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Estimating future costs for Alaska public infrastructure at risk from climate change

Peter H. Larsen [a,*], Scott Goldsmith [b,1], Orson Smith [c,2], Meghan L. Wilson [b,3], Ken Strzepek [d,4], Paul Chinowsky [d,5], Ben Saylor [b,6]

[a] The Nature Conservancy and Civil Engineering Department, University of Alaska Anchorage, 715 L Street, Suite 100, Anchorage, AK, USA
[b] Institute of Social and Economic Research, University of Alaska Anchorage, ISER-UAA, 3211 Providence Drive, Anchorage, AK, USA
[c] Civil Engineering Department, University of Alaska Anchorage, UAA Civil Engineering Department, 3211 Providence Drive, Anchorage, AK, USA
[d] Department of Civil, Environmental, and Architectural Engineering, University of Colorado at Boulder, ECOT 441, UCB 428, Boulder, CO, USA

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ABSTRACT

This analysis reports on the projected cost of Alaska's public infrastructure at risk from rapid climate change. Specifically, we coupled projections of future climate with engineering rules of thumb to estimate how thawing permafrost, increased flooding, and increased coastal erosion affect annualized replacement costs for nearly 16,000 structures. We conclude that climate change could add \$3.6–\$6.1 billion (+10% to +20% above normal wear and tear) to future costs for public infrastructure from now to 2030 and \$5.6–\$7.6 billion (+10% to +12%) from now to 2080. These estimates take into account different possible levels of climate change and assume agencies strategically adapt infrastructure to changing conditions. In addition to implementing a risk-based economic analysis of climate change impacts, this research effort demonstrates that implementing plausible adaptation strategies could offset impacts by up to 45% over the long-run.

1. Study context

Alaska has been called a "climate canary" because it is already seeing the early effects of global climate change. Climate researchers also expect future climate change in Alaska and other Arctic places to be more pronounced than it is elsewhere in the world. Alaska lies at the far northwest of the North American continent and it is separated from the other US states by Canada. At 152 million hectares, it is larger than the combined areas of the UK, Germany, Italy, and France—but it has a population of only about 650,000. Alaska is the only US state with vast areas of permafrost—permanently frozen ground—which makes it especially vulnerable to a warming climate (see Fig. 1). It also has more kilometers of coastline than the rest of the US combined. Some places in western Alaska are facing unprecedented erosion rates where the sea ice has retreated exposing the shore to direct wave action from Bering Sea storms. Fig. 2 shows that average annual temperatures around Alaska increased approximately 1–3 °C over the past five to six decades (UAFGI (University of Alaska Fairbanks Geophysical Institute), 2006; Chapman and Walsh, 2003). Furthermore, the most recent Atmosphere–Ocean General Circulation Models (AOGCMs) project that both temperature and precipitation will continue increasing in Alaska. The Intergovernmental Panel on Climate Change (IPCC) has concluded that people are responsible for much of the warming climate worldwide, by putting CO_2 and other greenhouse gases into the atmosphere. But natural climate variability and other factors also contribute. The

* Corresponding author. Tel.: +1 907 276 3133; fax: +1 907 276 2584.
E-mail address: PLARSEN@TNC.ORG (P.H. Larsen).
[1] Tel.: +1 907 786 7710; fax: +1 907 786 7739.
[2] Tel.: +1 907 786 1910.
[3] Tel.: +1 907 786 7710; fax: +1 907 786 7739.
[4] Tel.: +1 303 492 6382.
[5] Tel.: +1 303 492 6382.
[6] Tel.: +1 907 786 7710; fax: +1 907 786 7739.

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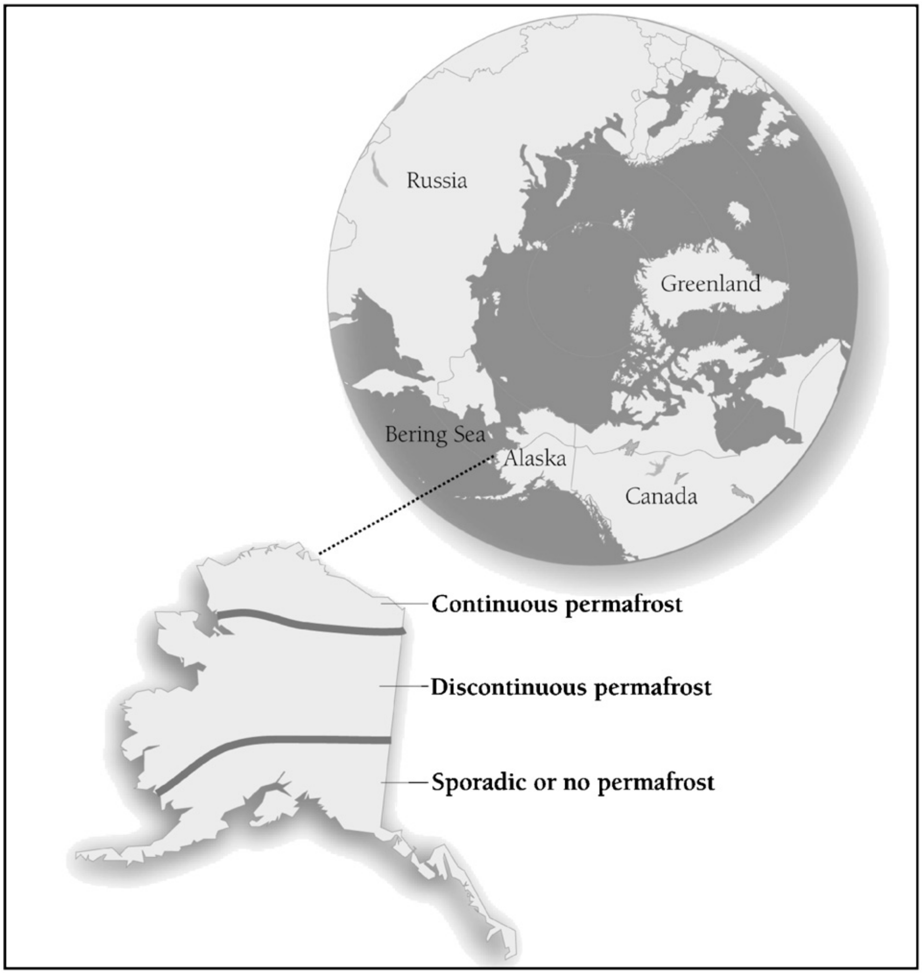

Fig. 1. Map of the arctic with general Alaska permafrost coverage.

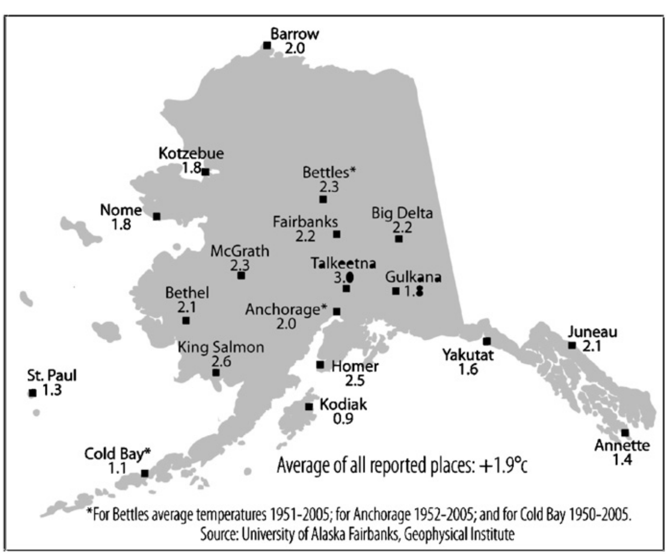

Fig. 2. Observed increase in average annual temperatures, Alaska locations, 1949–2005 (°C).

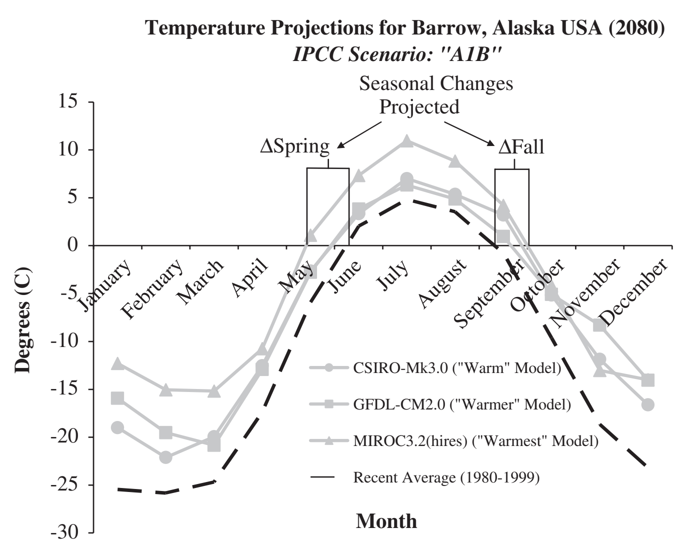

Fig. 3. Selected climate model projections for Barrow, Alaska, USA (2080).

findings are not as definite at the scale of Alaska, but scientists believe much of the warming in the Arctic is probably also due to human activities, with natural variability (e.g., see Overland and Wang, 2005) also playing a significant role. Fig. 3 shows selected AOGCM temperature projections for Barrow, Alaska under the IPCC's "A1B" emissions scenario (McGuinness and Tebaldi, 2006). Notice that under any of the projections, temperatures around Barrow are expected to rise enough by 2080 that break-up of ice will come significantly earlier and freeze-up later than today.

The effects of climate change are widespread throughout Alaska and are difficult to quantify. In addition to directly affecting *natural systems*, climate change will directly affect the people of Alaska. A number of sources (ANTHC (Alaska Native Tribal Health Consortium), 2005; USARC (United States Arctic Research Commission), 2003; ACIA (Arctic Climate Impact Assessment), 2005; Weller et al., 1999; Brown et al., 2003; Osterkamp et al., 1998; Hinzman et al., 2005; UCAR (University Corporation for Atmospheric Research), 2007) cite possible effects, some of which may be beneficial—but many of which won't. These effects include:

- difficulty maintaining subsistence hunting cultures;
- expanded marine shipping;
- declining food security;
- human health concerns (increased incidences of vector-borne diseases and asthma);
- effects on wildlife migratory patterns;
- increased access to offshore resources, including minerals and petroleum;
- changes in marine fisheries;
- decline in freshwater fisheries such as arctic char and salmon;
- enhanced agriculture growing seasons;
- increased forest fire and insect infestation activity;
- disrupted land transportation from thawing permafrost and melting ice roads;
- increased damage to community infrastructure from coastal erosion and thawing permafrost.

Problems associated with thawing permafrost, including effects on the foundations of buildings and roads, are well documented and often dramatic. See, for example: ACIA (Arctic Climate Impact Assessment) (2005), Nelson et al. (2003), USARC (United States Arctic Research Commission) (2003), Osterkamp et al. (1998), Romanovsky et al. (2002), and Couture et al. (2003). Utilities have reported that telecommunication towers are settling due to warming permafrost. United Utilities, for example, has said "warm permafrost is a result of global warming" and is seeking funds for cost overruns in the Yukon–Kuskokwim Delta of southwest Alaska (Hamlen, 2004).

Problems associated with increased rates of coastal erosion are the result of storm activity and wave action eroding shorelines once protected by shore-fast sea ice. This problem is expected to become chronic as the climate warms, sea ice continues to retreat, and coastal storms become more frequent.

A rapidly changing climate will affect both natural and man-made systems in Alaska, with many economic and social consequences. One effect will be to increase building and maintenance costs for public infrastructure, although not all areas or all infrastructure will be equally affected. This paper provides preliminary estimates of how much climate change might add to future costs of building and maintaining Alaska's public infrastructure.

2. What is known about potential costs of climate change?

The British government recently released what has become known as the Stern Report (or Stern Review). It found that climate change could cost the world's economy nearly 5% of global gross domestic product, if nations do not take action to mitigate the effects of greenhouse gases and adapt to projected changes in temperature and precipitation (Stern et al., 2006; Stern, 2007). However, a number of critics have disagreed with that report's conclusions. Nordhaus (2006) believes the authors chose an exceptionally low social discount rate for their analysis (e.g., 0.1%/year). The lower the discount rate used in such an analysis, the higher the present value of future costs. Tol and Yohe (2006) also detailed what they see as the shortcomings of the Stern analysis. Tol (2006) concluded that the Stern Review estimates are "well outside the usual range" and that the British government was "out of step with the economic literature on climate change" (Tol, 2006).

There have been a handful of papers on the costs of climate change for specific industries in the US. For examples of how other academics have attempted to quantify, adapt to, or frame how to address the effects of climate change, see Nordhaus and Yang (1996), Nordhaus and Boyer (2000), Smith et al. (2001), Yohe et al. (1996), Mendelsohn et al. (2000), Tol and Fankhauser (1998), Jorgenson et al. (2004), Yohe and Tol (2002), Mastrandrea and Schneider (2004) and Toman (1998).

In addition, there have been local efforts to study the effects of climate change on communities in several countries. For example, the city of Boston conducted a study on the dollar costs of climate change (Kirshen et al., 2006). Seattle and London also conducted their own analyses and concluded that inaction might have extremely high costs (London Climate Change Partnership, 2002; Cohen et al., 2005). Columbia University did a study for the US "Metro-East Coast," indicating the potential economic effects of climate change on that region (Rosenzweig and Solecki, 2001). Hamilton City in New Zealand recently conducted a study indicating that "energy infrastructure systems" and "transport systems" face the largest number of effects induced by climate change, cutting across all sectors of the city's economy (Jollands et al., 2007). Ruth et al. (2007) reported on climate change impacts to Hamilton City's urban water supply system.

Canadian researchers have studied effects of climate change in the Mackenzie River Basin area of northern Canada and estimated some economic effects on business sectors. In one study, researchers developed an integrated impact assessment to study the overall economic effects of climate change on the Mackenzie River Basin (Cohen, 1997). An earlier Canadian study, by Lonergan et al. (1993), used econometric analysis, stochastic (i.e., random) modeling, and input/output modeling to calculate the economic effects of climate warming in the Mackenzie River Valley and Northwest Territories.

There is very little information on the potential costs from damage to infrastructure resulting from climate change in Alaska. Some Alaska civil engineering and planning experts estimated in 1999 that the costs of dealing with infrastructure at risk from climate change would exceed the budgets of many of the agencies responsible for their upkeep and maintenance. Specifically they wrote:

> Based on these limited examples, the yearly cost for damages due to global climate change for the State of Alaska could be as high as \$35M, or 1.4% of the total state budget. This is a significant cost. It is very similar to the state and federal costs for fire fighting each year; it represents a sizeable fraction of the state's capital projects budgets of around \$70M; it is about equal to the budgets of the Department of Fish and Game at \$34M and the Department of Natural Resources at \$40M. ... If the costs due to global climate change grow in future years, and if the state acknowledges cost for climate change in its budgetary balance sheets, these costs, which cannot be avoided, will seriously cut into other standard state programs with serious consequences for state fiscal policy (Cole et al., 1999, p. 54).

This rough, incomplete cost estimate of \$35 million per year, made in 1999, would be more than \$40 million per year in 2006. If we then aggregate and discount from the year 2030 (using a 2.85% annual discount rate), we get a net present value of nearly \$1 billion needed to cover costs of climate change from now to

2030. And as we report later, the most recent projections of climate variation are higher than projections in the late 1990s, when Cole et al. made that estimate. This simple estimate demonstrates that the potential cost of climate change for Alaska's public infrastructure is large and that more attention needs to be devoted to better understanding its magnitude. A recent report of the United States Arctic Research Commission (USARC) says:

> Expected values of relocation and rehabilitation can be developed, given estimates of per-mile design and construction costs. A master plan of climate-change-induced major relocation and rehabilitation projects can be formed with this information (USARC (United States Arctic Research Commission), 2003, p. 30).

In the following sections, we report on a model we developed to estimate how much projected climate change could add to future costs of Alaska's public infrastructure.

3. Introducing the *ICICLE* model

Building the ISER Comprehensive Infrastructure Climate Life-cycle Estimator (or ICICLE) required several steps: (1) acquiring climate projections; (2) creating a database of public infrastructure throughout Alaska; and (3) estimating the replacement costs and life spans for existing infrastructure, with and without the effects of climate change (while assuming that planners will adapt structures strategically).

4. Projecting Alaska's future climate

4.1. Mean climate projections

To start our analysis, we needed to know how experts believe Alaska's climate will change in the coming years. The Institute for the Study of Society and the Environment at the National Center for Atmospheric Research provided us with 21 AOGCM climate projections for the years 2030 and 2080, developed by scientists in a number of countries (McGuinness and Tebaldi, 2006). AOGCMs couple atmosphere general circulation models with ocean general circulation models—thus taking into account the complex feedbacks between the earth's atmosphere and oceans—to provide detailed projections of future climate conditions on a regional basis. The models also include societal inputs, including projected greenhouse gas emissions. Consequently, their output depends on assumptions about future industrial growth, technology, and carbon emissions. These models are considered the most sophisticated climate models currently available.

The 21 sets of projections we obtained include projected mean monthly temperatures and precipitation for six Alaska locations for the years 2030 and 2080. All the projections show Alaska temperatures rising, but they vary in how much and how fast they project temperatures will rise. Joel Smith of Stratus Consulting, who is a lead author of reports for the IPCC, recommended that we use projections from three climate models—projecting less (i.e. "warm"), mid-range (i.e. "warmer"), and more warming (i.e. "warmest")—to use as inputs in our analysis (Smith and Wagner, 2006). That recommendation choice was partially based on the dual criteria of model bias and uncertainty (Tebaldi et al., 2004, 2005; Smith and Wagner, 2006). The AOGCMs selected for this analysis are:

1. *Warm Model*: CSIRO Atmospheric Research, Australia, CSIRO-Mk3.0.
2. *Warmer Model*: US Department of Commerce, NOAA, Geophysical Fluid Dynamics Laboratory, GFDL-CM2.0.
3. *Warmest Model*: Center for Climate System Research (University of Tokyo); National Institute for Environmental Studies; and Frontier Research Center for Global Change, Japan, MIROC3.2(hires).

All the climate models were calibrated and run as part of the IPCC's coordinated AOGCM model inter-comparison project at Lawrence Livermore National Laboratory: PCMDI. The underlying model assumptions are based on a middle-of-the-road "A1B" emissions and growth scenario defined by the IPCC. The A1 scenario assumes strong economic growth and liberal globalization, low population growth, very high GDP growth, high-to-very high energy use, low-to-medium changes in land use, medium-to-high resource availability (of conventional and unconventional oil and gas), and rapid technological advances. The A1B scenario represents a "balanced" development of energy technologies. It assumes that no one energy source is relied on too heavily and that similar improvement rates apply to all energy supply and end use technologies (Nakićenović and Swart, 2000). Table 1 provides more information about the projected changes in temperature in the six Alaska locations used in this analysis. It includes projections for both 2030 and 2080, illustrating the expected changes during that half century, as well as the historical averages. But we know that temperatures naturally vary from the averages in any given year, and Table 1 also shows the standard deviations from the historical average temperatures. Table 2 shows the projected annual average precipitation amounts under the three sets of projections used in our analysis, as well as the historical averages and standard deviations.

4.2. Developing annual and location-specific climate projections

Using the climate projections shown in the previous figures and tables, we developed annual projections for 350 Alaska locations, by year, in two steps. First, we interpolated mean temperature and precipitation values for all intervening years, using the available data for the 3 years 2006, 2030, and 2080.

Next, we identified the geographical center of each of the six climate regions and then spatially joined the 350 Alaska communities with public infrastructure to those regions. The

Table 1
Historical and projected annual temperature, Alaska locations

Alaska region	Annual mean temp. (1980–1999, °C)	Warm model projection		Warmer model projection		Warmest model projection		Historical standard deviations (°C)
		2030	2080	2030	2080	2030	2080	
Anchorage	2.6	3.2	4.8	3.8	5.6	4.7	7.4	1.2
Barrow	−11.8	−10.3	−7.6	−9.7	−7.0	−8.5	−4.3	1.2
Bethel	−1.0	−0.1	2.1	1.0	2.9	1.6	4.3	1.3
Fairbanks	−2.3	−1.6	0.1	−0.8	1.2	0.3	3.6	1.3
Juneau	5.6	6.1	7.6	6.6	8.4	7.5	10.6	1.0
Nome	−2.6	−1.6	1.2	−0.6	1.6	0.4	3.7	1.3

Table 2
Historical and projected annual precipitation, Alaska locations

Alaska Region	Annual mean precip. (1980–1999, cm)	Warm model projection		Warmer model projection		Warmest model projection		Historical standard deviations (cm)
		2030	2080	2030	2080	2030	2080	
Anchorage	42.5	44.9	44.1	44.4	49.3	44.5	51.3	8.4
Barrow	10.6	10.9	11.9	11.1	12.3	11.4	14.2	4.8
Bethel	42.5	45.9	47.2	44.9	46.0	44.5	51.7	12.4
Fairbanks	27.1	28.6	28.5	28.8	31.7	28.3	34.0	7.4
Juneau	155.0	153.2	165.7	164.9	185.6	160.8	186.2	27.7
Nome	44.2	48.8	51.2	46.2	48.9	47.7	55.4	10.9

spatial join involved selecting the community layer in our mapping program and joining the centers of the regions to it. This is known as a ‘‘points to points’’ join. In this type of join, each community is given the attributes of the region center closest to it, as well as a distance field to show how close that line is (ESRI (Environmental Systems Research Institute), 2006).[7,8]

4.3. Accounting for uncertainty in projections of future climate

The most recent academic literature reporting on the intersection of policy analysis and climate change focuses on the issue of conveying uncertainty when making projections of climatic events that are yet to happen (e.g., Schelling, 2007). Mastrandrea and Schneider (2004) and other authors they cite persuasively write that:

> Policy analysis regarding climate change necessarily requires decision-making under uncertainty. Without explicit efforts to quantify the likelihood of future events, users of scientific results (including policy makers) will undoubtedly make their own assumptions about the probability of different outcomes, possibly in ways that the original authors did not intend. … we believe that such probabilistic methods are more valuable for communicating an accurate view of current scientific knowledge to those seeking information for decision-making than assessments that do not attempt to present results in probabilistic frameworks (Mastrandrea and Schneider, 2004, p. 571).

The ICICLE model takes uncertainty into account partly by using projections from three climate models, but we also recognize the uncertainty surrounding point estimates of future temperature and precipitation. Therefore, we generated probability distributions around these annual mean projected values, using historical information on mean temperature and precipitation for roughly the past 75 years, provided by the University of Alaska Fairbanks' Geophysical Institute (UAF GI).

Specifically, we used a Gaussian multivariate Monte-Carlo simulation to proxy 50–75-year observed natural variability around the projected means. Greene discusses a technique to estimate multivariate normal probabilities given a specified mean (μ) and K-variate co-variance matrix (Σ) (Greene, 2003). Similarly, the SAS programming language has a command (i.e., VNORMAL) that generates a multivariate normal random series. This command allows us to use the projected means (μ) from the AOGCMs, along with the co-variances of the historical regional temperature and precipitation (Σ) measures, to generate preliminary likelihood probabilities around the climate projections (SAS (Statistical Analysis System), 2007).

This method does not take into account historical climate variability before the observed historical record. Forest et al. used natural variability to compute the noise co-variance matrix that was obtained for several AOGCMs. The authors point out that they ‘‘implicitly neglected the dependence of natural variability on climate sensitivity or ocean heat uptake’’ (Forest et al., 2002). This ‘‘dependence’’ will clearly influence the uncertainty of the AOGCM projections and the final likelihood estimation that policymakers need for robust analysis.

As examples, Figs. 4 and 5 show the results of our Gaussian Monte-Carlo numerical simulation, using the projected means and observed historical variances for two of the six locations—Juneau and Barrow—for which we had climate projections. The simulations in Fig. 4 are based on the warmest-model projections. Those in Fig. 5 are based on the warmer-model projections. Recent literature (e.g., Schar et al., 2004) has statistically tested the hypothesis that temperature variability may be increasing over time, using the increased mean temperatures being observed in Europe. However, we could not find conclusive academic literature describing similar long-run *increases* (i.e., 50 years or more) in natural variability for Alaska or other Arctic regions. Curtis et al. (1998) report that long-run precipitation frequency and intensity actually decreased for Barrow (and Barter Island) in northern Alaska. In addition, it was noted that variability of atmospheric pressure actually decreased over time. Therefore, we did not incorporate accelerating time trends in our distributions.

In their critique of the Stern Review, Carter et al. indicate that there is not enough empirical evidence to conclude whether extreme events are increasing in frequency or intensity (Carter et al., 2006). The authors point to the last IPCC report, implying through a selected quote that there is no evidence of a change in the frequency or severity of extreme events. However, the same IPCC report also concludes that:

> New analyses show that in regions where total precipitation has increased, it is very likely that there have been even more pronounced increases in heavy and extreme precipitation events…. Overall, it is likely that for many mid and high latitude areas, primarily in the Northern Hemisphere, statistically significant increases have occurred in the proportion of total annual precipitation derived from heavy and extreme precipitation events; it is likely that there has been a 2–4% increase in the frequency of heavy precipitation events over the latter half of the 20th century (IPCC, 2001, p. 33).

The method by which we capture the uncertainty associated with the climate projections is only the first step toward a more comprehensive approach to capturing theoretical uncertainty (i.e.,

[7] All layers were projected in Albers NAD1927, Datum, North American 1927.

[8] It is important to note that recent US congressional testimony detailed possible limitations when using global climate models to project regional climate (CEC (Committee on Energy and Commerce), 2002). Accordingly, empirical efforts are underway to address these limitations by ranking AOGCM performance at replicating Alaska's historical climate *and* statistically downscaling these regional results for inclusion in this impacts model.

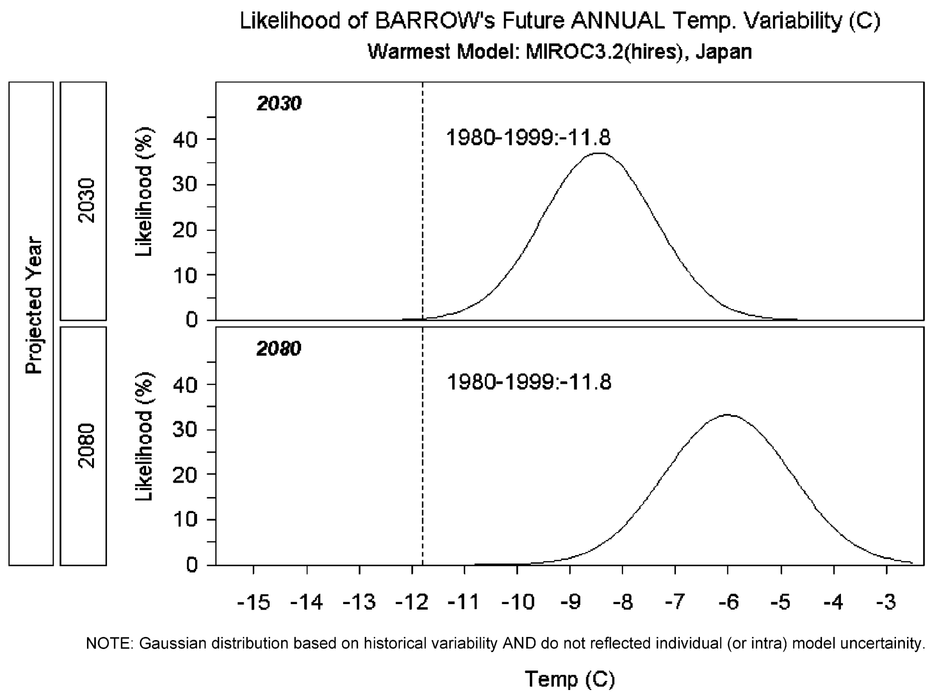

Fig. 4. Likelihood estimates of future climate: Barrow, Alaska, USA.

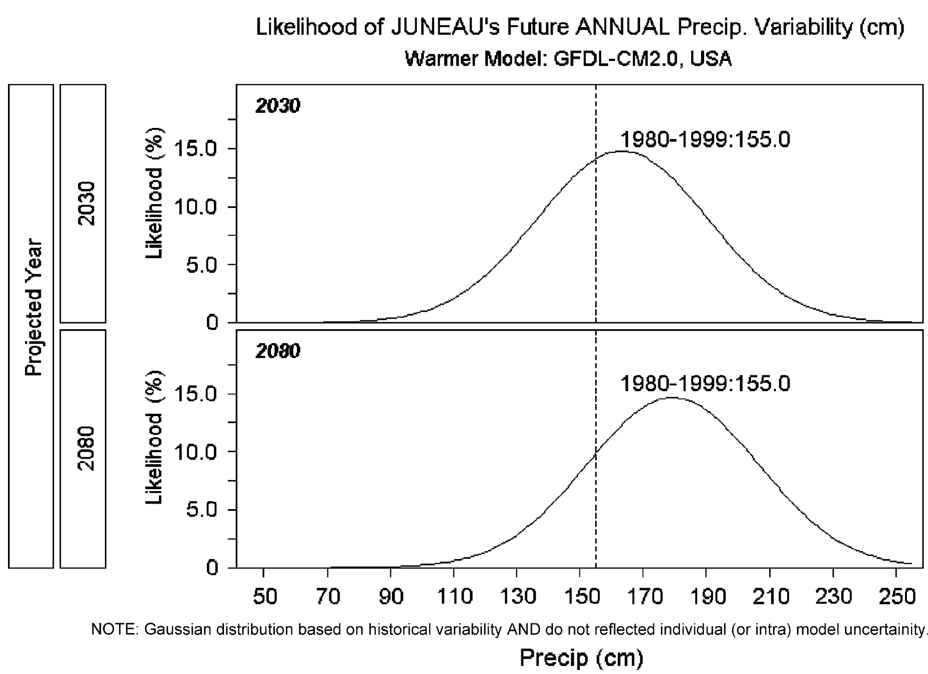

Fig. 5. Likelihood estimates of future climate: Juneau, Alaska, USA.

likelihood of future events), as suggested by probability theory and recent academic literature (Forest et al., 2002 and others). For example, alternative statistical distributions could be used around the mean projections to better proxy un-measurable or "long memory" climate processes (e.g., see Lavallee and Beltrami, 2004; Baillie, 1996). Furthermore, Mandelbrot and Hudson (2004) discuss the implications of using alternative, fat-tailed statistical distributions on predicting real-world economic behavior. Weitzman (2008) eloquently notes that fat-tailed structural uncertainty about climate change, coupled with a lack of information about high-temperature damages, can potentially outweigh the influence of discounting in a cost-benefit analysis framework. It is clear that relaxing the normality assumption with this Monte-Carlo simulation may generate more realistic likelihood estimates for both the climate and economic impact projections.

5. Inventory of Alaska's public infrastructure

The next step in our analysis was assembling a database of public infrastructure in Alaska. According to researchers at the Congressional Research Service, critical infrastructure is a term used to describe the "material assets" that are essential for society and the economy to function. In line with that definition, the cost calculations in this analysis are based on public infrastructure—assets owned by local, state, and federal governments that are critical for delivering goods and services communities depend on (Moteff et al., 2003).

We relied on many sources, including the Alaska State Office of Risk Management; the Denali Commission; and the Alaska Departments of Natural Resources, Transportation and Public Facilities, and Education and Early Development. The available information is not complete, and in some cases may not be accurate. Getting accurate information about all the public infrastructure in Alaska is difficult, for several reasons—including Alaska's huge size, security concerns in the aftermath of 9/11, and the fact that public agencies did not necessarily have reasons to collect and maintain that information in the past. Table 3 shows our preliminary count of public infrastructure statewide, as well as estimated useful life and replacement costs. There are about 350 cities, towns, and villages spread across the state's 152 million hectares. Some are on road systems or are regularly served by ferries or airlines. But many are far from regular transportation systems and are accessible by water only part of the year and by air taxis or charter airlines year-round, weather permitting. Different federal, state, and local agencies are responsible for the different types of infrastructure in all those diverse places. Fig. 6 helps illustrate just how scattered public infrastructure is in Alaska. It shows the general distribution of transportation infrastructure around the state—major roads, bridges, airports, harbors, and the Alaska Railroad. Other kinds of infrastructure are distributed in similar patterns.

We were not able to verify all the information for the hundreds of communities in our database. But we hope that when government agencies see the information we have so far, they will tell us what we are missing or what we have wrong.

Currently the database contains nearly 16,000 individual elements of public infrastructure in 19 categories. We placed each element in a category, identified it by location, and assigned it a useful life and replacement value. We also assigned each location a set of values associated with local permafrost conditions, susceptibility to flooding, and proximity to the coast (USACE (United States Army Corps of Engineers), 2006; USGS (United States Geological Survey), 2006). The infrastructure in our database has an estimated price tag of around $40 billion today. Much of that is in various types of transportation infrastructure—especially roads—which are expensive to build and maintain in Alaska. Sanitation systems are also expensive to build and very difficult to maintain in remote northern, western, and interior locales. The database clearly undercounts and undervalues some types of infrastructure, especially defense facilities and power and telephone lines. Information about the extent and value of defense facilities is often suppressed for reasons of national security. The database may also in some cases overcount infrastructure. Agencies often do not report replacement costs for infrastructure. Whenever possible, we got replacement costs from public agencies. But when no replacement cost was reported, we estimated, using average insured value or other available information. Information on the expected useful life and the actual age of infrastructure in Alaska is also scarce. For this initial work we made assumptions about the useful life of various types of infrastructure, based on information from the Alaska Division of Finance and personal communications with employees of government agencies and academic researchers. The length of "useful life" varies among different types of infrastructure, as Table 3 shows.

6. Estimation of annualized replacement costs for existing infrastructure, with and without the effects of climate change

6.1. Basic model structure

We combined the output from the climate models with the infrastructure database in a life-cycle cost model—the ISER

Table 3
Preliminary public infrastructure database[a]

Type of infrastructure	Count/length	Useful life (years)	Replacement cost per unit (in $2006)	Units	Replacement costs total (in $2006)
Airports	253	20	$20 million	Whole	$5.06 billion
Bridges	823/31.4 miles	40	$10,000	Per foot	$1.7 billion
Court facilities	42	40	$16 million	Whole	$678 million
Defense facilities[b]	178	40	$305,000	Whole	$54 million
Emergency services (fire stations, other)	233	20	$467,000	Whole	$108 million
Energy (fuel tanks, other structures off power grid)	234	30	$32,000	Whole	$7 million
Misc. gvt. buildings	1571	30	$1 million	Whole	$1.6 billion
Power grid (lines, transformers substations)[b]	68/768 miles of line	15	$100,000	Per mile	$77 million
Health buildings (clinics, other non-hospital facilities)	346	30	$1.6 million	Whole	$565 million
Harbors	131	30	$10 million	Whole	$1.3 billion
Public hospitals	18	40	$44.7 million	Whole	$806 million
Law enforcement (police stations, prisons, other)	66	30	$4 million	Whole	$259 million
Alaska railroad	45 structures/819 miles track	30	$2.8 million	Per mile	$2.3 billion
Roads	4564 miles paved/ 5000 miles unpaved	20	$1 million (unpaved) $3 million (paved)	Per mile	$18.7 billion
Schools	520	40	$2.5 million	Whole	$1.3 billion
Sewer systems	124	20	$30 million	Whole	$3.7 billion
Telecommunications (towers, satellites, other)	275	10	$300,000	Whole	$82 million
Telephone lines[b]	222 miles	15	$50,000	Per mile	$11.1 million
Water systems	242	20	$5 million	Whole	$1.2 billion
Total	15,665				$39.4 billion

Sources: Denali Commission; Alaska Departments of Transportation and Public Facilities, Administration (Risk Management), commerce, community and economic development, natural resources, education and early development; ISER.

[a] Compiled from publicly available information in 2006.

[b] The counts and the replacement costs in these categories are obviously low, especially for defense facilities. In part for security reasons, little public information is available about the size and value of defense facilities.

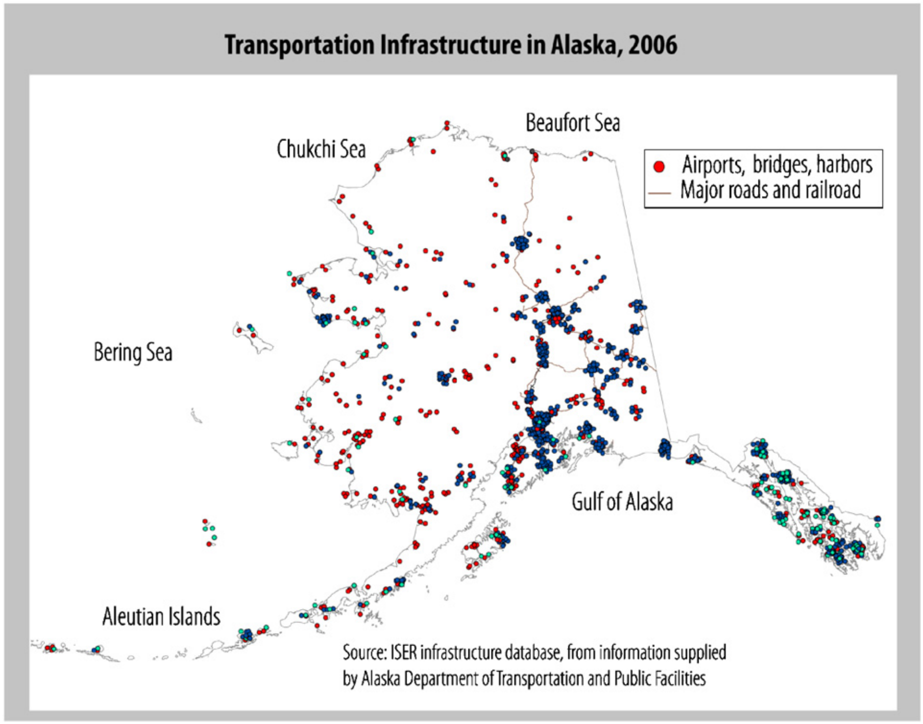

Fig. 6. Distribution of Alaska's transportation infrastructure.

Comprehensive Infrastructure Climate Life-Cycle Estimator (ICICLE). This model allows us to calculate the net present value cost of infrastructure at risk due to climate change, driven by changes in temperature and precipitation. That choice fits Professor Samuelson's definition of "True Economic Depreciation (TED)," as Rayner and Malone discuss in the context of the costs of inundation from sea-level rise (Samuelson, 1964; Rayner and Malone, 1998):

> True economic depreciation, modeled to start at some fixed time prior to [sea-level] inundation and to finish just when inundation would occur, is an appropriate representation of the maximally efficient market response to (known) risk of future sea-level rise. TED is, by definition, a representation of how the value of an asset declines over time as it moves toward its retirement from service (Rayner and Malone, 1998, p. 44).

r = Real Discount Rate
i = Year
j = Infrastructure Type

Base Case

$$\theta_j = \frac{\text{Replacement Cost j}}{\text{Basecase Useful Life}_j}$$

$$PV_{\text{Base}} = \sum_{j=1}^{20}\sum_{i=2006}^{2030} \frac{\theta_j}{(1+r)^{i-2006}}$$

Climate Change

$$\Delta_j = \frac{\text{Replacement Cost}_j}{\text{Adjusted Useful Life}_j}$$

$$PV_{\text{Climate Change}} = \sum_{j=1}^{20}\sum_{i=2006}^{2030} \frac{\Delta_j}{(1+r)^{i-2006}}$$

$$\Phi_{2030} = PV_{\text{Climate Change}} - PV_{\text{Base}}$$

Φ_{2030} = Additional Public Infrastructure Replacement Costs from Climate Change

Fig. 7. ICICLE model functional form.

The basis for the model is the calculation of the net present value of infrastructure replacement over time, under different conditions. For example, the average life span of a road might be 20 years. Therefore, if we know the current age of a particular road, we can estimate the number of times that road will have to be replaced in a given period. Calculating the base case replacement costs is simply a matter of taking the present value of the annualized replacement costs and aggregating them. Fig. 7 details the basic functional form for the ICICLE model.

We used a 7.25% nominal, or 2.85% real, discount rate in this analysis. We paid particular attention to the selection of a defensible discount rate, based on recent critiques of Stern (2006, 2007). Specifically, we calculated our real discount rate by subtracting the 30-year average Producer's Price Index (PPI) from the 30-year average of the Natural Resources Conservation Service's nominal discount rate for water resources projects (BLS (United States Bureau of Labor Statistics), 2007; USDA (United States Department of Agriculture), 2007). The Alaska branch of the US Army Corps of Engineers consistently uses the NRCS discount rates for its assessments of possible relocation projects, including its estimates of relocation costs for the communities of Shishmaref, Kivalina, and Newtok in western Alaska. We chose a market-based discount rate following the lead of the Corps of Engineers and after carefully considering the context of evaluating the costs of building public structures with public funds. There may be implicit benefits to society from building these structures, but this analysis narrowly focuses on the additional construction costs due to rapid climate change.

Using this base case scenario, and summing across all existing Alaska public infrastructure, we estimate it would cost \$32 billion (in net present value) to maintain and replace existing infrastructure through 2030 and \$56 billion through 2080. Those estimates do not take into account climate change: they represent the costs of ordinary wear and tear on Alaska infrastructure.

Our model assumes climate change will reduce the useful life of infrastructure, so that it has to be replaced sooner—and that costs will then be higher. (It is also possible, under some

Table 4
Examples of how increased temperatures and precipitation can harm infrastructure

Change in site conditions	Impact on infrastructure	Range of response actions
Thawing permafrost	Settlement of foundations	Repair, relocation, complete replacement at new site
Sea-level rise	Inundation of low-lying coastal property	Repair, build flood control works relocation, complete replacement at new site
Sea-level rise	Coastal erosion	Repair, build erosion control works, relocation, complete replacement at new site
Increased runoff	Flooding along rivers	Repair, build flood control works relocation, complete replacement at new site
Increased runoff	Stream bank erosion	Repair, build erosion control works, relocation, complete replacement at new site

circumstances, that climate change could actually increase the life of some infrastructure. In this initial work, we have not identified any such exceptions.)

6.2. Useful life adjustment coefficients

Warming air temperatures, increased precipitation, and storms result in environmental changes such as coastal erosion. Some examples of how climate change can harm infrastructure, as well as possible responses in the face of climate change, are listed in Table 4. The link between temperature and precipitation and secondary changes is complex and not easily characterized. For example, although global sea level rise is monitored, local projections for changes in sea-level vary widely and the effect will depend on conditions such as, in Alaska, tectonic upheaval and atmospheric pressure (Douglas and Peltier, 2002).

Furthermore, the responses required to maintain the quality of the infrastructure will depend on local site and infrastructure characteristics. Degradation may result in increasing costs for ordinary maintenance, for complete replacement of the facility at a different site, or for alternative responses. Buildings may require extraordinary maintenance and repairs to roofs, siding, windows and doors, plumbing, mechanical and electrical equipment, or other features due to deterioration of materials associated with freeze–thaw cycles. The most expensive damage will occur when a building's permafrost foundation thaws and settles. Buildings on the open coast may also experience more flooding and wave attack, because receding sea-ice cover allows more wave generation and coastal storm surge during increasingly frequent storms. Foundations of coastal and shoreline buildings erode faster during these storms, without the protection of shore-fast ice that was typical in previous decades. Buildings on riverbanks may experience more flooding from increased runoff or from ice jams induced by increased mid-winter thawing spells.

All these expenses, from increases in maintenance costs to costs for complete replacement at safer locations, are estimated here by the reduced useful life of the structure. Future enhancements of this work may distinguish more specific types of deterioration and more specific maintenance costs.

Both natural variability (weather) and systematic climate change affect the rate at which different classes of infrastructure depreciate (i.e., lose their useful value) over time. For example, increased flooding may undermine the foundation under a bridge, thus shortening the useful life span of the bridge from 50 years to 40 years or less. Excessive coastal erosion caused by intense storms can wash away roads, and warmer temperatures can cause permafrost layers to thaw, cracking building foundations. Climate-change effects are qualitatively discussed in the Arctic Climate Impact Assessment (Instanes et al., 2005). Quantitative predictions of effects on infrastructure are, however, rare (e.g., Soo Hoo et al., 2005).

We recognize and incorporate into our modeling the fact that the additional costs for infrastructure resulting from climate change depend on the presence of permafrost and the location of the infrastructure in relation to the coast or floodplains.

Table 5
Summary of reduction in useful life of infrastructure due to Thawing Permafrost[a]

Basic permafrost condition	Reduction of life (%) per °C increase
Continuous permafrost	0.9
Discontinuous permafrost	0.4
Sporadic permafrost	0.2
Isolated patches	0.0

[a] Treated independently from flooding or coastal exposure.

6.2.1. Presence of permafrost

Widespread thawing of permafrost is the most worrisome potential effect of climate warming on Alaska infrastructure (Nelson et al., 2003). Thawing across the region surrounding a building or a pipeline with a permafrost foundation will render ineffective thermopiles or other means of protecting the frozen ground from warming by the structure itself. Dramatic settlement will occur if the frozen ground has high ice content and fine soil grains. This type of soil is generally classified as "frost-susceptible" soil. Non-frost-susceptible soil has coarse grains of sand and gravel and does not lose as much bearing capacity when ice thaws in the pores.

In this analysis we consider two types of building response to thawing permafrost foundations: (1) dramatic settlement and complete loss of the facility that will occur for buildings over permafrost composed of frost-susceptible soil; and (2) moderate settlement requiring substantial repairs that will occur for buildings over permafrost composed of non-frost-susceptible soil. Structures not located on permafrost are not anticipated to experience settlement attributable to climate change. Buildings or other structures that require relocation are assumed to be moved to sites without risk of thaw settlement and thus regain their full useful life. Warming and precipitation effects on building materials—roofs and windows, for example—are not considered in this analysis.

Infrastructure's useful life consequently depends on its location in relation to permafrost and on temperature. Appendix A shows our assumptions about thaw settlement for infrastructure on the four basic categories of permafrost. In future work, we hope to conduct site-specific case studies to learn more. Table 5 is a summary of the reduction in useful life, per °C increase, of public infrastructure due to thawing permafrost.

6.2.2. Location of infrastructure in relation to coast or flood prone area

ISER's public infrastructure database notes coastal and riverside infrastructure and also categorizes some sites as "exposed," "protected," "interior," or "prone to flooding." Alaska coastal and riverine infrastructure is particularly vulnerable to flooding and erosion induced by climate change (e.g., see GAO (United States

Table 6
Summary of reduction in useful life of infrastructure due to coastal exposure[a]

Coastal location	Reduction of life (%) per °C increase
Exposed	13.5
Protected	1.8
Interior	0.0

[a] Treated independently from permafrost or flooding exposure.

Table 7
Summary of reduction in useful life of infrastructure due to flooding exposure[a]

Flood location	Reduction of life (%) per cm increase
Coastal	0.8
River	3.0

[a] Treated independently from permafrost or coastal exposure.

General Accounting Office), 2004). When the effects of climate change on coastal and riverine infrastructure are objectively quantified in future studies and distinguished from the many other causes for problems at coastal locations, we will have a basis for refining our approach. Table 6 shows the authors' judgments about reductions in life span of infrastructure with coastal exposure. Table 7 details the authors' judgments about reductions in life span of infrastructure with exposure to floodplains.

In this formulation of the model, the functional relationship between temperature precipitation and reduction in useful life is linear,[9] except at the "tipping point" where average annual temperature becomes greater than 0 degrees Celsius. That implies the cost of climate change could increase without bound for longer planning horizons. This approximation is sufficient for small changes over modest planning horizons. For the longer period to 2080, we de-coupled the "useful life adjustment coefficients" from the equations and held the values constant at the 2030 values. This approximation, in which the effects of climate change move northward across the state over time, is analogous to northward shifts in the southern limit of continuous permafrost.

6.2.3. *Extreme events scalar*

Yohe and Tol (2002) indicate that social systems typically respond to variability and "extreme events" before they respond to changes in the mean. Flooding, severe storms, and other extreme events will also influence the schedule of infrastructure replacement, but in a more discontinuous fashion. For example, floods undermine bridge foundations, and droughts (i.e., warmer than average temperatures with lower than normal rainfall) provide ideal conditions for wildfires that damage structures.

We assume an extreme event occurs when the temperature and precipitation are both in either the 1st or 99th percentile of the historical variance. In that event we use a simple scalar to accelerate the depreciation (or appreciation) by an additional 10%.

[9] It is highly likely that the relationship between climate drivers, including temperature and precipitation, and changes in a structure's useful life, are not of a linear functional form. Hitz and Smith (2004) surveyed the literature on the shape of climate change "damage curves" and concluded that these curves were non-linear at the global level. Additional research by the engineering community is needed to study these complex relationships by type of structure and local topography. "On the ground" case studies that monitor slight changes in the useful life of structures over time would give us valuable insights about a more appropriate shape for our damage function assumptions.

7. Strategic adaptation

7.1. *Background*

Agencies like the Alaska Department of Transportation and Public Facilities, as well as private companies, have historically designed and adapted structures for Alaska conditions, including underlying permafrost. They are likely to increase their efforts as the effects of climate change become more evident. In this section we discuss adaptation to climate change rather than building for current (or recent) climatic conditions.

A big example of how private industry has built for Alaska conditions is the trans-Alaska oil pipeline, constructed in the 1970s. Over much of the 800-mile pipeline route, Alyeska Pipeline Service Company installed thermosyphons (i.e., pipes that remove heat from the permafrost) near the vertical support members (VSMs), to dissipate heat away from the foundation of the pipeline. Of the nearly 80,000 VSMs, 61,000 were equipped with pairs of thermosyphons as of 2003. In 2001, the Joint State-Federal Pipeline Office indicated that at least 22,000 VSMs might be having problems caused by climate change along the pipeline route (USARC (United States Arctic Research Commission), 2003; JPO (Joint Pipeline Office), 2001).[10]

McBeath (2003) points out that there is no *formal* criterion for evaluating the long-term consequences of climate change on the Alaska transportation system. However, he does note that the agencies responsible for Alaska's roads, railroad, airports, and ferry systems do *consider* the effects of climate change on the permafrost layer and other factors when building and maintaining structures.

7.2. *Alaska climate change adaptive model*

We considered how the various kinds of responses to different natural disasters might apply to analyzing the effects of climate change on public infrastructure costs. Earthquakes are a regular occurrence in the US West, hurricanes are regular events in the Southeastern US, and floods make annual appearances in the US Midwest. Although these natural events are not directly analogous to climate change, the local, regional, and federal government responses that have been documented over the last several decades provide foundational models from which to anticipate the adaptation response that may occur in the case of climate change in Alaska.

7.2.1. *Adaptation to hurricanes*

The study of natural disaster response has been a priority for agencies such as the Federal Emergency Management Agency (FEMA), as they try to improve both recovery response and resilience of structures to natural events. Leaders in these studies have been the states of Florida and South Carolina, where hurricanes introduce a continuously evolving set of requirements and recommendations for improving structure resilience. Since Hurricane Hugo in 1989 and Hurricane Andrew in 1992, Florida and South Carolina have aggressively focused on improving the resilience of structures to major storms. Clemson University (Clemson, 1999) and the State of Florida (Florida, 1996, 2002) have generated major studies about the costs of adaptation and the adoption of proposed solutions.

7.2.2. *Adaptation to earthquakes*

California and other states where earthquakes occur frequently have also attempted to quantify the risks associated with adapting

[10] The oil pipeline is private infrastructure not included in this analysis. We talk about it only as an illustration of current designs for Alaska conditions.

structures to resist earthquake damage. These efforts have attempted to balance the cost of adaptation with the potential loss associated with earthquake damage (FEMA, 1995, 1998). The difficulty is balancing the cost of adaptation with the risk of earthquake exposure (Stein and Tomasello, 2004). As outlined in research efforts, the question of earthquake frequency and exposure needs to be balanced with regulations that require *forced* adaptation through building codes.

7.2.3. Adaptation to floods

The final adaptation response effort that seems a relevant model for climate change is the response to floods that occur regularly in the US Midwest (Aglan et al., 2004). This model differs from the previous two models in that flood response is primarily an *event-driven* model. In this form of model, adaptive responses are not put into place until there is a flood that significantly reduces the useful life of infrastructure. Local authorities determine when that threshold has been crossed. If they decide a specific flood did not reach that threshold, then they do not take any action, with the understanding that this event is part of the natural cycle. New structures are constructed with the same specifications as existing ones, since they are still considered the standard. By contrast, if there is a flood that exceeds what is considered part of the natural cycle, then a rapid adaptation response is put into place, resulting in a change of building codes that requires a stair-step increase in building costs. This response is seen as indirectly based on the rate at which states report and classify floods and the resulting responses to those reports (Pielke et al., 2002).

7.2.4. Event-driven adaptation model

For this analysis, we selected an *event-driven* adaptation model. The concept of an event-driven adaptation model is that adaptation research is being conducted, but no action is taken for a particular structure until damage reduces the life span enough to reach some critical threshold. Until that point, it is assumed additional repair money could maintain a reasonable useful life span. The threshold used in this model is 20%. We adopted that percentage based on a rule of thumb in planning—that once a building loses 20% of its useful life, economically it becomes more feasible to rebuild than repair. If the event threshold is achieved and the new structure is built with a full useful life value, then an additional 5% adaptation cost is incurred. However, the 20% event threshold and 5% additional adaptation cost should be considered assumed values for this model and not an absolute for every future scenario.

7.2.5. Adaptation example: water treatment services with single climate change exposure

In this example, we model a water treatment plant with an anticipated 20-year useful life, to illustrate a structure with a shorter life span and a single climate exposure. This figurative building is exposed to coastal flooding and minimum permafrost thawing. The base cost of the plant is $5 million per structure.

Fig. 8 shows the effect of climate change on the remaining lifespan of the structure, using three cases: the *base case*, showing lifespan if there were no climate change; the "*no-adaptation*" *case*, assuming moderate climate warming but no adaptation to that change; and the "*event-based*" *adaptation* case, assuming moderate climate warming with adaptations to reduce the effects of climate change. The base case, without climate change, requires four generations of structures to be built through 2080—one in 2006 and then one every 20 years after that. Bringing a discount factor into the scenario, the total cost of the four generations of the structure under the base case is $10.3 million.

When climate change is factored into the scenario, the structure loses useful life and this changes the present value replacement costs. The no-adaptation case requires three additional generations of the structure, for a total of seven. There is no investment in adaptation. The result of those extra generations is a cumulative cost of $14.8 million.

The no-adaptation and event-driven cases show the same reduction in life span through 2040. However, that changes as the scenario is taken further out, and in later generations the event threshold is met. In this example, the no-adaptation case results in seven generations of the structure being built, with the last generation having a useful life of only 6.4 years when it is built. However, the event-driven case deviates from this pattern, as the useful life threshold is met in 2040 and the structure is returned to its original useful life in this and later generations. In the event-driven case, there are additional costs for adaptation, but the overall cost is less than under the no-adaptation case. With an investment in adaptation, five instead of seven generations of the structure have to be built, with an overall cost of $12.3 million.

We analyzed all 19 categories of infrastructure identified for the Alaska climate change model, resulting in the adaptation parameters shown in Table 8. The table shows the cost savings from active adaptation to climate change under three climate projections. It shows, for example, that adapting airports to climate change, under the warmest climate projection, would cost just 85% as much as it would if there were no adaptations. Alternatively, we can say that adapting airports to climate change could save an estimated 15% over the next few decades.

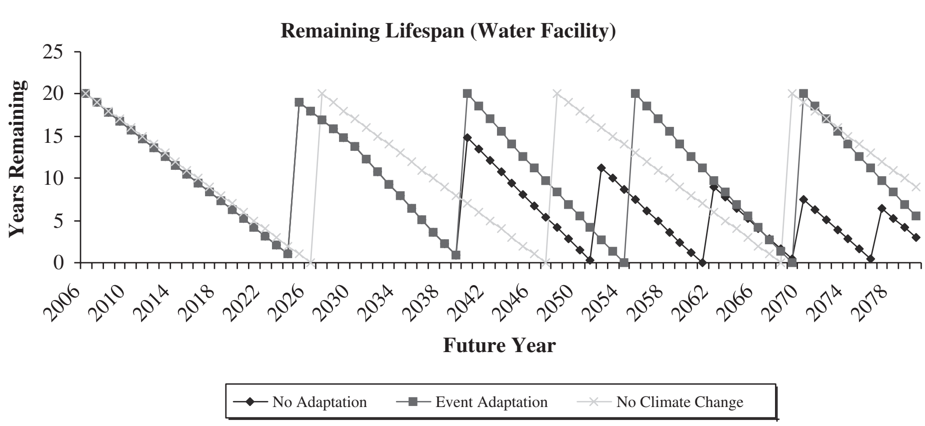

Fig. 8. Example of water facility life cycle: present to 2080 (with event-based adaptation).

Table 8
Ratio of total cost of infrastructure replacement with and without climate change adaptation

Public infrastructure classification	2006–2030			2006–2080		
	Warm (%)	Warmer (%)	Warmest (%)	Warm (%)	Warmer (%)	Warmest (%)
Airport	100	99	85	88	69	51
Bridge	100	98	88	91	74	60
Courts	100	100	100	99	82	67
Defense	100	100	100	99	85	69
Emergency services	100	100	100	100	86	70
Energy	100	100	100	99	85	68
Grid	100	99	90	93	81	65
Harbor	100	97	84	84	65	48
Hospital	100	100	100	99	78	62
Law enforcement	100	100	100	99	84	68
Misc. building (government)	100	100	100	99	85	70
Misc. building (public health)	100	100	100	100	85	69
Railroad	100	99	90	94	81	62
Roads	100	98	89	92	75	60
School	100	100	100	100	87	72
Sewer	100	98	84	87	68	49
Telecommunications	100	99	85	88	69	50
Telephone line	100	95	87	92	78	57
Water	100	98	84	87	69	50

Table 9
Additional public infrastructure costs from climate change ($billions of 2006 US Dollars, net present value)

Projected year	Ordinary wear and tear (no climate change)	Warm model		Warmer model		Warmest model		Potential savings from strategic adaptations (%)
		No adaptation	With adaptation	No adaptation	With adaptation	No adaptation	With adaptation	
2006–2030	$32	$3.6	$3.6	$6.1	$6.0	$7.0	$6.1	0–13
2006–2080	$56	$6.2	$5.6	$10.6	$7.6	$12.3	$6.7[a]	10–45

[a] Although it seems counter-intuitive, additional costs are estimated to be higher under the warmer model than under the warmest model by 2080. That's largely because the ICICLE model projects that in the long-run both the incentives for and the savings from adaptations would be greater under more rapid climate change than under more moderate climate change.

8. Alaska's public infrastructure at risk from climate change

8.1. Background on terminology

Within the context of climate change, there has been a significant amount of recent literature devoted to formally defining what it means for social systems to have *adaptive capacity*, *resilience*, and *vulnerability*. Smit and Wandel (2006) point out that in impact studies, adaptations are often hypothetical and their effect on the social system is estimated relative to the calculated raw impacts. These authors also indicate that the term *vulnerability* has "sometimes been used to describe the estimated net or residual impacts (initial impact costs minus net adaptation savings)" (Smit and Wandel, 2006, p. 284). Yohe and Tol (2002) and Adger (2006) indicate that vulnerability to environmental change is an extraordinarily complex function of system sensitivity, exposure, and adaptive capacity. Adger (2006) states that vulnerability is not "easily reduced to a single metric and is not easily quantifiable" (Adger, 2006, p. 274). For lack of a better term, we use the term *infrastructure at risk* to denote the additional costs to public infrastructure from projected climate change net of event-based structural adaptation. In this section, we present our additional cost estimates with and without the event-based adaptation scenario.

8.2. Results

Table 9 shows estimates of additional costs both with and without strategic adaptations to climate change. Even without climate change, maintaining and replacing infrastructure in Alaska is an expensive proposition—costing an estimated $32 billion between now and 2030 and $56 billion by 2080—as the first column of Table 8 shows. The additional costs resulting from climate change are the averages under each of the three climate projections, and it is most probable that costs would be close to those averages. But there is some chance that the additional costs could be much higher or much lower than the averages. That is because in reality temperatures and precipitation in any given year vary from the averages. The three climate projections we used project trends in temperature and precipitation—but there will inevitably be years when either temperature or precipitation, or both, will be higher or lower than the trend projection. As noted earlier, our model uses historical observations to project how additional infrastructure costs might vary, when temperature and precipitation differ from the projected average. We did repeated model runs—up to 100 for each climate projection—to estimate the range of possible costs. Fig. 9 shows our preliminary estimates of the range of possible additional costs from climate change, taking likely adaptations into account, under each climate projection for the years 2030 and 2080.

Projected climate change could add 10–20% to infrastructure costs by 2030 and 10–12% by 2080, under different climate projections and taking design adaptations into account. The additional costs are relatively higher in the short run, because agencies have not had as much time to adapt infrastructure to changing conditions.

It is important to note that strategic design adaptations have much more potential to reduce extra costs in the long-run. Between now and 2030, adaptations might reduce costs related to

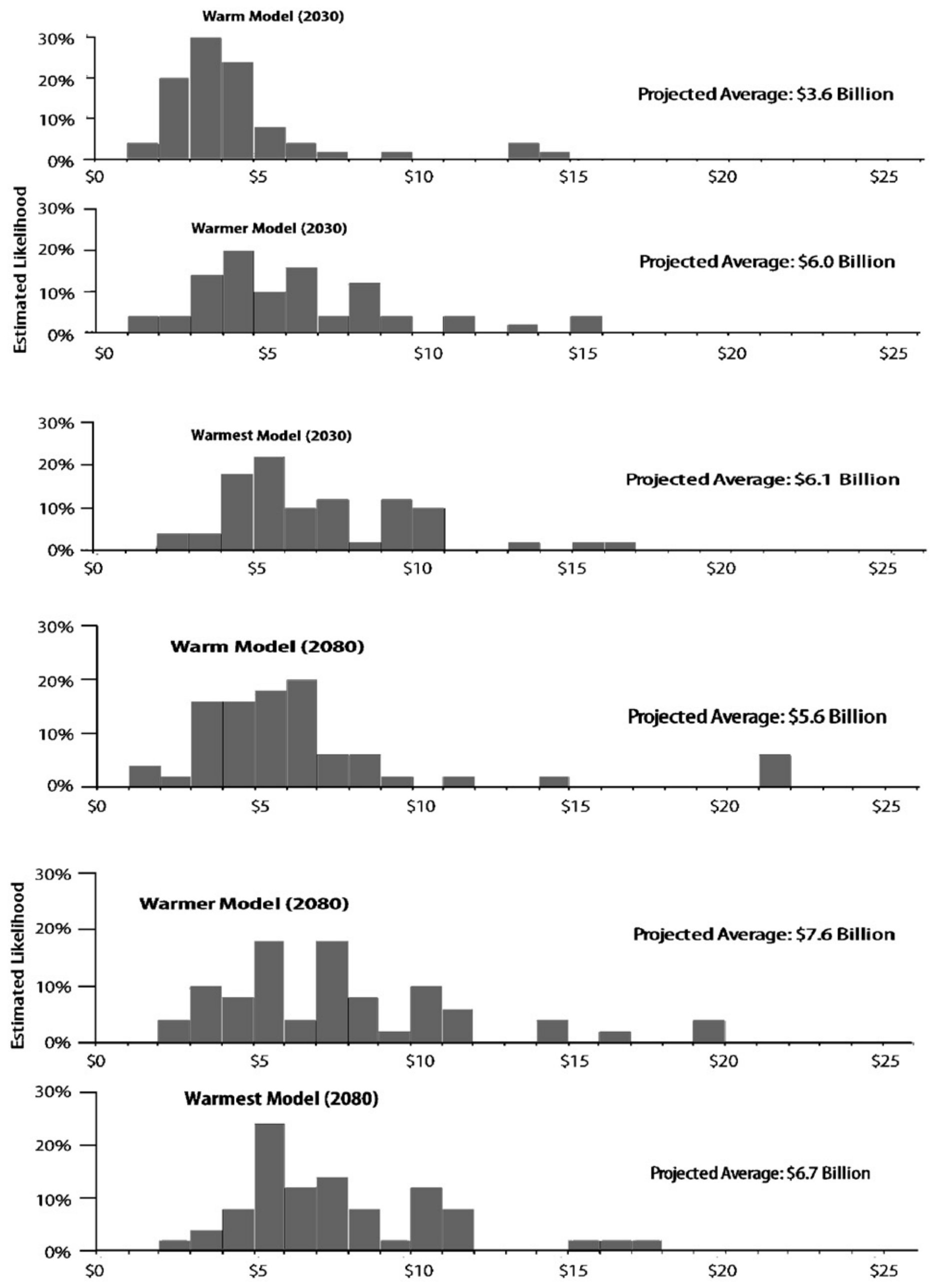

Fig. 9. Preliminary likelihood of additional costs to Alaska public infrastructure from projected climate change: 2030 and 2080 ($billions of 2006 US dollars; assumes event-based adaptation).

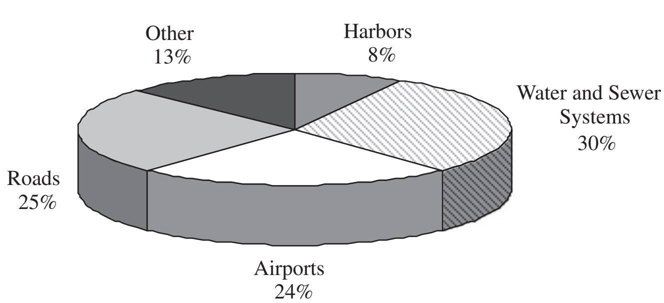

Fig. 10. Likely share of additional costs by infrastructure type (2030).

climate change by anywhere from zero to as much as 13%, depending on the extent of climate warming. But between now and 2080, adaptations could save anywhere from 10% to 45% of costs resulting from climate change.

As Fig. 10 indicates, transportation infrastructure—especially roads and airport runways—will account for most of the additional costs between now and 2030. That's because transportation infrastructure is expensive to build and maintain in Alaska under any circumstances, and many airports and some roads are in areas that will be most affected by a warming climate. But water and sewer systems—which are very expensive to build and difficult to maintain in areas with a lot of permafrost—will also account for nearly a third of the costs resulting from climate change by 2030.

9. Directions for future research

We plan to improve both our modeling techniques and cost estimates in the future. To make those improvements, we need more information about existing infrastructure. We also need to refine our methods for estimating effects of climate change on building conditions and to learn more about techniques for adapting infrastructure. The climate projections we used are among the best available today—but as time goes on scientists will learn more about climate trends and will update their projections. We are publishing these estimates, even though they are preliminary, because they show the magnitude of extra costs agencies could face and the potential value of efforts to adapt to climate change. We also hope they will stimulate more efforts to better understand and measure the problem. We anticipate that continuing research in a number of areas will allow us to refine our model and the cost estimates, both for the state as a whole and for regions and particular types of infrastructure.

9.1. Climate projections

As time passes, we will need to get new climate projections. We hope the next generation of climate projections will be available for smaller geographic areas and will be ranked according to their ability at replicating Alaska's highly variable climate.

9.2. Alaska public infrastructure database

We need more complete information about the count, the assumed useful life, the age, and the average replacement costs of public infrastructure in Alaska. What we have currently is a good start toward creating the first comprehensive database of federal, state, and local infrastructure in the state. Also, as time goes on and more public infrastructure is built, we need to work with public agencies to make sure new infrastructure is added to our database.

9.3. Changes in building conditions

We also would like to learn more about how changing building conditions resulting from climate change affect the life-cycle costs for infrastructure and we need better information about how building on permafrost affects soil temperatures, regardless of climate change.

9.4. Plausible adaptation scenarios

We need more information about the array of techniques that could be used to adapt infrastructure to changing climate conditions. What would specific adaptations cost? And which would not only ameliorate the effects of climate change on infrastructure but also be cost-effective?

10. Conclusion

Until now, a majority of the studies detailing the potential effects of climate change have focused on how natural systems are likely to be affected. But our preliminary estimates of how climate change might increase future costs for Alaska's public infrastructure show that the potential risks for man-made systems are also considerable. We plan to continue our study of the potential economic costs of climate change—and we hope to learn more from other researchers doing similar work worldwide.

Acknowledgments

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Appendix A. Assumptions about thaw settlement of facilities on permafrost

A.1. Facilities on continuous permafrost

- 95 percent of infrastructure is on permafrost ($pf = 0.95$).
- 5 percent of infrastructure is not on permafrost and will not settle ($npf = 0.05$ and $loss = 0.0$).
- 50 percent probability that soil is frost susceptible ($fs = 0.5$ and $nfs = 0.5$).
- No permafrost thaws until average annual temperature exceeds 32 °F (0 °C).
- 20 percent increase in chance of consequences occurring with each 1 °F/0.56 °C rise above 32 °F/0 °C ($cf = 0.2$).
- Infrastructure age ranges uniformly from new to the last year of its normal useful life ($age = 0.5$).
- Dramatic thaw settlement occurs in frost susceptible soil that renders infrastructure unusable and its full value is lost ($loss = 1.0$).
- Moderate thaw settlement occurs in non-frost-susceptible (NFS) soil, requiring repairs equivalent in cost to 10 percent reduction in remaining useful life ($loss = 0.1$).

A.2. Facilities on discontinuous permafrost

- 70 percent of infrastructure is on permafrost ($pf = 0.7$).
- 30 percent of infrastructure is not on permafrost and will not settle ($npf = 0.3$).
- 50 percent probability that soil is frost susceptible ($fs = 0.5$ and $nfs = 0.5$).
- No permafrost thaws until average annual temperature exceeds 32 °F (0 °C).
- 10 percent increase in chance of consequences occurring with each 1 °F/0.56 °C rise above 32 °F/0 °C ($cf = 0.1$).
- Infrastructure age ranges uniformly from new to the last year of its normal useful life ($age = 0.5$).
- Dramatic thaw settlement occurs in frost susceptible soil that renders infrastructure unusable and its full value is lost ($loss = 1.0$).
- Moderate thaw settlement occurs in non-frost-susceptible (NFS) soil, requiring repairs equivalent in cost to 10 percent reduction in remaining useful life ($loss = 0.1$).

A.3. Facilities on sporadic permafrost

- 30 percent of infrastructure is on permafrost ($pf = 0.3$).
- 70 percent of infrastructure is not on permafrost and will not settle ($npf = 0.05$).
- 50 percent probability that soil is frost susceptible ($fs = 0.5$ and $nfs = 0.5$).
- 10 percent increase in chance of consequences occurring with each 1 °F/0.56 °C rise above 32 °F/0 °C ($cf = 0.1$).
- Infrastructure age ranges uniformly from new to the last year of its normal useful life ($age = 0.5$).

A.4. Facilities on sporadic permafrost (cont.)

- Dramatic thaw settlement occurs in frost susceptible soil that renders infrastructure unusable and its full value is lost ($loss = 1.0$).
- Moderate thaw settlement occurs in non-frost-susceptible (NFS) soil, requiring repairs equivalent in cost to 10 percent reduction in remaining useful life ($loss = 0.1$).

A.5. Facilities on isolated patches of permafrost

- Assume this area experiences no significant impacts on buildings from climate change-related thawing of permafrost.

An example of the calculation of the relationship between mean temperature and infrastructure useful life, based on these assumptions, is shown below.

Weighted average by area for buildings on continuous permafrost:

$$\frac{npf(loss) + pf(fs)[age(loss)(cf)] + pf(nfs)[age(loss)(cf)]}{1.00}$$
$$= \frac{0.05(0) + 0.95(0.50)[0.5(1.0)(0.2)] + 0.95(0.50)[0.5(0.1)(0.2)]}{1.00}$$
$$= 0.005$$

Appendix B. ICICLE model characteristics

Model component	Assumption
Functional form	Probabilistic life-cycle analysis
Discount rate	2.85%/year (real)
Base year	2006
Projected years	2030, 2080
Public infrastructure count	15,665 Pieces
Public infrastructure value:	$39.4 billion ($2006)
Infrastructure base costs (per unit)	See Table 3
Infrastructure useful life by type	See Table 3
Depreciation matrix version	January 31, 2007
Climate projection regions	$5.6^\circ \times 5.6^\circ$ grid box centered at Anchorage, Barrow, Bethel, Juneau, Fairbanks, and Nome
IPCC SRES scenario	A1B
Preferred climate models	CSIRO-Mk3.0 (Australia), MIROC3.2.(HIRES) (Japan), and NOAA.GFDL-CM2.0 (US)
Climate model base years	1980–1999
Observed climate variability data source	University of Alaska Fairbanks Geophysical Institute
Distribution shape for observed regional climate	Gaussian
Extreme climate events probability	Less than 1st percentile, greater than 99th percentile (for observed range of climate)
Extreme climate events scalar	+10% Increase in impact to useful life
Natural variability forward in time	Static at observed regional annual variances
TAPS included in results	No
Event-based adaptation	Yes
Infrastructure growth forward in time	Static at 2006 count (i.e. 15,653)
Permafrost state forward in time	Static at 1965 location (USGS)
Impacts from changes in relative sea-level	Implicit, but not locally projected
Software system	SAS 9.1 TS Level 1M3, XP_PRO Platform
Hardware system	Dell Dimension 8300 (intel pentium 3.06 GHz; 500 GB hard drive)

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