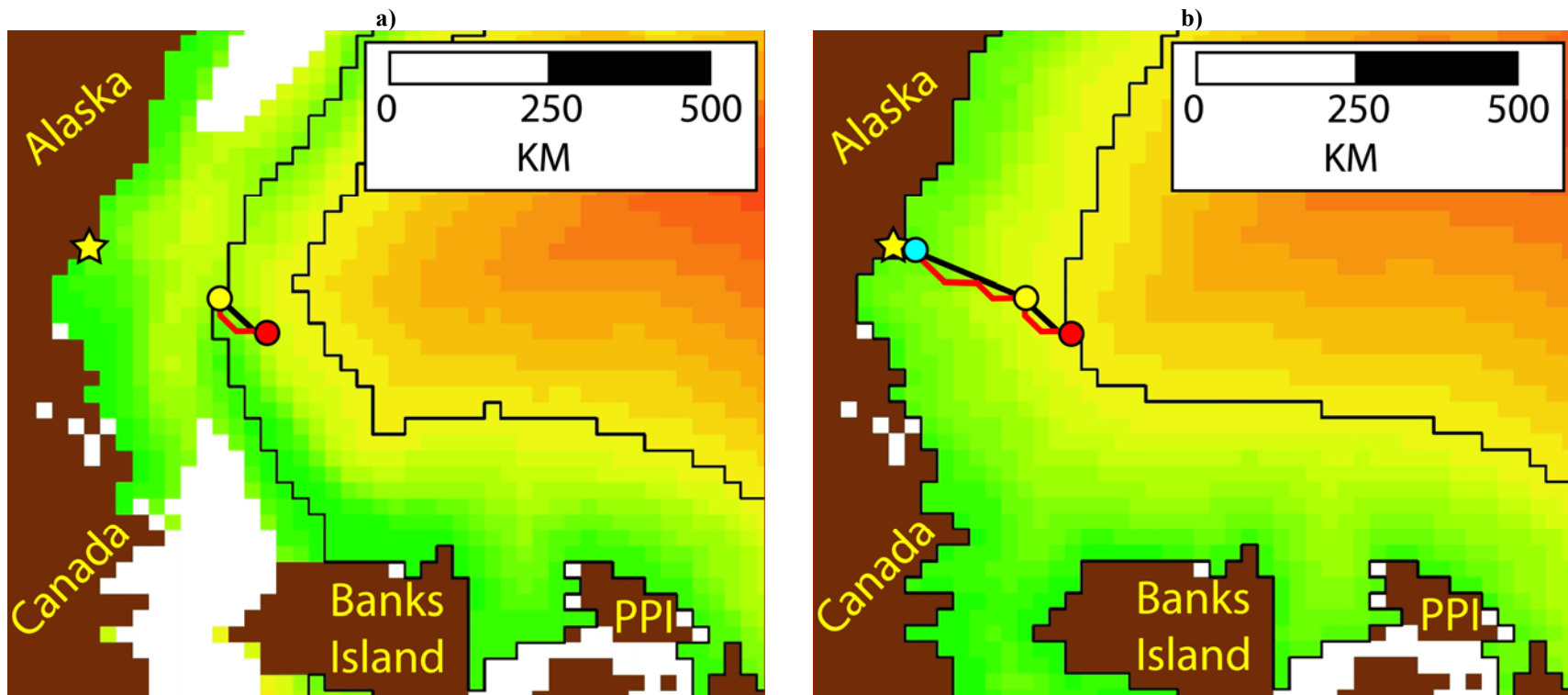
**Table 2.** Linear regression results for estimated travel distances by pregnant polar bears between September sea ice and a terrestrial denning site in northeast Alaska based on ice observations (PMW) and ice projections by 5 GCMs, and the 10-year running mean of their multi-model averages.

Data source	Period	Path type	Slope (km/yr)	P-value	R <sup>2</sup>	F <sub>(df)</sub>
PMW	1979-2006	No cost	6.6	0.05	0.14	4.9 <sub>(1, 26)</sub>
		Least cost	8.0	<0.05	0.16	4.2 <sub>(1, 26)</sub>
CCSM3	1979-2060	No cost	24.3	<0.001	0.56	102.4 <sub>(1, 80)</sub>
		Least cost	32.5	<0.001	0.60	122.3 <sub>(1, 80)</sub>
CGCM3-T47	1979-2060	No cost	4.2	<0.001	0.13	12.1 <sub>(1, 80)</sub>
		Least cost	4.9	0.01	0.08	6.9 <sub>(1, 80)</sub>
GFDL CM2	1979-2060	No cost	3.0	<0.001	0.22	22.8 <sub>(1, 80)</sub>
		Least cost	4.5	<0.001	0.20	20.3 <sub>(1, 80)</sub>
HadGEM1	1979-2060	No cost	19.5	<0.001	0.64	139.4 <sub>(1, 80)</sub>
		Least cost	25.4	<0.001	0.61	126.4 <sub>(1, 80)</sub>
CNRM-CM3	1979-2060	No cost	20.0	<0.001	0.69	182.0 <sub>(1, 80)</sub>
		Least cost	28.5	<0.001	0.60	121.7 <sub>(1, 80)</sub>
Multi-model GCM Average	1985-2060	No cost	15.8	<0.001	0.92	799.3 <sub>(1, 74)</sub>
		Least cost	18.2	<0.001	0.91	757.8 <sub>(1, 74)</sub>



**Figure 1.** Methodology for selecting the nearest point of the available sea ice habitat for a hypothesized polar bear to travel to a den site (yellow star). (a) Monthly polar basin RSF-valued polar bear habitat (Durner et al. 2007; blue = low RSF, orange = high RSF). (b) Monthly sea ice concentration estimates derived from passive microwave satellite imagery (NSIDC; white = high ice concentration, black = water). (c) Upper 50% of the RSF-valued habitat area. (d) Extent of ice cover  $\geq 50\%$  ice concentration. (e) Union of c) and d), defining the area of “good” habitat (black region) that the modeled bear movement is allowed to cross.

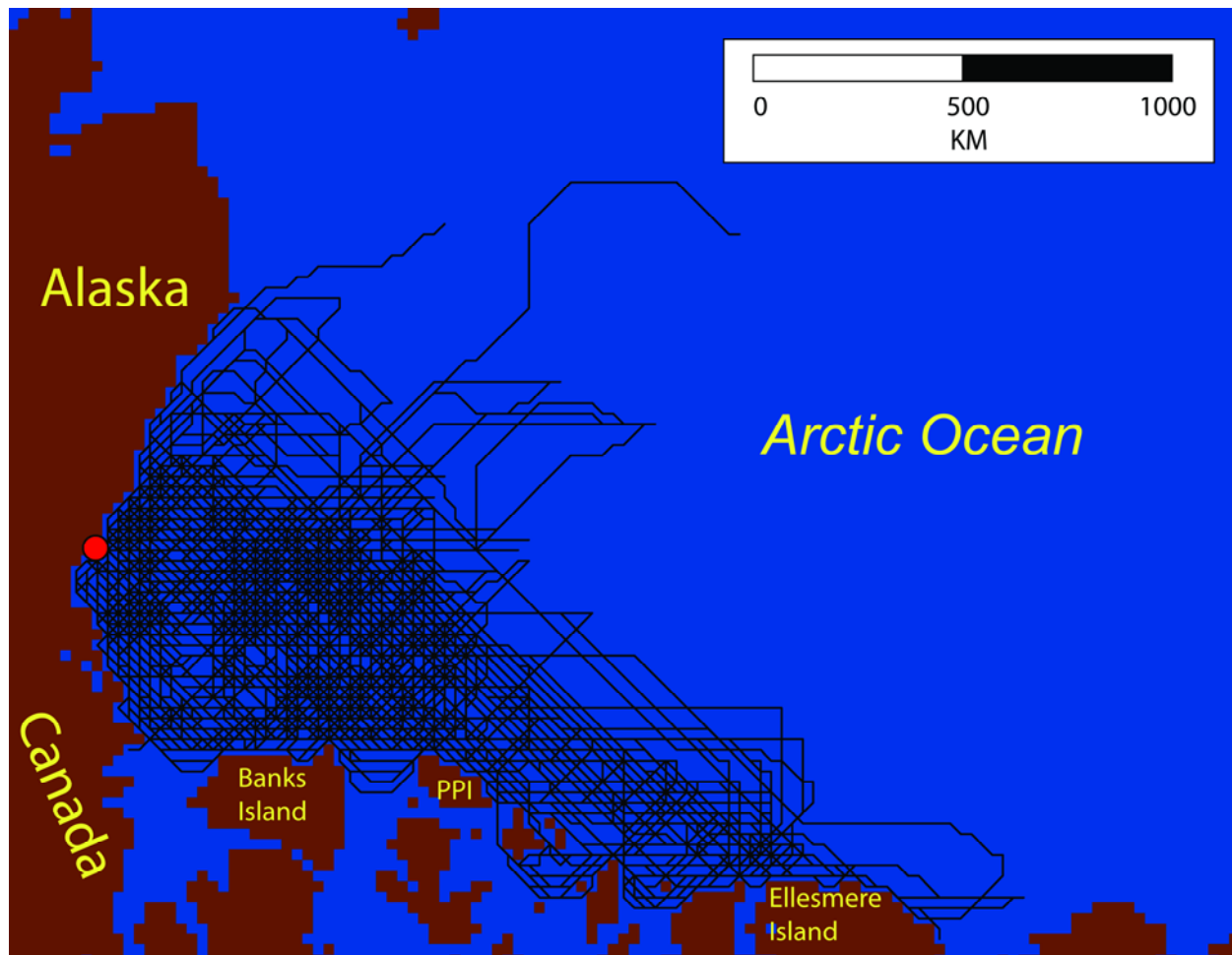
The pixel of good habitat nearest the denning locale (red dot) is chosen for the bear’s starting position. The monthly procedure is repeated until the bear’s movement path reaches the denning locale. BI = Banks Island, EL = Ellesmere Island, WI = Wrangel Island.



**Figure 2.** Example of modeled movement paths of a polar bear from sea ice habitat (beginning at the red dot) to a terrestrial den location on the Alaska coast (yellow star on land) for (a) September to October (red dot to yellow dot) and (b) October to November (yellow dot to blue dot).

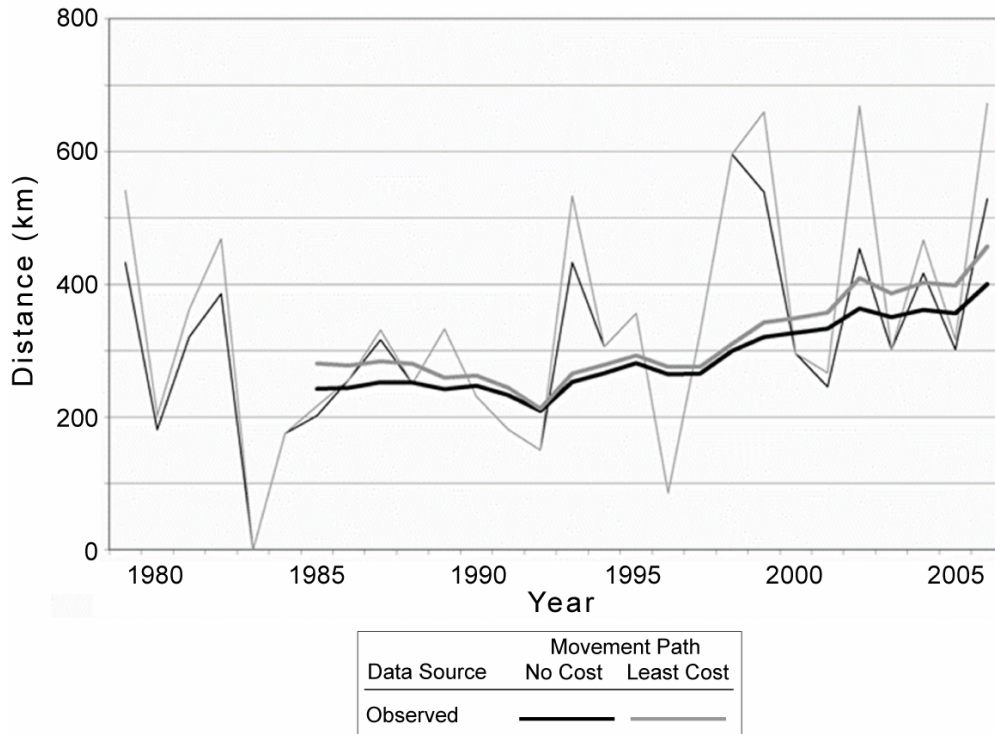
Paths are illustrated as a straight-line (no cost, black line), and by a path that follow the best sea ice habitat (least cost, red line). Sea ice habitat is illustrated in this figure as a Resource Selection Function (Durner et al. 2007) where increasing intensity of orange shows decreasing habitat quality and increasing intensity of green shows increasing habitat quality. PPI = Prince Patrick Island.





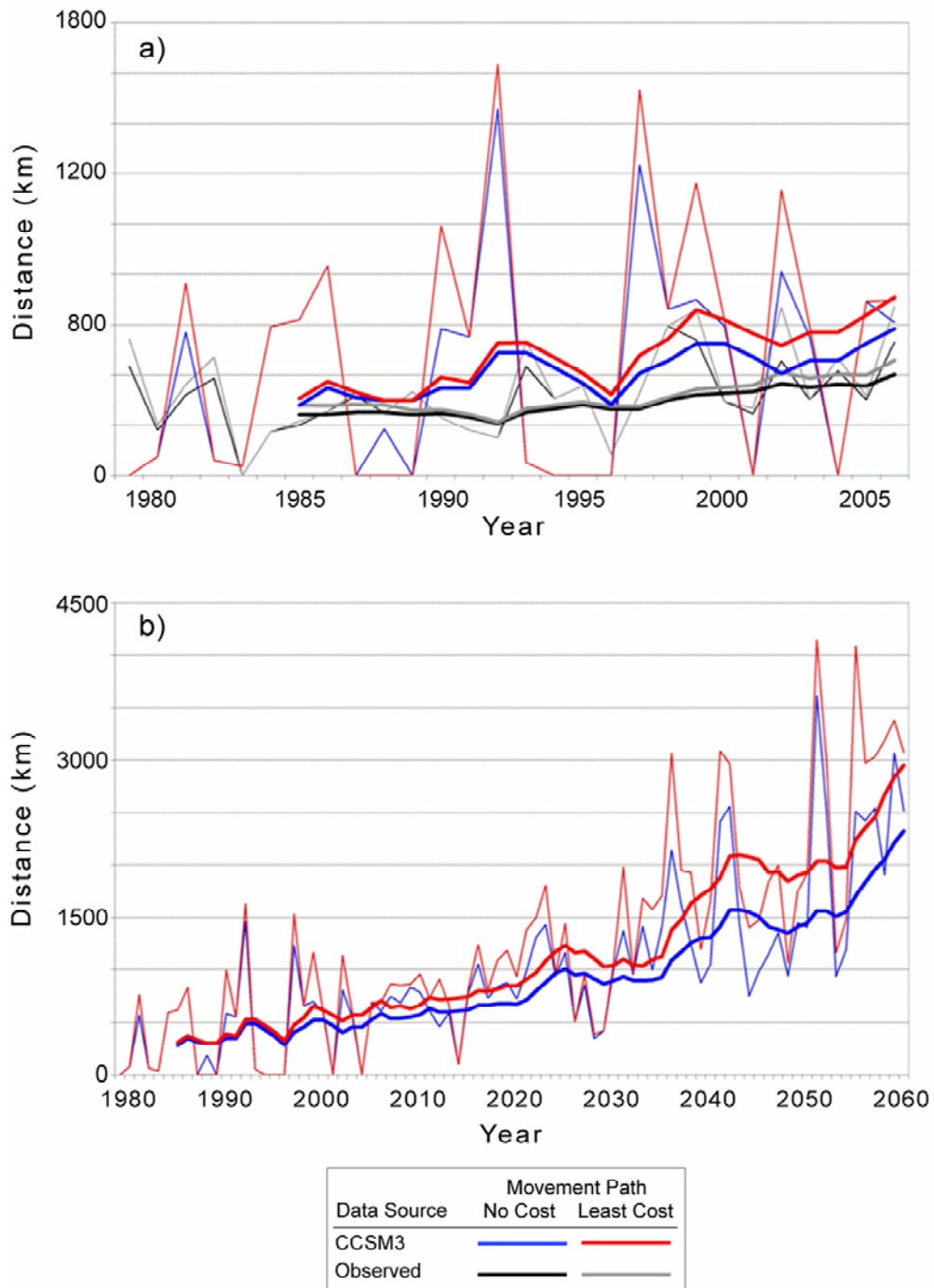
**Figure 3.** Compilation of 5 GCM no cost and least cost paths of polar bears movements between summer sea ice habitat and a traditional terrestrial denning locale in Alaska (red point), 1979-2060.

This compilation of paths shows a distinct pattern of good 21st century ice habitat near the Prince Patrick (PPI) and Ellesmere Islands rather than deep water regions in the Arctic Basin.



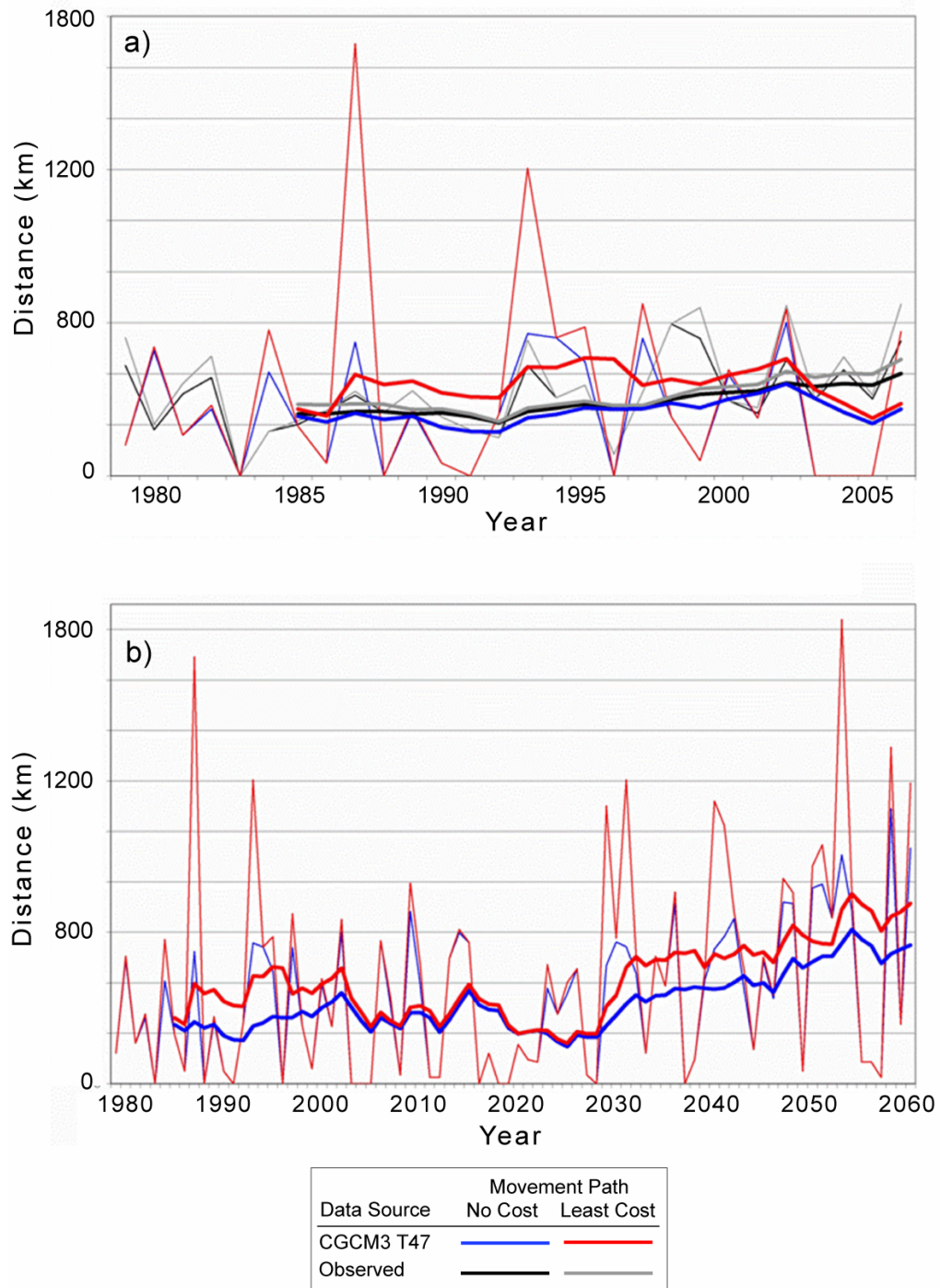
**Figure 4.** Estimated annual distances for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska following no cost and least cost paths, derived using the observational record of sea ice distributions, 1979-2006.

Bold lines show 10-year running means.



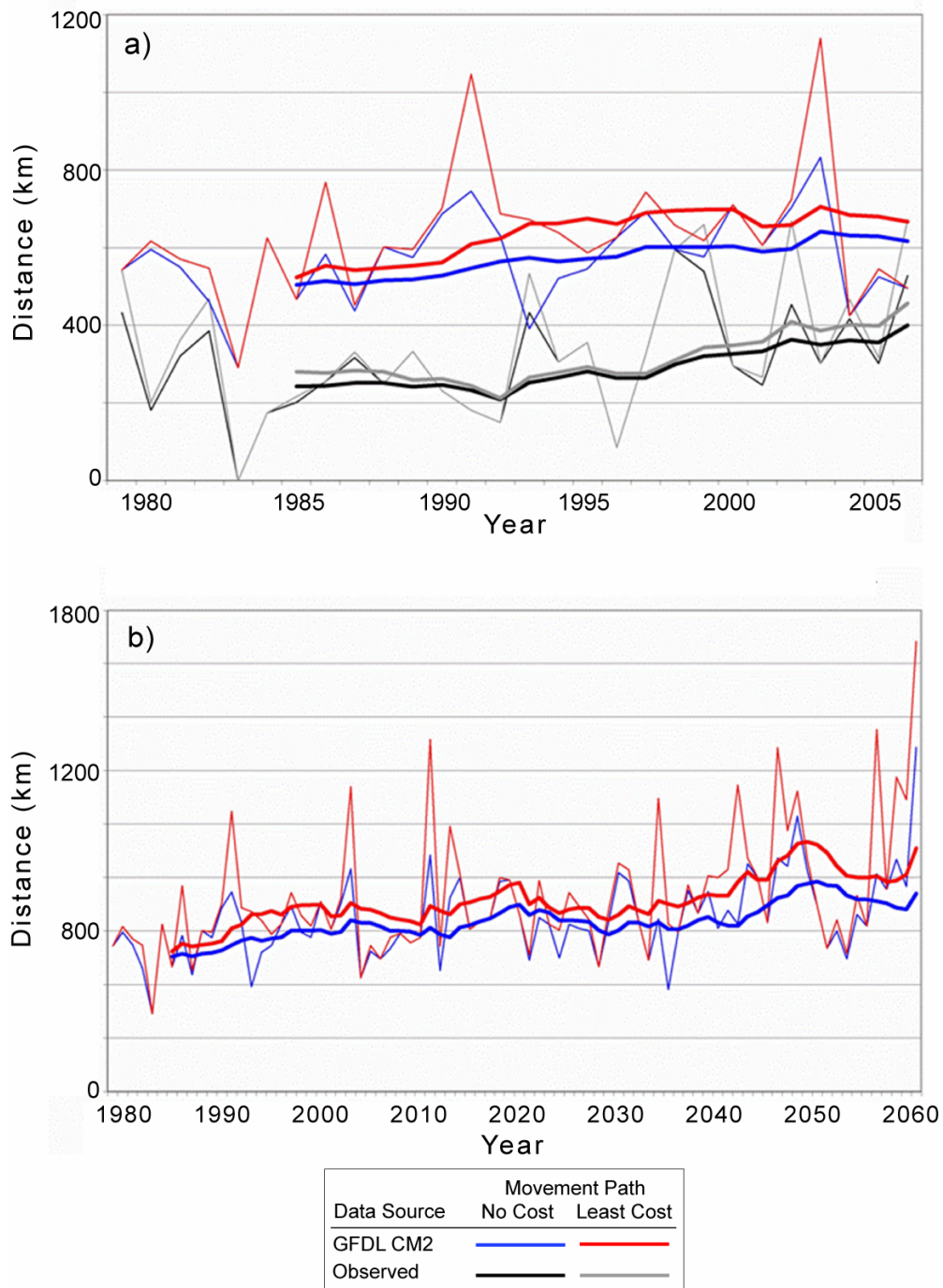
**Figure 5.** CCSM3 model results for the no cost and least cost distances required for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska. (a) The CCSM3 model results compared to the observational sea ice record, 1979-2006; (b) CCSM3 results for 1979-2060.

Bold lines show 10-year running means.



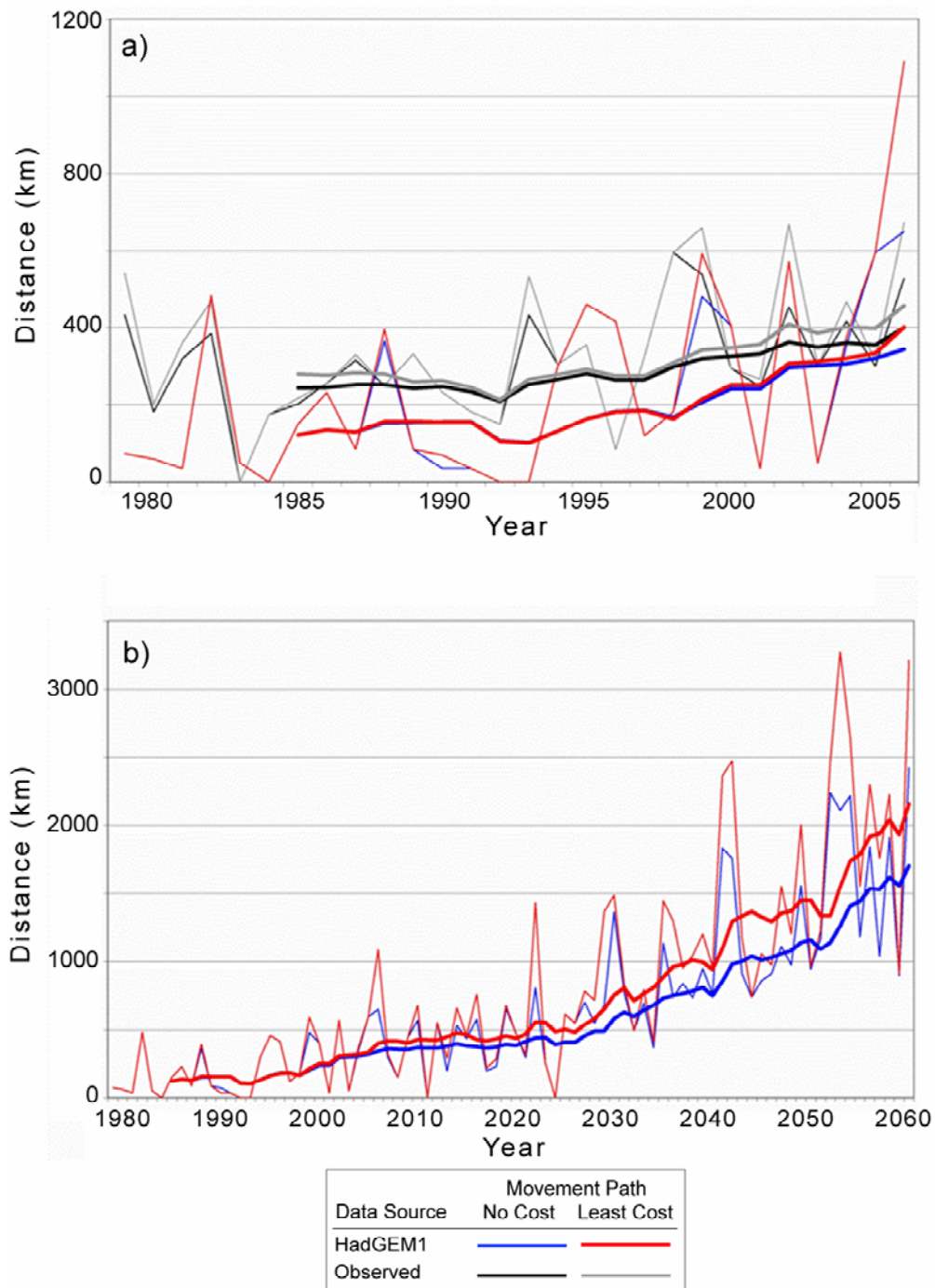
**Figure 6.** CGCM3-T47 model results for the no cost and least cost distances required for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska. (a) The CGCM3-T47 model results compared to the observational sea ice record, 1979-2006; (b) CGCM3-T47 results for 1979-2060.

Bold lines show 10-year running means.



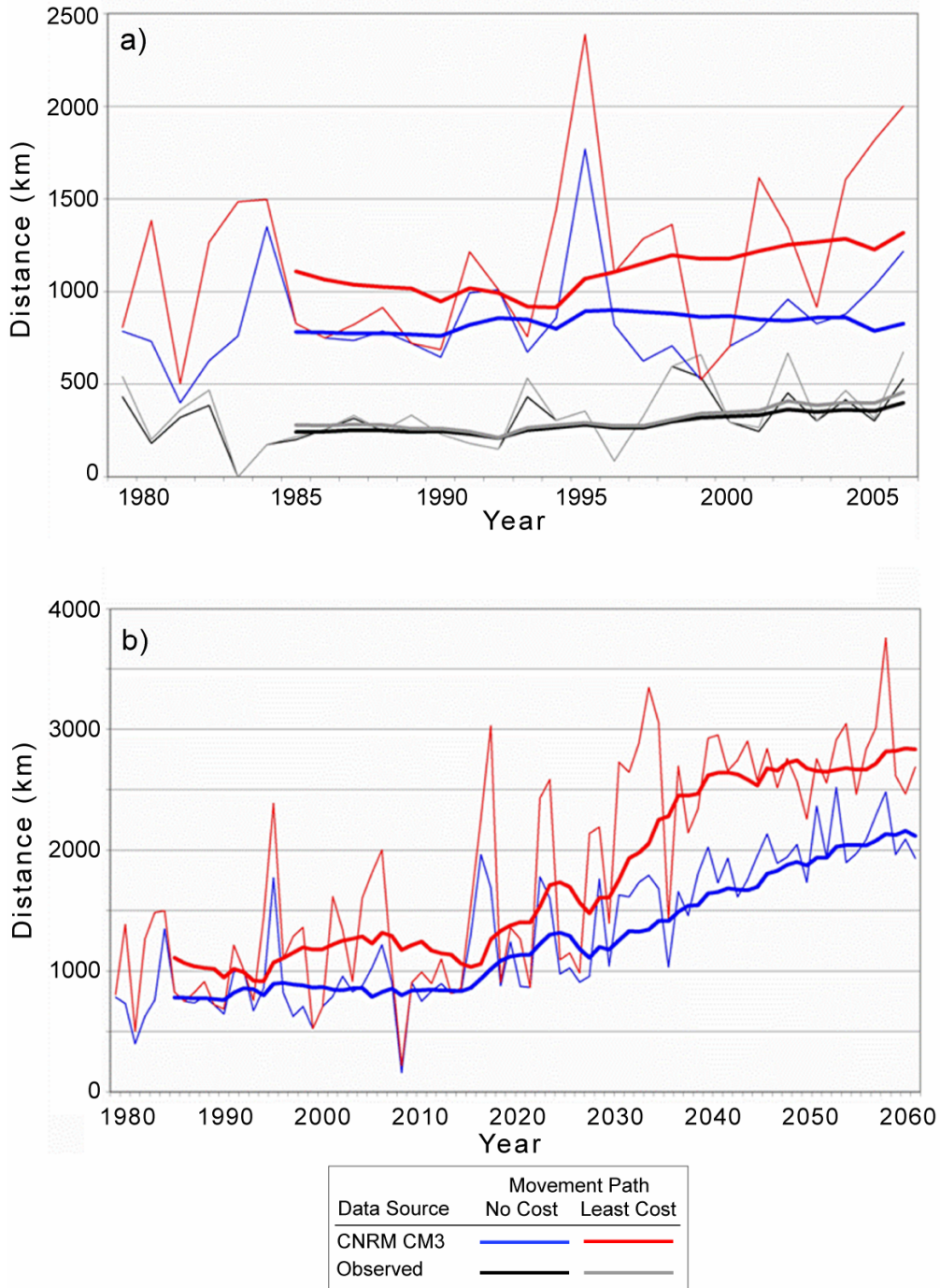
**Figure 7.** GFDL-CM2 model results for the no cost and least cost distances required for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska. (a) The GFDL-CM2 model results compared to the observational sea ice record, 1979-2006; (b) GFDL-CM2 results for 1979-2060.

Bold lines show 10-year running means.



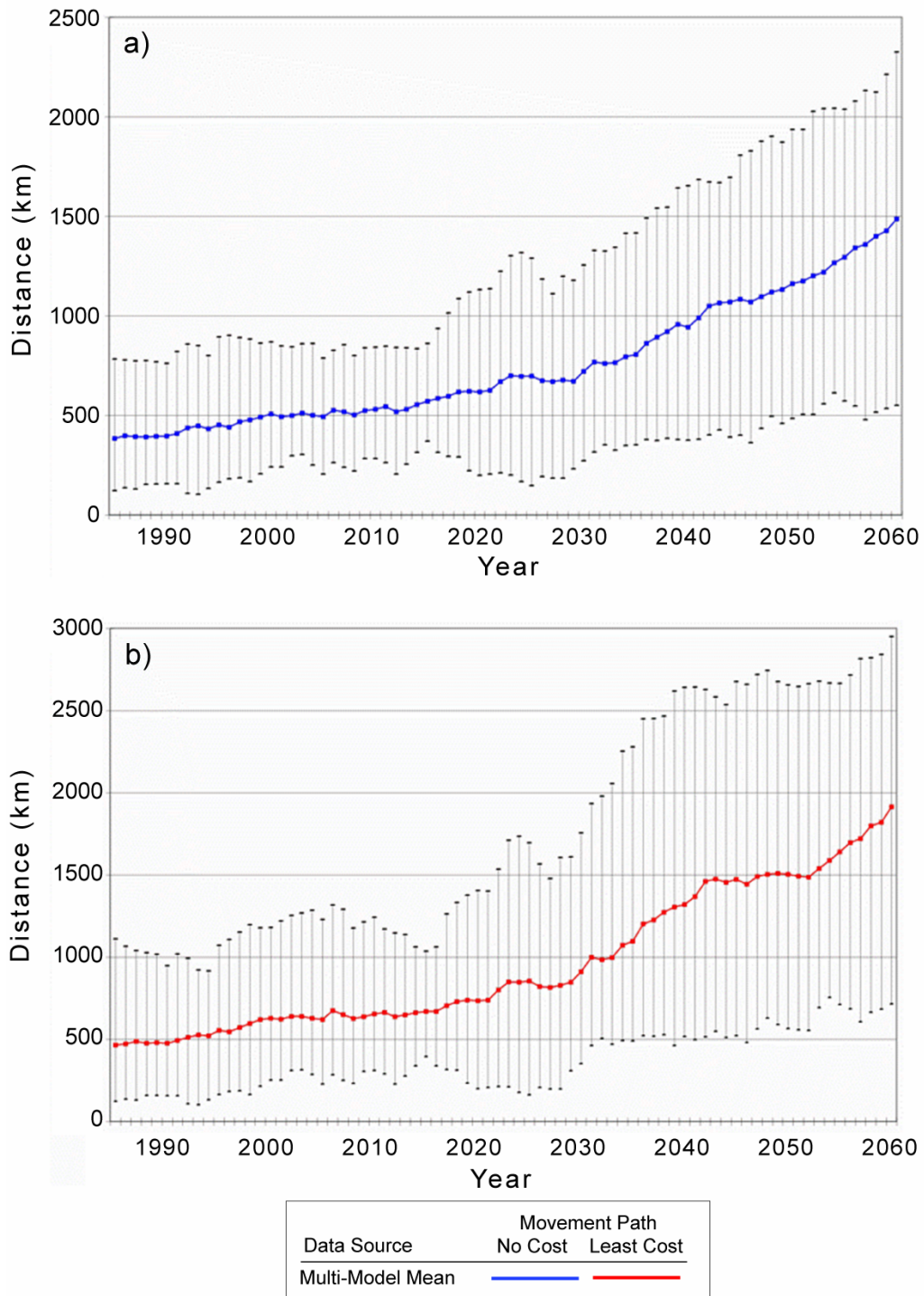
**Figure 8.** HadGEM1 model results for the no cost and least cost distances required for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska. (a) The HadGEM1 model results compared to the observational sea ice record, 1979-2006; (b) HadGEM1 results for 1979-2060.

Bold lines show 10-year running means.



**Figure 9.** CNRM-CM3 model results for the no cost and least cost distances required for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska. (a) The CNRM-CM3 model results compared to the observational sea ice record, 1979-2006; (b) CNRM-CM3 results for 1979-2060.

Bold lines show 10-year running means.



**Figure 10.** Average of 5 GCM 10-year running mean distance estimates ( $\pm$  maximum and minimum) for polar bears to travel from summer sea ice habitat to terrestrial denning habitat in northeast Alaska. (a) Average no cost distance; (b) average least cost distance.