Supplement 1*:* Diamond Mine Ice Roads: Computing Expected Costs

The Northwest Territories (NT) Transportation Department builds, maintains, and oversees about 2,200 km of ice roads each winter that service remote communities (Fig. S1-1). In addition, commercial ice roads are built to access remote mines, including the diamond mines discussed in the text. The ice road to the diamond mines is built by a joint venture company (http://www.jvtcwinterroad.ca/jvwr/), a partnership between de Beers, BHP, and Rio Tinto mining companies. The commercial ice road is wider and carries heavier loads than its government counterparts, but is still regulated by the NT government. Over 80% of both types of ice roads run on frozen lakes. The commercial ice road achieved a certain amount of notoriety when it appeared in Season 1 of the popular reality TV show, *Ice Road Truckers.*

Figure S1-1: The ice road system (black dashed lines) in the Northwest Territories, Canada. The commercial road to the diamond runs NNE from Yellowknife.

Only a limited record of season open length is available for the commercial ice road, so we had to develop a longer climate time series based on weather records. We did so by modeling the freezing of lake ice, with and without snow plowing, from which we then computed ice road opening and closing dates for the period 1943-2012. For the ice thickening part of the model we used the parameterized ice freezing equation developed by (Pfirman et al., 2004), in which the daily increase in ice thickness in meters (Dh_{ice}) is controlled by the air temperature (T_{air}, °C) and the snow and ice thickness:

$$\Delta h_{ice} = 86400 \cdot (-T_{air} / L_{freezing}) \cdot \frac{k_{ice} \cdot k_{snow}}{\left(k_{ice} \cdot h_{snow} + k_{snow} \cdot h_{ice}\right)} \quad \text{[Equation S1-1]},$$

where $L_{freezing}$ is the latent heat of freezing of freshwater (3 X 10^8 J m^{-3}), h_{snow} is snow depth, and h_{ice} is the existing ice thickness. Daily increments of ice thickening computed using Equation [S1-1] were accumulated to produce a running total of ice thickness through the winter season. Air temperature and snow depth data came from the Yellowknife airport, available from http://climate.weather.gc.ca/index_e.htm.

To tune and test Equation [S2-1] we used paired ice thickness and snow depth values collected by the Canadian government on the lake ice of Back Bay near Yellowknife (http://www.ec.gc.ca/glaces-ice/). When tuning the model, the thermal conductivity of fresh water ice (k_{ice}), which does not vary much, was held fixed at 2.3 W m^{-1} K^{-1} (Slack, 1980), while the thermal conductivity of the snow (k_{snow}) was adjusted until modeled ice thickness matched observed thickness. Snow thermal conductivity varies with snow density and texture (Sturm et al., 1997), data not available for the ice roads. Changing snow conditions result in year-to-year variations in k_{snow}. The tuning results (Table S1-1) indicate an average value of 0.216 W m^{-1} K^{-1}, which corresponds with a bulk snow density of 0.38 g/cm^3. That density is typical of a moderately hard wind slab, a realistic type of snow cover for Arctic lakes (Sturm and Liston, 2003). Using this average value and Equation [S1-1] produced satisfactory agreement between observed and modeled ice thicknesses for all 37 cases in which we had both snow depth and ice thickness (Fig. S1-2).

Table S1-1: Tuned values of k_{snow} based on snow and ice measurements from Back Bay

Year	k_{snow}	Year	k_{snow}	Year	k_{snow}
1960	0.29	1972	0.23	1984	0.18
1961	0.32	1973	0.2	1985	0.19
1962	0.29	1974	0.19	1986	0.25
1963	0.22	1975	0.16	1987	0.15
1964	0.28	1976	0.19	1988	0.24
1965	0.26	1977	0.22	1989	0.25
1966	0.29	1978	0.19	1990	0.2
1967	0.22	1979	0.18	1991	0.22
1968	0.24	1980	0.16	1992	0.16
1969	0.08	1981	0.21	1993	0.28
1970	0.27	1982	0.10	1994	0.18
1971	0.22	1983	0.22	1995	0.2
				1996	0.28
average:	**0.216**	W/m K			
std. dev.	**0.053**	W/m K			

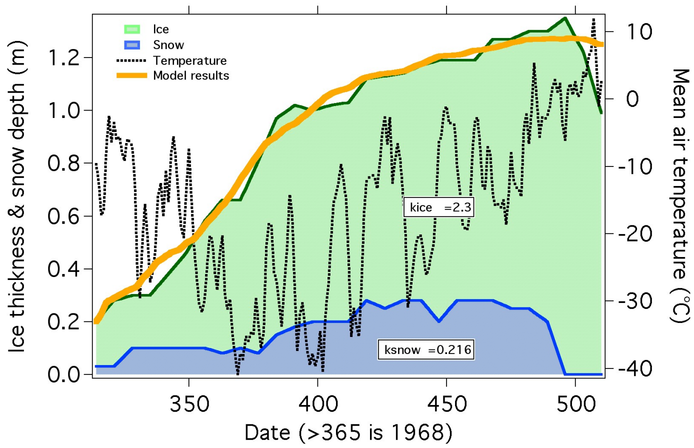

Figure S1-2: Model results (gold line) compared to measured ice thickness (green fill) at Back Bay for the winter of 1968 using the average value of k_{snow}. Snow depth data are from Back Bay; air temperature data from the Yellowknife airport.

Removal of snow by plowing is the only practical way to create thicker ice over a long route. We simulated plowing by essentially reducing the snow depth to zero. This could not happen until the ice was thick enough through natural growth to support a plow vehicle. Typically, a Bombardier BR-275 Snocat with plow is used for this work. It has a curb weight of approximately 8000 kg and requires a minimum of 0.45 m of ice for support. We applied a safety margin (35%) to account for the fact that the plowing would traverse a long route with uncertain ice conditions in some locations. Consequently, in our model plowing begins when there is 61 cm of ice. Further, since plowing a 450-km long ice road (even with multiple plow vehicles) takes a finite amount of time, we simulated a delay in the plowing by reducing the snow depth to zero linearly over a 7-day period. Model runs with shorter (2 days) and longer (10 days) delay times had only a minimal impact on the ice road opening date. Mathematically, the delayed reduction in snow depth was achieved by increasing the snow thermal conductivity until it was ten times the normal snow value. In the model the snow was plowed only once and then it was assumed that any additional snow was removed instantaneously. This assumption is realistic because once the road is in place and cleared of initial snow, snow removal by casting plow trucks can be started. These can clear snow much more rapidly than the initial pass done by the Snocats.

We based the road opening criterion on discussions we held with the operators of the Tibbitt to Contwoyto Joint Venture Winter Road (TCWR) and the NT government officials who operate the community ice roads. In point of fact, these ice roads "open" when the ice is thick enough to support a given vehicle load (P[kg]) as predicted by the Gold formula (Gold, 1971):

$$P = A \cdot h^2 \qquad [S1\text{-}2].$$

where A is a safety factor set to 4 for government ice roads and 6 for the commercial ice roads, and h is the ice thickness (cm) from Equation [S1-1]. A higher value of A is allowable for the commercial road because the operators can control the speed, load, and frequency of transits, while their government counterparts cannot. Moderate-sized trucks, cars and other light vehicles can begin to transit the ice road immediately after it is plowed, but they can only carry limited cargo, so for purposes of computing load-carrying capacity on the commercial road, the opening is when a truck (semi or a Super-B, which is slightly larger than a semi) can transit the road. In most model years the opening for these two types of trucks is separated by just a few days. For simplicity, we assumed haulage began when the ice reached the thickness required for Super-B (85 cm for A=6: Table S1-2). The difference in accumulated carrying capacity proved negligible because the larger cargo capacity of the Super-B quickly offset any loss in road-open time due to the later Super-B opening date.

Table S1-2: Vehicle weights, Load capacity and Ice thickness

Vehicle	Curb Weight (kg)	Load Capacity (kg)	Gross Weight (kg)	Ice (A=4) (cm)	Ice (A=6) (cm)	Safety Factor 35%
Snowmobile (Skandic WT)	318	0	318	9	7	
Bombardier BR-275 Snocat	8133	0	8133	45	37	61
Ford F-350	3182	1818	5000	35	29	
Fuel truck (1000 gallons)	5000	2727	7727	44	36	
Fuel Truck (2800 gallons)	7273	7636	14909	61	50	
Semi tanker (9000 gallons)	9091	27273	36364	95	78	
Semi: 18-wheeler	9091	27273	36364	95	78	
Super-B	9091	34545	43636	104	85	

Figure S1-3 shows a typical model result with plowing. At the start of plowing the worked ice thickness (red) begins to exceed the natural ice thickness (gold). This results in a Super-B opening date 28 days earlier than would have been the case without plowing and 0.48 m more ice than would have occurred naturally (essential work effort harvesting the ecosystem service sooner). For the 70 years for which we ran the model the ice due to plowing was on average 0.32 m thicker, an increase of 30% over natural ice (Fig. S1-3).

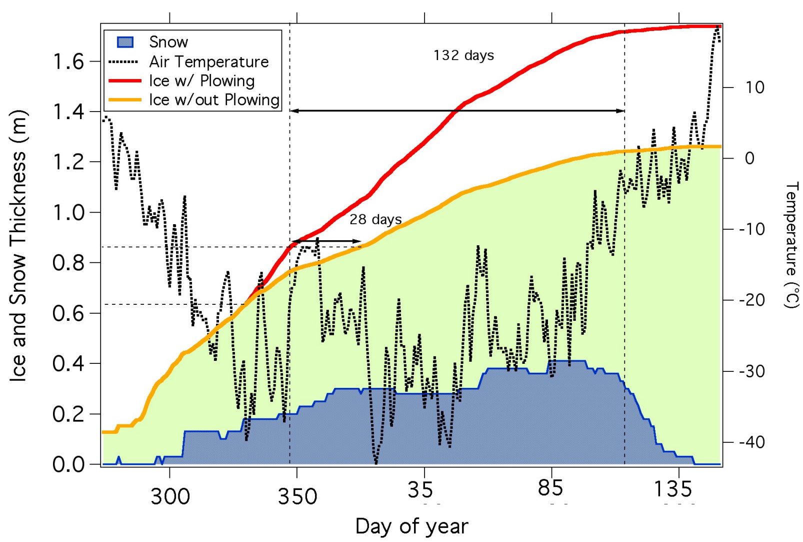

Figure S1-3: Model results for 1967 weather data. Plowing started when there was 0.61 m of ice. At 0.85 m, the road opened for super-Bees. It closed (April 24th) thirteen days before consistent above-freezing temperatures were observed. The plowing created ice that was 0.48 m thicker than natural and allowed the ice road to open 28 days earlier than would otherwise have been possible. 1967 was a very good year for ice roads: there was little snow overall, particularly in early season, when low temperatures occurred.

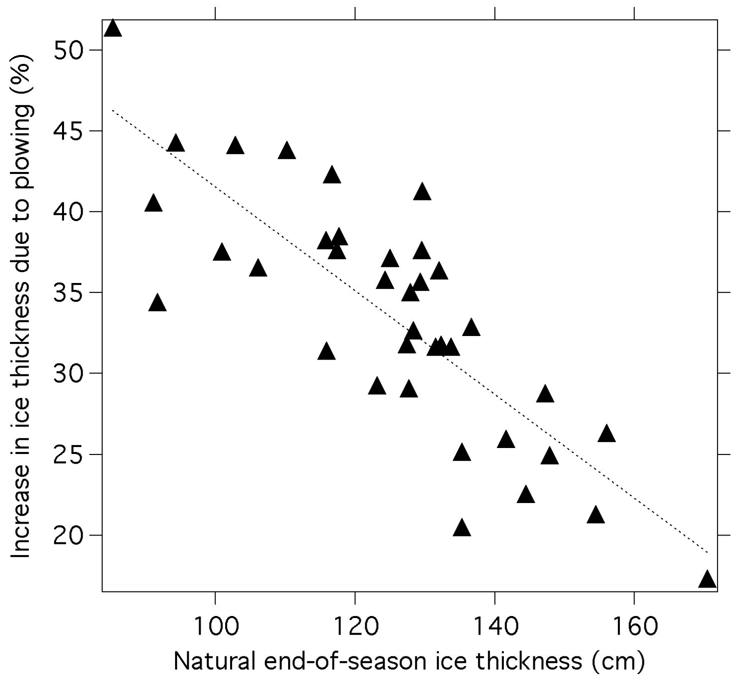

Figure S1-4: Model results showing the percent increase in ice thickness due to removal of snow by plowing. The effectiveness of plowing increases in winters when natural ice thickening (x-axis) is reduced.

Modeling the date the ice road closed was more difficult because "official" closure dates reflect when all material has been hauled up the road, not when the road is physically incapable of being used. The official closure can occur weeks before the latter condition is realized. Sunny, above-freezing weather produces snow rutting, stuck trucks, and damage to the underlying ground on the portages. This is generally what causes the ice road to close physically. The softening of the snow in a gully just a few tens of meters wide is sufficient to close the whole road. These bad spots arise from vagaries in snow and ice conditions, as well as local weather anomalies, but we had no choice but to model the system using weather data from Yellowknife as a proxy for conditions across the whole road. The match between model results and observed closing dates was limited.

To better simulate closing dates, we examined the closure date of the 7-km long ice road that connects Yellowknife to Dettah, a small aboriginal community across Yellowknife Bay from the capital. Unlike the other ice roads, this road is used by cars and trucks right up until it physically can no longer be used. We computed the date of the start of the thaw based on Yellowknife airport weather data (defined as 3 consecutive days of above-freezing temperatures), then compared the actual road closure date to this thaw metric. As expected, the road closed well before the onset of consistent above-freezing temperatures due to solar effects and local warm pockets. The results (Fig. S1-5) show that the road closed on average 13 days before the weather records indicated a consistent thaw. We then applied this offset to the Yellowknife records for 1943-2012 to produce a time series of closing dates. Combining the opening and closing dates, we computed the Super-B season length, 1943-2012 (Table S1-3).

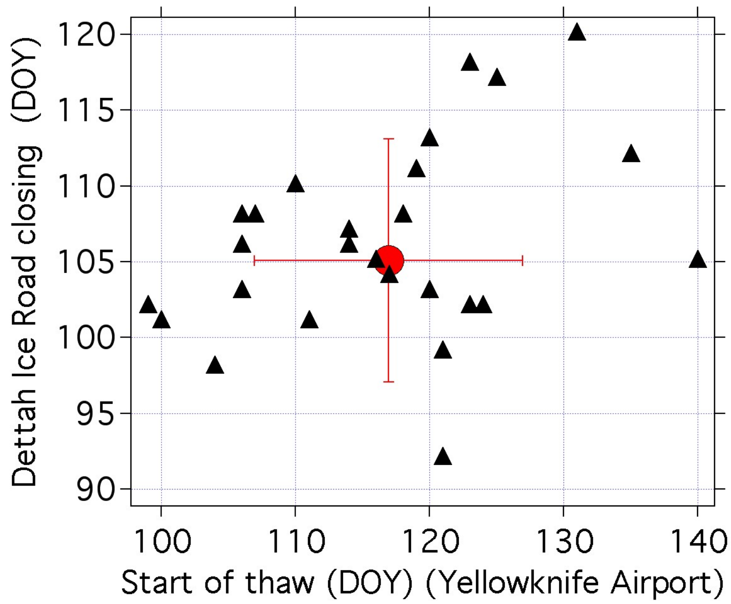

Figure S1-5: Closing dates for the Dettah ice road compared to dates of the onset of the spring thaw in Yellowknife. The red circle marks the average value for both parameters. They differ by 13 days. DOY=day of year.

In the simulated season length time series (1943-2012) we found considerable year-to-year variability and a strong secular trend driven by recent higher winter temperatures and more, and earlier, snowfall (Fig. S1-6). We de-trended the data, then used the residuals (top, Fig. S1-6) to create a trend-free time series. In order to preclude negative season lengths and to match current conditions, we offset the residuals by an amount (+47.3 days) sufficient that the model season length for 2012 equaled the observed season length.

In the simulated time series for road open and closing dates, the mean number of days open dropped from 100 (in 1943) to 50 (in 2012). We removed this trend (-0.76 days per year) by fitting a line to the data then using the residuals from the fit. To these residuals we added a fixed offset of 47.3 days to produce a de-trended but realistic season length record. The offset is the amount needed to match the observed season length of 2012, which allows us to check our calculations against the 10-year observed record. De-trending reduced the standard deviation by 3.3 days (since some of the variance was due to the trend). We then used this offset and de-trended series for our calculations. We note that the de-trended series had 9 (out of 70) years (13%) in which there was a “negative” season length. These were truncated to zero, which introduced an insignificant shift in the computed series mean (49.3) and reduced the standard deviation (30.3) by a further 10%, making the resultant series realistic but conservative for variance.

Table S1-3: Ice Road Open Season Length, 1943-2012

	Opening Dates			Closing Dates	Season Length		
Winter	Bombardier	Semi	SuperB	All	Bombardier	Semi	SuperB
1943	352	364	369	97	110	98	93
1944	361	373	380	89	93	81	74
1945	355	364	368	121	131	122	118
1946	326	339	344	103	142	129	124
1947	375	389	395	106	96	82	76
1948	343	352	360	109	131	122	114
1949	337	345	348	104	132	124	121
1950	353	363	367	107	119	109	105
1951	342	355	360	105	128	115	110
1952	333	344	349	102	134	123	118
1953	358	373	377	107	114	99	95
1954	351	364	367	112	126	113	110
1955	366	381	388	101	100	85	78
1956	349	363	371	112	128	114	106
1957	408	435	461	109	66	39	13
1958	404	433	463	112	73	44	14
1959	352	365	370	121	134	121	116
1960	408	431	442	98	55	32	21
1961	410	427	435	125	80	63	55
1962	376	394	401	121	110	92	85
1963	369	381	387	89	85	73	67
1964	386	399	409	109	88	75	65
1965	347	356	360	103	121	112	108
1966	387	400	407	114	92	79	72
1967	330	342	347	127	162	150	145
1968	384	397	402	113	94	81	76
1969	375	387	392	106	96	84	79
1970	350	364	372	93	108	94	86
1971	335	341	345	97	127	121	117
1972	370	384	391	116	111	97	90
1973	393	415	425	104	76	54	44
1974	372	387	394	114	107	92	85
1975*	393	461	461	96	68	0	0
1976	399	422	433	84	50	27	16
1977	342	353	359	101	124	113	107
1978	355	372	380	106	116	99	91
1979	351	366	375	117	131	116	107
1980	397	419	427	96	64	42	34
1981	372	397	405	106	99	74	66
1982	369	378	382	122	118	109	105
1983	343	359	365	98	120	104	98
1984	348	355	359	94	111	104	100
1985	351	361	366	109	123	113	108
1986	418	447	465	110	57	28	10
1987	326	338	343	103	142	130	125
1988	401	417	432	128	92	76	61
1989	345	362	367	104	124	107	102
1990	365	384	393	111	111	92	83
1991	363	382	393	110	112	93	82
1992	403	431	454	108	70	42	19
1993	361	373	381	108	112	100	92
1994	367	377	381	105	103	93	89
1995	411	428	436	106	60	43	35
1996	333	342	346	102	134	125	121
1997	355	367	372	93	103	91	86
1998	385	407	420	93	73	51	38
1999	378	394	401	108	95	79	72
2000	380	406	414	98	83	57	49
2001	431	475	475	110	44	0	0
2002	405	430	438	118	78	53	45
2003	389	399	406	94	70	60	53
2004	387	404	413	123	101	84	75
2005	386	406	417	98	77	57	46
2006	425	466	466	101	41	0	0
2007	379	403	412	86	72	48	39
2008	409	441	453	88	44	12	0
2009	418	443	463	107	54	29	9
2010	367	383	395	91	89	73	61
2011	365	379	384	112	112	98	93
2012	387	410	421	106	84	61	50

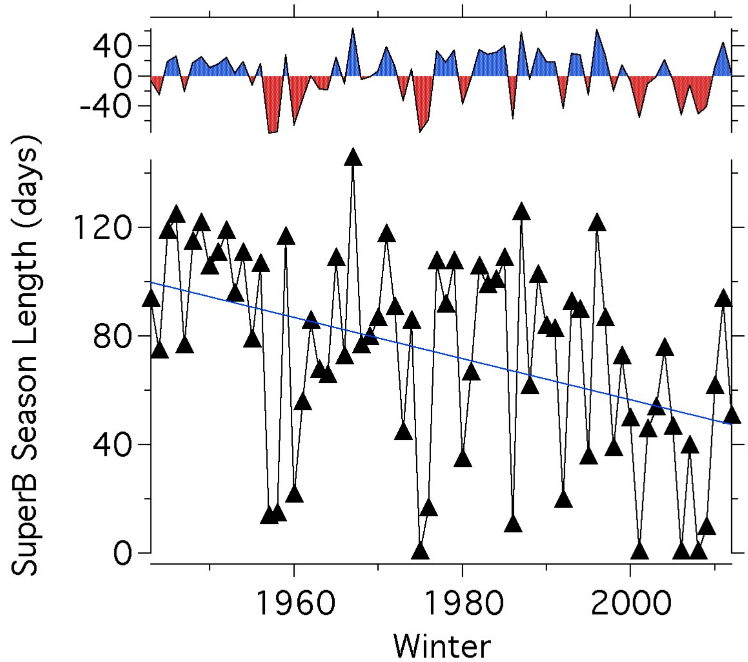

Figure S1-6: The Super-B season length time series, showing a strong secular trend due to climate warming. The residuals of this time series (top) were used as the basis for our load and cost calculations.

Using the estimate of the number of days the road would be open each winter over a 70-year period, we could then compute how much freight could be moved up the road *vs*. how much would need to be flown for each simulated year. For ease of analysis, we assumed transport was by Super-B trucks only. From discussions with the operators, we modeled the duty cycle as four (4) Super-Bs every 20 minutes during a 14 hour duty cycle per day. This results in 168 trips/day for a total of 5,455 tonnes hauled. The relationship between open season length (L_o) hauled on the ice road and total tonnes moved (T_t) per year becomes:

$$T_t = 5455 * L_o \qquad \text{[S1-3].}$$

We tested Equation S1-3 using operational data (http://www.jvtcwinterroad.ca/jvwr/) compiled by the operators. The average number of trips/season over the ten years of record was 6,606 and the average amount hauled was 216,643 tonnes/year. Estimates using Equation S2-3 came within 66 trips and 4.7 metric tonnes of these values. We then set the essential amount that had to be hauled to the mines (the need) at 180,000 tonnes/year, a conservative value approximately equal to the amount that was hauled at the height of the recession when worldwide demand for diamonds was at a recent low.

It was assumed that any shortfall below 180,000 tonnes would have to be flown as air cargo. The marginal air cargo costs over driving were computed from the bulk air cargo rate ($2155/tonne), less the cost of truck fuel and driver ($60/tonne), or $2,096/tonne. The total air cargo cost (A_t) was then:

$$A_t = \$2096*(180{,}000-T_t) \qquad \text{where } T_t < 180{,}000$$
$$A_t = 0 \qquad \text{where } T_t \geq 180{,}000 \qquad \text{[S1-4].}$$

If all cargo had to be shipped by air the total bill would be $387,900,000 less the cost of the ice road ($18,600,000), or $369,900,000 net, and absurdly high amount. If all cargo could be shipped by Super-B without resorting to air cargo, then the cost would be the $18,600,000 road construction/maintenance cost plus $10,800,000 (for fuel and driver), or a total of $29,400,000. These end-member transportation costs form a ratio of 13:1 (air cargo to trucking). In Figure S1-7 the red squares are the *realized* marginal air cargo costs for each year of the 70-years of simulated climate data (air cargo costs less savings in driving costs). They are marginal *realized costs* because they reflect the amount actually spent on cargo transport (less the savings on not paying drivers or fuel), but they are not very useful for decision-making because they cannot be known until after the haulage season is over.

The *expected costs* are more useful in this regard. For the same 70-year time series, the *expected* air cargo marginal costs, which are essentially the probable additional costs incurred, can be computed by assuming each of the 70 realizations has equal probability of occurrence and then averaging the costs for all of them. In this case, the amount is $74 million, shown by the dark blue diamond in Figure S1-7. For our time series, in 20 of the 70 seasons (29%), some air cargo costs were realized, while in 9 of these seasons (13%), the ice road never opened at all for Super-Bs so the full marginal cost was realized.

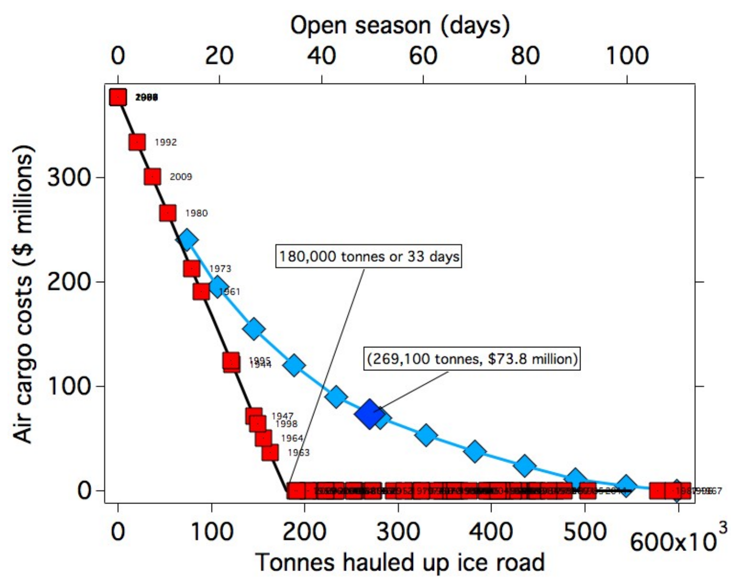

Figure S1-7: Realized (red) and expected (blue) cost functions for the ice road system where the required tonnage at the mines is 180,000 tonnes, as computed for the time series data using the method described in Supplement 1.

We can vary the mean open season length of the time series in order to examine the impact of a warming or cooling climate change on the expected costs (see Supplement 2). By subtracting or adding a fixed amount (±50, ±100 and so on) from each yearly value, we create a new time series with a different means.

References

Gold LW (1971) Use of ice covers for transportation. Canadian Geotechnical Journal 8:170-181.

Pfirman S, Haxby W, Eicken H, Jeffries M, Bauch D (2004) Drifting Arctic sea ice archives changes in ocean surface conditions. Geophysical Research Letters 31.

Slack GA (1980) Thermal conductivity of ice. Physical Review B 22:3065.

Sturm M, Holmgren J, König M, Morris K (1997) The thermal conductivity of seasonal snow. Journal of Glaciology 43:26-41.

Sturm M, Liston GE (2003) The snow cover on lakes of the Arctic Coastal Plain of Alaska, USA. Journal of Glaciology 49:370-380.