The Value of Weather Information Services for Nineteenth-Century Great Lakes Shipping

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The U.S. government established a national weather organization in 1870. Changes in Great Lakes cargo and hull losses, and shipping rates from Chicago to Buffalo, provide evidence of the value of storm warnings on the Great Lakes. Nearly half of the Great Lakes storm-warning stations were closed during the fall of 1883 because of appropriations reductions. This exogenous shock permits the econometric estimation of the value of storm-warning locations on the Great Lakes. The results indicate that the social rate of return for weather expenditures during the Weather Bureau's founding period was at least 60 percent. (*JEL* N71, H41, H43)

The importance of government investment in achieving economic growth has been an issue of contention in understanding both the historical development of the United States and the appropriate role of the state today. Given that a state's resources may be limited and that the social cost of publicly financed projects may exceed the private cost, our understanding of the optimal provision of services, both in the past and present, is not complete without rate-of-return estimates and marginal analysis.

This paper seeks to provide credible evidence of the high rate of return from the creation of weather information by the federal government. It neither claims that the timing of the establishment of a weather service was optimal nor that government provision was necessary. The paper, however, derives one of the perhaps earliest estimates of the value of government-provided information. A complementary product of this research has been a better understanding of the history of Great Lakes shipping.

The United States Congress established a national weather organization in 1870 when it instructed the Secretary of War to organize the collection of meteorological observations and forecasting of storms on the Great Lakes and Atlantic seaboard. See Cleveland Abbe, Sr. (1871), J. Cecil Alter (1949), James Rodger Fleming (1990), and Craft (1995), for details of prior attempts to organize and to sell weather information. A reduction in the Army Signal Service budget in fiscal year 1883 on account of an embezzlement scandal caused the number of storm-warning stations on the Great Lakes during the autumn of 1883 to fall by nearly one-half, thereby offering a natural experiment with which to estimate the value of the storm warnings. If severe weather forecasts on the Great Lakes were a valuable transportation input, one also would expect insurance and shipping rates to change after the introduction of the service in the early 1870's. Specifically, the differences between rates during peaceful summer months and relatively stormy fall months should diminish.

The first section will provide background information on both shipping and early Signal Service weather activities on the Great Lakes

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after the Civil War. Section II will estimate an econometric relationship between the availability of weather information on the Great Lakes and its value. Section III presents a history of grain cargo rates from Chicago to Buffalo which supports the hypothesis that storm warnings were socially valuable. Section IV combines estimates of the value of storm warnings on the Great Lakes with previously derived cost data to calculate a minimum bound for the rate of return to United States and Canadian weather information expenditures from 1870 to 1888. Section V provides the concluding summary.

I. Shipping and Weather Information on the Great Lakes After the Civil War

There are at least five reasons why the value of weather information during the early years of the Weather Bureau is best and most easily observed by studying transportation on the Great Lakes. First, reducing shipping losses was specifically identified by Congress as the primary purpose of a weather network (*U.S. Statutes at Large,* 1871 pp. 90, 369). Second, one dimension of the distribution of weather information on the Great Lakes is known with great accuracy. That dimension is the number of locations offering storm warnings during any fall season, when storms cause the most damage. Third, reasonably reliable data on shipping losses and factors affecting shipping losses are available. Fourth, the geographic placement of the Great Lakes offers an essentially self-contained region in which the stock of ship tonnage is calculated with more confidence than on an ocean coast. And fifth, ships on the Great Lakes are more susceptible to being stranded or thrown ashore than ocean-going vessels. Great Lakes vessels do not have as much open sea in which to navigate during poor weather conditions, and the nature of Great Lakes shipping means that the craft were often near the coastline.

Ships can be damaged in many ways, and not all are weather related. Ships can sink, collide, become stranded, burn, spring leaks, hit piers, capsize, be blown on the rocks, and have their sails and masts ruined [Chief Signal Officer (hereafter CSO), *Annual Report of the Chief Signal Officer,* 1871–1890]. An entire cargo can be destroyed with little loss to a ship, just as a vessel can be totally lost with minimal damage to the cargo. Different types of ships are more susceptible to different types of accidents. Steam-powered vessels are more likely to burn on account of onboard propulsion machinery; sailing vessels are more likely to be thrown on the rocks, stranded, or have masts and sails damaged in bad weather.

Although the *Annual Report of the Chief Signal Officer* in 1871 records the Milwaukee natural scientist Increase A. Lapham as having telegraphed a storm warning on the Great Lakes on November 8, 1870, his very first day of work, the Chief Signal Officer reports no other storm warnings until the system of flag signals began in the fall of 1871 (CSO, 1871 pp. 263–65). Lapham resigned as forecaster on December 26, 1870, for personal reasons (Eric R. Miller, 1931b p. 69). For months before October of 1871, the Signal Office in Washington, DC prepared practice synopses showing times and locations of warning signals. The month of October was spent distributing information on the interpretation of the signals which would be displayed with combinations of flags in daylight and lights by night.[1]

The Signal Service storm-warning network system formally began operation on October 23, 1871, with flag displays at 8 ports on the Great Lakes and 16 ports on the Atlantic seaboard (CSO, 1871 p. 265). The ports on the Great Lakes at which cautionary signals were displayed initially were Buffalo, Chicago, Cleveland, Detroit, Grand Haven, Milwaukee,

[1] In a description of one storm tracked eastward from Omaha beginning on November 11, 1871, and lasting five days, the chronology in the *Annual Report of the Chief Signal Officer* indicates that flag warnings were displayed at all eight Great Lakes ports in the Great Lakes warning network (CSO, 1872 pp. 749–50). The warnings preceded the storm by between 5 and 22 hours at each port. No vessels left the Milwaukee harbor. Some remained in the Chicago port. Some vessels remained at port in Cleveland, while those that put out returned damaged and with loss of life. At least one vessel sank. At Oswego, some craft remained in port while others left. Again, some of those that put out were forced to return in damaged condition, and the storm wrecked one vessel totally. No reports of shipping behavior are recorded from stations in Grand Haven, Toledo, and Detroit.

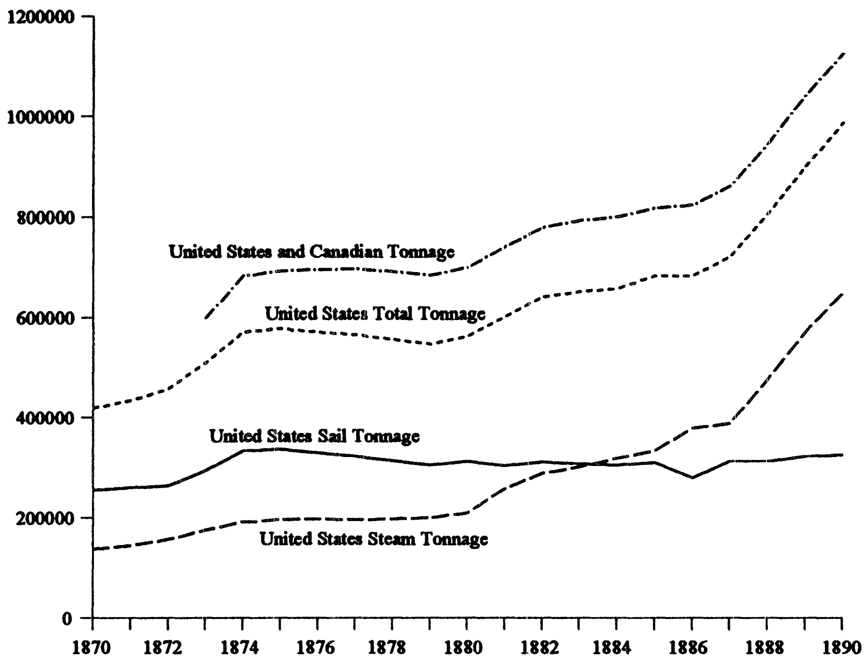

FIGURE 1. TONNAGE ON THE GREAT LAKES

Notes: United States tonnage data are found in the U.S. Department of the Treasury's *Annual Statement of the Chief of the Bureau of Statistics on the Commerce and Navigation of the United States* (1870–1890a). Canadian data are listed in Mansfield's *History of the Great Lakes* (1899).

Oswego, and Toledo. A cautionary signal was flown "whenever the winds are expected to be as strong as twenty-five miles per hour, and to continue so for several hours, within a radius of one hundred miles from the station." (CSO, 1872 p. 573.) In the first year of operation, ending June 1, 1872, 354 cautionary signals were flown on both the Great Lakes and Atlantic seaboard, approximately 70 percent of which the Signal Service verified as correctly forecast (CSO, 1872 p. 573).

Figure 1 shows the total U.S. tonnage on the Great Lakes from 1870 to 1890, its decomposition into sailing and steam craft, and the combined total of U.S. and Canadian tonnage after 1873.[2] The tonnage of U.S. steam vessels increased rapidly in the late 1880's as iron ore shipments expanded in the Lake Superior region. Anecdotal evidence regarding the increasing efficiency of loading and unloading technology and of fueling facilities for steam vessels suggests that shipping capacity on the Great Lakes grew faster than tonnage capacity. Such technological advances, though, are described as occurring predominantly after the mid-1880's (U.S. Congress, 1898 pp. 9, 47). At least in the late 1890's, common judgement held that a steamer could do two and one-quarter times the work of a sailing vessel on account of speed (U.S. Congress, 1898 p. 4). Sailing vessel tonnage statistics from around

[2] Canal boat tonnage is not included in the figure, as it is not as directly engaged in long hauls on open water, where severe weather was a factor. The data begin in 1868, when the United States implemented a new admeasurement system based on internal capacity. I have not reported the first two years, as the transition period figures beginning in 1866 are not consistent and suggest the removal of unusually large amounts of obsolete tonnage.

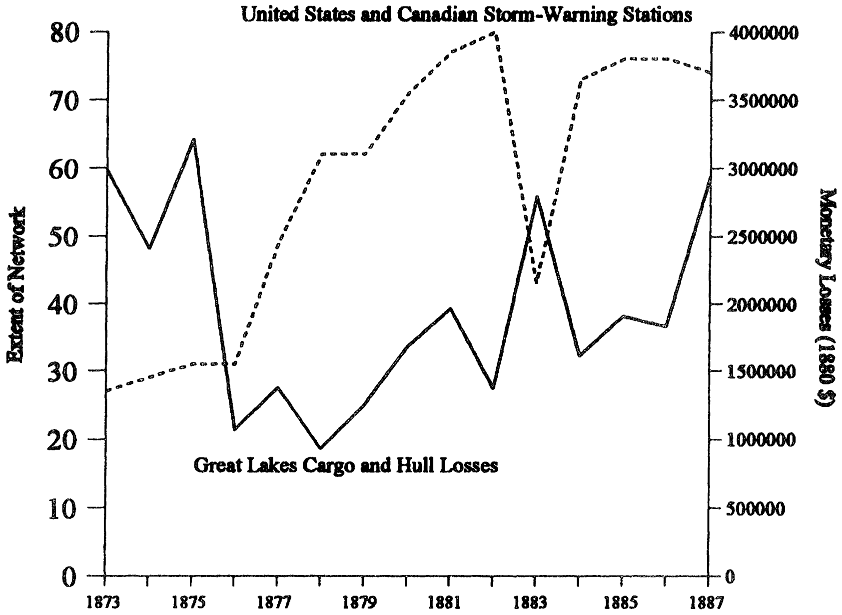

FIGURE 2. GREAT LAKES PROPERTY LOSSES AND NUMBER OF STORM-WARNING SIGNAL STATIONS

Notes: The data are found in the following: *Chicago Daily Inter Ocean* (December 5, 1874 p. 2; December 18, 1875; December 27, 1876 p. 6; December 17, 1878; December 29, 1879 p. 6; February 3, 1881 p. 12; December 28, 1883 p. 3; December 5, 1885 p. 4); *Marine Record* (December 27, 1883 p. 5; December 25, 1884 pp. 4–5; December 24, 1885 pp. 4–5; December 30, 1886 p. 6; December 15, 1887 pp. 4–5); Chief Signal Officer, *Annual Report of the Chief Signal Officer,* 1871–1890. Series E 52 of the *Historical Statistics of the United States* (U.S. Bureau of the Census, 1975) was used to adjust all values to real 1880 dollars.

1884 to 1895 are misleading, as "Many of the vessels classed as sailing vessels have really been transformed into barges, for they are now habitually towed." (U.S. Congress, 1898 p. 14). By the mid-1890's, commercial sailing vessels are said to have disappeared from Lake Superior entirely (U.S. Congress, 1898 p. 14). The use of iron and steel for hulls does not grow significantly until the early 1880's and comprised only 10 percent of all steam tonnage in 1885 on the Great Lakes (U.S. Department of the Treasury, 1885a). The development of a weather service probably slowed the transition from sailing to steam vessels, as the mobility of sailing vessels is more impaired in severe weather conditions.

Figure 2 gives the estimates of monetary losses on the entire Great Lakes, both Canadian and United States, in 1880 dollars, according to a series of consistent annual reports in the *Chicago Daily Inter Ocean* (1874–1885) and the *Marine Record* (1883–1890). Although the recording methodology may have been different, Lapham had submitted a memorial to Congress listing Great Lakes shipping losses of 2.0 and 2.7 million (1880 $) for 1868 and 1869, respectively (U.S. Congress, 1870). The standard historical interpretation (Fleming, 1990 pp. 152–56) attributes to these losses a major role in the creation of support for a federal weather service. Figure 2 also shows how the combined number of U.S. and Canadian storm-warning stations changed over time. The large decrease in losses from 1875 to 1876, occurring before the significant expansion of the storm-warning display system, is not surprising, as 1876 registered the lowest level of commerce on the Great Lakes in the sample. In addition, the weather severity variable for the year is also nearly a standard deviation below the mean, and the Great Lakes Life-Saving Service system expanded (see Section II). Descriptions and summary statistics of the variables in this paper are found in Table 1.

The reduction in storm-warning stations in 1883 occurred due to a decrease in the Army Signal Service budget. Congress reduced direct weather appropriations after 1882 on account of embezzlement charges against the disbursing officer of the Signal Service (Donald R. Whitnah, 1961 pp. 46–7). According to General William B. Hazen, the Chief Signal Officer, Captain Henry W. Howgate may have stolen up to $237,000 at a rate of $60,000 per year. With annual Signal Service budgets around $1 million, Congress might have concluded that service would not suffer after the embezzler's portion of the budget was removed. The variation in the number of stations providing storm warnings offers an unusual opportunity to estimate their effectiveness and value.[3]

Although records indicate precisely which storm-warning locations were closed during the fall of 1883, ship loss records and cargo loss records are not disaggregated enough to observe if the increased losses that season occurred near the ports losing service. There existed two types of storm-warning stations on U.S. Great Lakes shores. The first type was a Signal Service Observation Station maintained by Signal Service personnel. These stations took observations three times daily year-round and telegraphed the data immediately to Washington, DC. There were 16 such stations at major ports and key locations on the Great Lakes in 1883. All of the storm-warning stations that were closed in 1883 with one exception were display stations and were operated only during the navigation season by civilians. The closed display stations were located primarily in small ports in Michigan and Wisconsin.

The defining characteristic of a display station is that it did not collect meteorological information; it only displayed storm warnings. The choice to close these stations is consistent with the goal of not interrupting the observation system, which provided data for formulating "indications" for the entire country. The civilians hoisted storm-warning signals upon receiving telegraphic instructions from Washington, DC (CSO, 1871–1890). In 1889, the mode cost of paying civilian storm-warning personnel at Great Lakes ports was $120 per year (U.S. Congress, 1890). The costs of a pole, flags, and telegraphic messages were trivial. In other words, the marginal cost of an additional storm-warning location on the Great Lakes was extremely low. Since the budgetary category "Observation and Report of Storms" dropped by over $130,000 from 1882 to 1884, other national weather activities were curtailed also (U.S. Department of the Treasury, 1882–1884c).

A key feature of my study of weather information on the Great Lakes is that the number of storm-warning stations will serve as an independent variable in a regression analysis of Great Lakes shipping losses. The reader might ask if the number of warning stations is an exact measure of the *use* of the storm-warning network. In other words, is the number of weather stations an appropriate metric for the amount of weather information provided?

Optimistic discussion of the newly formed meteorological network in 1871 and explanations of the signals in 1874 in *Barnet's Coast Pilot*, as well as the reports described in footnote one of this paper, provide evidence that independent transportation authorities had faith in the benefits of the service from its inception (Barnet, 1871 pp. 130–32; 1874 pp. viii, 148). *Barnet's Coast Pilot* was a prominent guide to Great Lakes masters and sailors. It listed, for example, exact sailing directions

[3] One can argue a priori that a storm-warning system could be so reliable that captains would leave port under what in the past had been considered marginally dangerous conditions, thereby leading to increased damages with a storm-warning system. Increased losses would be a cost outweighed by increased earnings due to greater use of vessels. In the limit, imagine a scenario whereby before weather information was available, there was no shipping commerce due to the high probability of wreck. If most storms are effectively forecast, a shipping industry begins and vessels are lost. This bias implies that analysis of loss data will underestimate the value of storm warnings.

TABLE 1—DESCRIPTIVE STATISTICS AND VARIABLES

	Mean	Standard deviation	Minimum	Maximum
GREAT LAKES LOSSES (1880 DOLLARS)	1,900,735	777,662	929,670	3,212,966
WARN	57.4	20.2	27	80
WIND	14,022	1,306	12,660	16,180
STEAM	0.415	0.077	0.337	0.554
TREND	8	4.5	1	15
LIFE	29.5	18.2	0	54
TON	737,340	71,429	599,300	860,900
COM	4,564	1,006	3,228	6,857

CORRELATION MATRIX

	WARN	WIND	STEAM	TREND	LIFE	TON	COM
WARN	1.00						
WIND	0.43	1.00					
STEAM	0.70	0.30	1.00				
TREND	0.82	0.38	0.95	1.00			
LIFE	0.86	0.36	0.85	0.95	1.00		
TON	0.68	0.24	0.93	0.95	0.85	1.00	
COM	0.83	0.74	0.83	0.84	0.79	0.74	1.00

VARIABLE DESCRIPTIONS

WARN	the number of United States Army Signal Service and Canadian Meteorological Service storm-warning locations on the Great Lakes during the fall
WIND	the total wind miles during October and November at Alpena
STEAM	the percentage of U.S. Great Lakes tonnage that was steam powered
TREND	a trend variable
LIFE	the number of U.S. and Canadian Life-Saving Service stations on the Great Lakes
TON	Great Lakes tonnage
COM	a proxy for commerce on the Great Lakes[a]

Notes: The annual data correspond to the years 1873–1887, not including 1885 loss data. See text for sources.

[a] The commerce proxy was constructed from information in James David Rae's Ph.D dissertation (1967) "Great Lakes Commodity Trade, 1850 to 1990" and James Barnet's *Barnets Coast Pilot.* I calculated millions of cargo ton miles of the following commodities and routes: flour, wheat, corn, and oats from Duluth, Chicago, Milwaukee, and Toledo to Buffalo; iron ore through the St. Mary's Falls Canal (assumed average origin of Octonagon) to Cleveland; lumber to Cleveland, Toledo, Buffalo, and Oswego (assumed origin the Saginaw River); and lumber to Chicago and Milwaukee (assumed origin Manistee). Coal is not included, as it is a return trip from the East. A few missing years in these series had to be interpolated.

for standard routes, locations of prominent lights, and navigation rules.

Two approaches are used to estimate the value of storm warnings on the Great Lakes. A direct analysis studies how vessel and cargo losses change as factors such as a storm-warning network, weather, level of commerce, shipping capacity, internal improvements, and technology change. An alternative strategy is to analyze how insurance and shipping rates, which should reflect the probability and magnitude of vessel damage, are influenced by the same factors.

II. Analysis of Cargo and Hull Losses

Although the Board of Lake Underwriters and United States Coast Guard records provide extensive information on annual losses from 1855 to 1873, the loss data, as well as the tonnage data, are inconsistent.[4] The tonnage classification system changed during the

[4] The Coast Guard did not exist during the 1860's, but later presumably came into the possession of records gathered by the Treasury Department's customs houses.

mid-1860's, and the total tonnage by customs districts became available only in 1868. In addition, from 1868 onward, the data allow the subtraction of canal boat tonnage. This is appropriate as canal boats were a significant portion of Great Lakes customs districts' tonnage, yet did not venture into open water generally, where storms are a problem. As described above, no weather agency existed before 1870 which could provide objective *ex post* weather observation data on the severity of storms. Data on Great Lakes commerce are also more limited before 1870. A consistent series of cargo and hull loss data reported by the *Chicago Daily Inter Ocean* and later in conjunction with the Great Lakes trade publication *Marine Record* begins in 1873 and ends in 1887. Loss data for 1885 may be underestimated and are therefore excluded in the following analysis.[5]

The primary challenge of the analysis is distinguishing the influence of weather information from other factors that could have reduced losses during the same period. Examples of these other factors are: internal improvements, construction of lighthouses, establishment of life-saving stations, and general technological change. Technological change can be manifest in the ships, in the process of recovering damaged ships, and in the loading and unloading of ships. One expects improvements in steam-power technology to reduce the probability of ships exploding or burning. Deepening harbors, creating safe harbors on coastlines where no safe ports existed, and deepening critical waterways such as the St. Clair Flats between Lakes Huron and Erie are examples of internal improvements. Holding other factors constant, it seems likely that losses will diminish as tonnage capacity rises, because vessels can transport a larger share of the commodities during the safer summer season. Measures of the severity of weather and the level of commerce should have a positive effect on shipping losses. Since steam-powered vessels were generally more valuable, losses should rise as the percentage of lake tonnage that was steam powered rose.

A. *A Simple Wald Estimate of the Value of Storm Warnings*

Before proceeding with an econometric analysis of shipping losses, an initial estimate of the value of storm-warning stations can be derived by calculating the percentage (ln change) increase in Great Lakes losses and the drop in storm-warning losses between the years 1882 and 1884 and the year 1883. The ratio of this percentage increase in shipping losses to the decrease in the number of storm-warning stations is a simple Wald estimator (Abraham Wald, 1940) of the marginal proportionate effect of storm-warning signals on losses. Other than weather severity and perhaps the level of commerce, all other factors affecting losses changed slowly, so this exercise approaches the conditions of a natural experiment. The level of Great Lakes shipping losses in 1883 was 87.6 percent higher than the average of the preceding and following year. The number of storm-warning stations dropped from an average of 76.5 in 1882 and 1884 to 43 in 1883. The ratio of the (natural) log change in losses to the drop in the storm-warning locations is 0.019, implying that the average reduction in Great Lakes losses accounted for by each warning stations was 1.9 percent. As we shall see, this simple estimate is very close to regression estimates below. For the years 1882, 1883, and 1884, this estimate implies that the marginal storm-warning station reduced losses by \$26,007, \$50,353, and \$29,032, respectively.

The above discussion and available data suggest a regression of Great Lakes losses on the number of storm-warning stations, a proxy for the severity of Great Lakes weather, the level of tonnage, the percentage of tonnage that was steam powered, the level of commerce, the

[5] The December 5, 1885, edition of the *Chicago Daily Inter Ocean* summarizes losses of 1.91 million (1880 \$), but that year's loss list acknowledges the omission of most minor losses. The wreck report also appears to contain an unusually large amount of losses that were not storm related. The coefficient and standard error estimates for the storm-warning variable including the 1885 data point are quite similar to those given in Tables 2 and 3. In an era when economists are accustomed to working with enormous data sets, the size of this data set may give pause. Although the data set is small, this observation by itself is no reason to discount the results. Statistical procedures are adjusted for small samples by raising the thresholds at which results are judged to be significant. Results in Section III provide additional evidence that estimated coefficients are not the result of random variation.

number of Great Lakes Life-Saving Service stations, the number of Great Lakes lighthouses, a measure of internal improvements, and a trend variable.

B. *Regression Estimates*

Two specification issues suggest that a standard linear regression analysis may be most inappropriate. First, recall that the Army Signal Service storm-warning network on the Great Lakes ranged in size from zero to 55 stations during the years 1870 to 1889. The Signal Service established the first stations at the major ports, and no evidence has been found to indicate that the storm-warning network did not expand in a generally optimal manner. The last ports to receive funding for storm-warning services and the first to lose services seem to have been the smallest. These were primarily northern Wisconsin and northern Michigan ports. Intuition suggests a diminishing marginal effect as the network of stations was extended to more and more ports. Likewise, one hypothesizes that the costs of severe weather may not increase linearly. The semilog specification implies a diminishing marginal effect of any right-hand variable whose coefficient is negative and an increasing marginal effect of any right-hand variable whose sign is positive.[6]

Second, in any given year, the number of storm-warning locations can be expected to affect the marginal cost of weather severity and visa versa. Both a semilog specification and linear specification with quadratic terms and interaction terms can capture these characteristics. In addition, in the limit, with perfect weather information and distribution, the effect of the severity of weather variable on losses should be zero. A linear specification does not capture this property.

Alpena, Milwaukee, and Cleveland are the only locations whose wind data are consistent over the period 1873 to 1886. Given its location in northeast Michigan on Lake Huron, it is not surprising that wind at Alpena most successfully explains shipping losses.[7]

No lifesaving stations existed on the Great Lakes until 1876, the year the U.S. federal government established 29 posts. By 1886, 48 Canadian and American stations could be found (John B. Mansfield, 1899 pp. 378–80). Although generally equipped and outfitted with apparatus intended to save lives, not property, extensive reports in the various *Annual Report of the Operations of the Life-Saving Service* (U.S. Department of the Treasury) indicate that keepers and surfmen often assisted stranded boats in getting off rocks and bars and provided relief and support to tug boats rescuing damaged vessels.[8]

Tables 2 and 3 show the regression analysis results for Great Lakes vessel and cargo losses. The coefficients of lighthouse and internal improvement variables are statistically insignificant in all nontrivial specifications and have been removed from the estimated specifications. Regression coefficients indicating the value of Great Lakes storm-warning locations remain relatively stable as the semilog specifications are altered and statistically insignificant variables are removed. The storm-warning coefficient in column (V), which includes a maximum-likelihood correction for first-order negative serial correlation, implies that each additional storm-warning location on the Great Lakes decreased losses by just under 1 percent from what they otherwise would have been.[9] As

[6] There does not appear to exist any endogeneity problem in the specification, since new warning stations were established almost invariably before the dangerous fall season began. If there was an endogenous relationship between the severity of weather, level of commerce, and losses on the one hand and the extent of the warning network on the other hand, the coefficient on the value of storm-warning locations would be biased downward.

[7] The variable wind miles is positively correlated with trend, suggesting that the instruments were moved to higher ground between 1873 and 1887. Wind data come from the U.S. Weather Service's Climatological Record Books, Alpena (1871–1890).

[8] The Life-Saving Service generously accepted responsibility for saving property each year of an amount equal to the surviving value of any vessels assisted. Such estimates on the Great Lakes for the *fiscal years* 1879, 1880, 1883, and 1884 equaled \$408,970, \$910,556, \$1,510,000, and \$2,145,640, respectively, in 1880 dollars (U.S. Department of the Treasury, 1879b pp. 15–16; 1880b p. 15; 1883b pp. 16–17; 1884b, p. 17). Frederick Stonehouse (1994) discusses the Life-Saving Service on the Great Lakes, as well as providing data on the dates of establishment of individual stations.

[9] N. E. Savin and Kenneth J. White (1978) find that

TABLE 2—SEMILOG ESTIMATES OF GREAT LAKES SHIPPING LOSSES

	I	II	III	IV	V	VI	VII	VIII
CONSTANT	6.16** (2.87)	7.35** (3.33)	6.70** (2.85)	9.44*** (1.38)	6.37** (2.40)	8.95*** (0.91)	12.24*** (0.99)	9.17*** (1.76)
WARN	−0.0116* (0.0068)	−0.0152** (0.0078)	−0.0124* (0.0068)	−0.0155** (0.0063)	−0.0097* (0.0063)	−0.0127** (0.0053)	−0.0160* (0.0082)	−0.0151* (0.0083)
WIND	2.29E-4*** (0.75E-4)	1.90E-4** (0.86E-4)	2.58E-4*** (0.70E-4)	2.29E-4*** (0.66E-4)	2.22E-4*** (0.59E-4)	2.16E-4*** (0.48E-4)	1.30E-4* (0.90E-4)	2.19E-4*** (0.74E-4)
STEAM	6.88** (3.34)	—	8.22** (3.11)	8.56** (3.13)	8.35** (3.35)	10.65*** (2.29)	—	—
TREND	−0.216** (0.095)	−0.133 (0.102)	−0.186** (0.091)	−0.118* (0.068)	−0.218** (0.076)	−0.159** (0.052)	—	—
LIFE	—	—	—	—	—	—	−0.0080 (0.0190)	−0.0118 (0.0122)
TON	5.12E-6 (3.69E-6)	6.71E-6* (4.28E-6)	3.86E-6 (3.52E-6)	—	4.49E-6 (3.75E-6)	—	—	4.55E-6** (2.21E-6)
COM	1.67E-4 (1.58E-4)	2.92E-4 (1.74E-4)	—	—	0.95E-4 (1.51E-4)	—	3.20E-4** (1.50E-4)	—
Durbin-Watson statistic	2.90	2.21	3.00	2.90	2.18	2.37	1.99	2.11
Rho (ARI)	—	—	—	—	(0.56)* (0.35)	(0.61)* (0.27)	—	—
Adjusted R^2	0.65	0.51	0.65	0.64	—	—	0.46	0.46
Adjusted R^2 in terms of losses	0.70	0.51	0.75	0.70	—	—	0.52	0.59

Notes: Losses are in 1880 dollars. The data include the years 1873 through 1887, omitting 1885. Standard errors are in parentheses.

* Significant at the 10-percent level of confidence for a one-tailed test.
** Significant at the 5-percent level of confidence for a one-tailed test.
*** Significant at the 1-percent level of confidence for a one-tailed test.

noted above, this specification also implicitly imbeds the notion of diminishing returns to additional stations into the estimating procedure. Already by 1872 the largest ports on the Great Lakes had Army Signal Service observation and warning stations, thereby causing the above estimating procedure to underestimate the total value of the weather stations, since there was no variation in service to the largest port cities in the sample.[10]

Table 3 presents linear estimates with specifications including quadratic terms on the storm-warning stations and weather severity variables and a warning stations-weather severity interaction term. The quadratic weather severity terms are consistent with threshold values, above which increasing weather severity causes increasingly greater losses. The warnings-weather interaction terms capture the greater value of storm warnings in the presence of severe fall weather and the lower cost of severe weather in the presence of many storm-warning stations.

Durbin-Watson test statistics are still valid in the presence of missing observations, even though the power of alternative tests may be higher.

[10] By 1873, when the data set begins, Alpena, Buffalo, Chicago, Cleveland, Detroit, Duluth, Erie, Escanaba, Grand Haven, Milwaukee, Oswego, Rochester, and Toledo already had Signal Service stations. A standard linear specification of the regression equation does not take into account the conjecture that these first few storm-warning stations were probably considerably more valuable than the subsequent stations. Consistent data are available beginning only in 1873.

0.00E-4***0.00E-4***

TABLE 3—LINEAR ESTIMATES OF GREAT LAKES SHIPPING LOSSES

	IX	X	XI	XII	XIII
CONSTANT	1.10E7	−3.24E7	2.36E7*	−41.1E7**	−1.17E7**
	(1.43E7)	(2.68E7)	(1.38E7)	(1.32E7)	(0.55E7)
WARN	6.50E5***	1.70E5	5.89E5***	3.49E5**	−0.27E5**
	(1.12E5)	(1.43E5)	(1.22E5)	(1.59E5)	(0.13E5)
WARN^2	−942*	−1682	—	−1580*	—
	(547)	(1214)		(995)	
WIND	−7001**	1405	−8095***	1542**	472***
	(2114)	(3110)	(2324)	(558)	(137)
WIND^2	0.359***	−0.027	0.403***	—	—
	(0.088)	(0.107)	(0.097)		
WARN-WEATHER	−41.04***	—	−44.62***	−13.59*	—
	(7.93)		(8.83)	(7.99)	
STEAM	3.02E7***	2.80E7**	2.32E7***	2.76E7**	1.43E7**
	(0.52E7)	(1.20E7)	(0.38E7)	(0.98E7)	(0.60E7)
TREND	−8.18E-5***	−7.61E-5**	−5.94E-5***	−8.28E5**	−3.21E5*
	(1.58E5)	(3.64E5)	(1.05E5)	(3.01E5)	(1.77E5)
TON	16.85***	14.59*	13.22***	18.01**	7.08
	(3.91)	(8.95)	(3.80)	(7.41)	(6.84)
Durbin-Watson statistic	2.09	2.75	2.16	2.43	2.92
Adjusted R^2	0.93	0.63	0.91	0.75	0.64

Notes: Losses are in 1880 dollars. The data include the years 1873 through 1887 omitting 1885. Standard errors are in parentheses.

* Significant at the 10-percent level of confidence for a one-tailed test.
** Significant at the 5-percent level of confidence for a one-tailed test.
*** Significant at the 1-percent level of confidence for a one-tailed test.

The signs of the quadratic warning stations terms, however, are the opposite of the expected results.

Table 4 presents estimates of the value of marginal storm-warning stations at the mean of all variables. The semilog specification of column (V) captures all the desirable theoretical properties described above and offers a conservative estimate of the value of storm-warning stations relative to the other regression equations. Using the means of all other variables, the marginal savings of the first storm-warning station and the mean storm-warning station are estimated to be \$33,285 and \$19,074, respectively.

The Box-Cox test also can check whether a linear specification should be rejected in favor of a transformed left-hand and/or right-hand variable. When λ in the Box-Cox transformation of the left-hand variable in column XIII is allowed to vary, the linear specification is rejected at the 20-percent significance level. Using a grid search from −1 to 2, λ is estimated as 0.1. Recall that the limit as λ approaches zero gives the natural logarithmic function.[11]

Using the specification in column (V), the subtraction of actual losses from the expected losses without a storm-warning system yields estimates of savings averaging nearly 1 million dollars during the early years and rising to between 1 and $4\frac{1}{2}$ million dollars per year near

[11] Similar results obtain for the Box-Cox test where both the left-hand and right-hand variables are transformed. Estimation using a log-linear specification is problematic since the variable representing Great Lakes

TABLE 4—ESTIMATED MARGINAL BENEFIT OF AN ADDITIONAL STORM-WARNING STATION AT THE MEAN OF ALL VARIABLES

V	VI	IX	X	XI	XII	XIII
$19,074	$22,986	$33,998	$13,389*	$36,392	$15,922*	$21,544*

* Corrected for first-order autocorrelation.

the end of the period. Table 5 contains estimated losses without a storm-warning system, reported losses, and savings from storm warnings.

As discussed by Craft (1995), false warnings were not rare. Some vessels undoubtedly were delayed by false warnings, especially as winds can be both strong and safe if in the appropriate direction. The preceding discussion excludes the value of shipping time lost due to incorrect forecasts, as well as including reduced wreckage from false warnings keeping vessels in ports. During the first 7 years of operation, an average of 17 false warnings per year were displayed in Chicago (CSO, various years). These warnings cover 8 percent of the navigation season's days. If other ports had as many false warnings and if half of all damages are nonweather and nonport related, then these false warnings imply a loss reduction of 4 percent due to wasted time in port. In reality, other ports had fewer false warnings, implying that this reduction in losses due to false warnings is small relative to savings from accurate warnings.

Likewise, I have placed no value on the time savings due to fewer vessels being damaged. In samples of the proportion of monetary losses that were total cargo and total hull losses, the figure is consistently under 50 percent. From 1869 until 1871, 46.5 percent of losses were total losses of hulls and cargo (United States Coast Guard, 1962). The years at the end of the sample for which the calculation is possible (1884, 1886, 1887, and 1889) average 43.7 percent. Clearly, if more than half of all losses are only partial losses, many ships spent time in port repairing sails, masts, centerboards, and vessel bodies. These are common damages if one reads a typical list of the season's disasters. I assume that the value of time lost through false storm warnings and the value of reduced wreckage due to false warnings is at least offset by time gained through reductions in the number of damaged vessels. To the extent that some vessels may have left port on occasions when no storm warnings were forecast, but under conditions that prior to the establishment of a weather organization would have restrained captains—fall months, for example—the preceding calculations are underestimates of the value of storm warnings.

III. Grain Shipments from Chicago to Buffalo

This section uses Chicago Board of Trade statistics on weekly shipping prices and monthly shipping levels of grain from Chicago to Buffalo to investigate the value of weather information. If storm forecasts proved valuable to lake shippers, one expects the price of shipping grain from Chicago to Buffalo to diminish. But it is also true that other factors could be expected to have lowered shipping costs during the 1870's. Improved dock and ship technology, as well as increased competition from railroads, could be expected to lower the price of shipping grain from Chicago to Buffalo.

Figures 3 and 4 contain data on the level, timing, nominal prices, and price differentials of shipping wheat, oats, and corn by sail from Chicago to Buffalo and the East.[12] The fall is

Life-Saving Service stations takes the value zero in some years. In addition, the primary goal of this paper is to estimate Great Lakes cargo and hull losses in the counterfactual world of no storm-warning stations. See William H. Greene (1993) for a discussion of the Box-Cox test.

[12] The portion of grain shipments from Chicago by sail

TABLE 5—SAVINGS FROM STORM WARNINGS ON THE GREAT LAKES (MILLIONS OF 1880 DOLLARS)

Year	Expected losses without storm warnings	Recorded losses[a]	Estimated savings from storm warnings
1873	3.93	2.99	0.94
1874	3.31	2.41	0.90
1875	3.72	3.21	0.51
1876	2.45	1.07	1.38
1877	1.92	1.38	0.54
1878	1.98	0.93	1.05
1879	2.80	1.24	1.56
1880	3.90	1.68	2.22
1881	5.19	1.96	3.23
1882	3.30	1.37	1.93
1883	3.85	2.80	1.05
1884	4.42	1.61	2.81
1885	2.48	1.09	1.39
1886	5.42	1.83	3.59
1887	7.65	2.94	4.71

Notes: See text, Figures 1 and 2, and Table 1 for sources. The expected losses without a storm-warning system in dollars equal $\exp(\mu + 1/2s^2)$.

[a] Actual losses for 1885 were estimated using the regression equation.

defined as September, October, and November; the summer as May, June, July, and August.[13] The Chicago Board of Trade recorded lake shipments by commodity by month and the price of grain shipments by week. I constructed weighted averages of prices by taking the average corn shipping price per bushel by sail for a month and weighting it by the shipments of corn, wheat, and oats for that month.[14] Figures 3 and 4 indicate, at most, weak relationships among the factors amount of grain shipped per calendar year, the portion shipped during the fall months, and the summer-fall price differential. Both figures show, however, that the absolute level and the percentage premium of the summer-fall price differential falls over time, especially after 1872 and 1873, the first two years of full fall operation of the Army Signal Service's storm-warning system.

Consider first the hypothetical effect on shipping prices of doubling the capacity of

is not available. Anecdotal evidence suggests that steam vessels carried larger and larger portions, beginning sometime during the early 1880's. The practice of steam vessels towing sail vessels became more and more common in the early 1880's. Sail and steam cargo rates did rise and fall together.

[13] Some grain was also shipped in April. The amount depended on the timing of the opening of the Straights of Mackinac, in addition to the size of the crop to be transported.

[14] Ten and 11 weeks of price data during the 35-week shipping seasons in 1868 and 1867, respectively, were unavailable. Monthly averages were still constructed. In the case of October of 1867, when no data were available, the average September price was used. This would create a downward bias in the estimated fall premium.

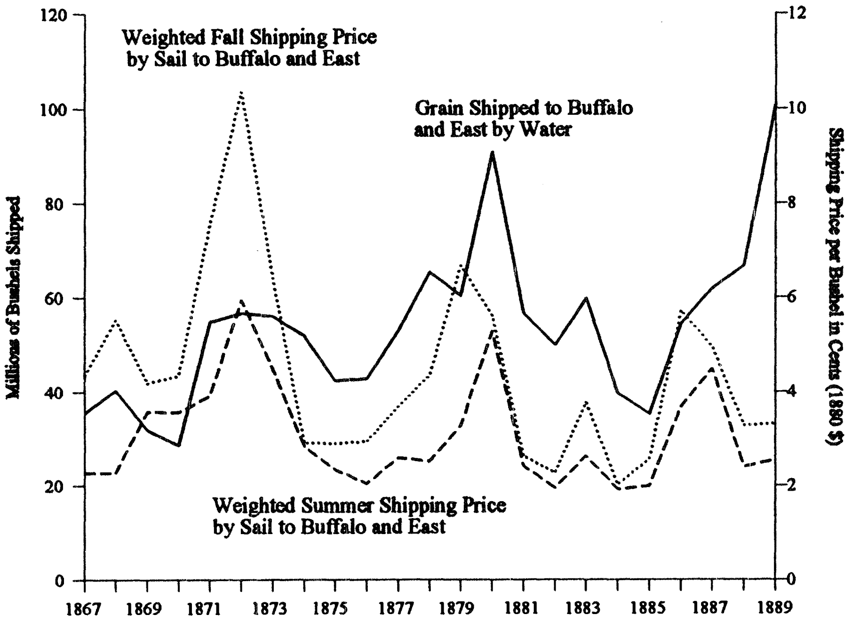

FIGURE 3. CHICAGO GRAIN SHIPMENTS EAST BY WATER

Notes: The data are found in the Chicago Board of Trade's annual *Statement of the Trade and Commerce of Chicago.* Real values are calculated using Series E 52 of the *Historical Statistics of the United States* (U.S. Bureau of the Census, 1975).

vessels by increasing the number of trips per year from better dock technology. If we assume all dock and operating costs remain constant and storms do not cause shipping damage during the summer months, summer shipping prices would fall by 50 percent before reaching a new equilibrium. Fall shipping prices would fall by a lower absolute amount because damages due to storms would rise. Improved loading and unloading technology could be expected then to *increase* the absolute summer-fall price differential, as well as the percentage fall premium. Similar logic holds for increased capacity and efficiency of ships due to size and speed, if safety is unaffected by marginal increases in the size of sailing vessels.[15] The creation of deeper channels permits the use of larger vessels. Other internal improvements such as improved lighting of dangerous passageways and the construction of safe harbors will lower shipping costs, but the effect on the summer-fall price differential is uncertain.

Alternatively, imagine all technology except storm forecasting remaining constant on the Great Lakes. Since severe storms are much rarer during summer months, storm warnings would have a correspondingly greater effect on the fall shipping price.[16] Under reasonable assumptions, storm warnings should lead to greater percentage decreases in fall shipping rates than summer rates.[17] The data in Figures

[15] The average size of sailing vessels on the Great Lakes increased from 156 tons in 1870 to 209 tons in 1880 to 258 tons in 1890 (U.S. Congress, 1898 p. 12). For steam vessels, the average size was 223 tons in 1870, 228 tons in 1880, 286 tons in 1885, and 427 tons in 1890 (U.S. Department of the Treasury, 1870–1890a). The average tonnage data for steam-powered vessels include tug boats.

[16] See Val Eichenlaub's *Weather and Climate of the Great Lakes Region* (1979).

[17] Assume weather-related costs entail 4 percent of expected summer costs but 30 percent of expected fall costs

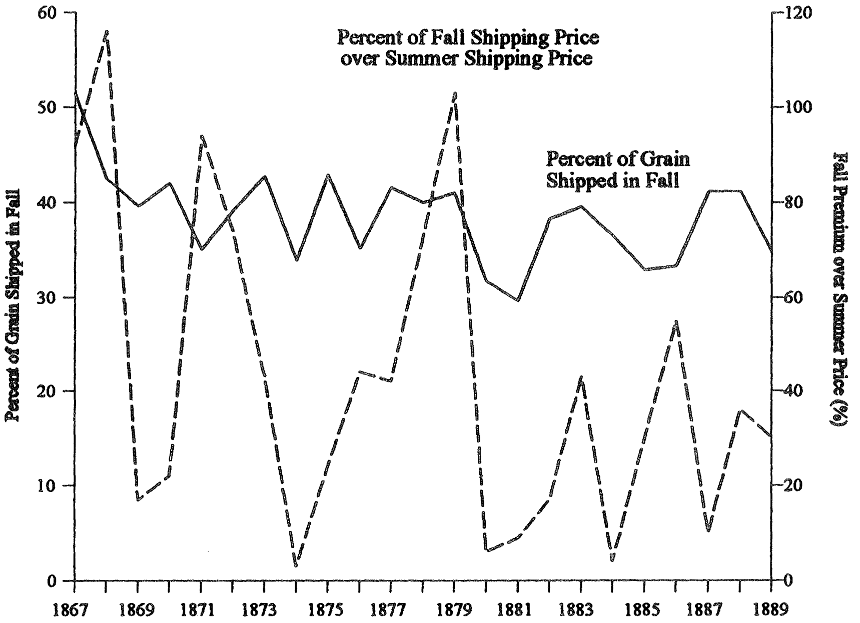

FIGURE 4. TIMING OF CHICAGO GRAIN SHIPMENTS AND FALL PREMIA

Notes: The data are found in the Chicago Board of Trade's annual *Statement of the Trade and Commerce of Chicago.*

3 and 4 show that the average fall percentage premium drops from 68 percent during the period 1867 to 1872 to 31 percent over the years 1873 to 1877. In other words, the fall over summer shipping premium dropped by one-half after the advent of a storm-warning system. The decrease in premium is statistically significant at the 10-percent level for a one-tailed test. The result holds if the postestablishment time period is extended to 1882 as well. As argued above, other identifiable factors such as improvements in loading and unloading technology and increased capacity and efficiency of ships imply an increased fall premium, ceteris paribus.

The fall-summer rail shipping premia from Chicago to New York mirror the lake rates in that the relative premia start between 20 and 45 percent in 1869 and 1870 and fall to zero in some years after 1872 (Chicago Board of Trade 1968–1887). If lower fall lake shipment rates forced fall rail shipment rates down toward the marginal cost of rail shipment, then lake savings are an underestimate of all social savings.

The reader may recall the reduction in storm-warning locations on the Great Lakes during the fall of 1883. One might presume that cargo insurance rates would rise. Large cities, however, such as Chicago, Detroit, and Buffalo, did not lose their storm-warning service. Since grain-laden vessels would not be expected to stop at smaller ports en route between Chicago and Buffalo, there is no reason to expect cargo insurance premiums or shipping charges from Chicago to change during the fall of 1883.[18]

and that other costs are identical for both the fall and summer seasons. By reducing expected weather damages by one-half on account of forecasts and assuming all other costs are identical, the ratio of costs falls from 1.25 to 1.13.

[18] *Barnet's Coast Pilot* (Barnet, 1871, 1874, 1881), a recognized resource for lake vessels, gives precise instructions for sailing from Chicago to the head of the St. Clair River near Detroit. The route was essentially a straight line on Lake Michigan with one kink at the South Manitou Island; ships would not pass within sight of the small ports which lost storm-warning services during the fall of 1883.

One can estimate a general magnitude of potential savings from weather information by multiplying a 35-percent reduction in the fall over summer premium times the average summer shipping rate times the annual bushels shipped times the portion of grain transported in the fall. This calculation, which is only illustrative, gives an approximate figure of \$200,000 in savings per year for fall grain shipments from Chicago to Buffalo. Samuel H. Williamson (1977 pp. 188–89, 212–13) reports that for the years 1873–1886, 60 percent of all Great Lakes grain shipments came from the southern Lake Michigan region, including Chicago. During the same period, grain comprised 27 percent of all Great Lakes shipments by weight. Although other products' times of shipment and distances traveled differed from grain leaving Chicago, the savings implied by these figures are consistent with the estimated transportation savings in Section II.

Marine insurance data for grain shipped from Chicago to Buffalo present another opportunity to confirm the claim that storm-warning information was valuable. Again, a decreasing ratio of fall-to-summer insurance premia would suggest that reductions in risk were due to weather information, since other sources of risk reduction raise the ratio of fall-to-summer insurance premia. The incomplete record of insurance premia shows rates which are extremely sensitive to the shipping season and effectiveness of the Board of Lake Underwriters cartel (Craft, 1995 p. 66). In the three years following the establishment of the storm-warning system during the fall of 1871, summer grain insurance premia rose while fall insurance premia remained constant. These data are consistent with the strengthening of the Board of Lake Underwriters insurance cartel and acknowledgment by the cartel that the risk of fall shipments relative to the summer season had eased.

IV. Social Rate of Return

If one calculates a minimum bound on the value of weather information without explicitly including human lives, one must show that loss of human life did not increase with the advent of storm warnings on the Great Lakes. Signal Service reports (CSO, 1875–1881) record an average 145 lives lost per year due to Great Lakes disasters for the years 1874 to 1876. The figure drops to 100 for the period 1877 to 1881. Annual newspaper accounts from seven years in the 1860's yield an average of 173 lives lost each year on vessel disasters.[19]

In any particular year, the calculated savings in reduced losses to vessels and cargo may be quite plausible, whereas the sum of all the reductions in losses over many years is, in general, not an accurate measure of the social value of reduced transportation costs on the Great Lakes. If vessel owners know or expect weather information to lower the probability of damage to their property or the property they transport, the existence of a storm-warning system lowers the expected cost of transportation on the Great Lakes. A lower equilibrium cost of transportation services implies a higher equilibrium quantity. Safer passage on the Great Lakes increases the level of commerce on the Great Lakes.

Therefore, when one seeks to calculate the social rate of return to the creation of a storm-warning system on the Great Lakes, avoided losses are the relevant benefits to be summed. Assuming an infinitely elastic transportation services supply curve, these benefits correspond to the increased consumer surplus resulting from lowered transportation costs. The standard linear approximation for estimating the first-order effects of the welfare loss if storm warnings did not exist is given by the formula *Lost Consumer Surplus* $= P_1 X_1 \tau (1 - {}^1/_2 \tau \eta)$, where P_1 and X_1 are, respectively, the initial price and quantity of transportation services on the Great Lakes, τ is the percentage price increase in transportation services resulting from the removal of storm warnings, and η is the absolute value of the price elasticity of demand for transportation services.[20]

In effect, Section II estimated $P_1 X_1 \tau$ (a rectangle) as the value of storm warnings on the

[19] See Craft (1995).

[20] See Joseph D. Reid (1970) for a clear and concise extension of such welfare analysis in the evaluation of the British Navigation Acts preceding American independence.

Great Lakes for each year, so a conservative estimate of the social value of the weather service requires the removal of the value $(\frac{1}{2})P_1X_1\tau\eta$ (a triangle) from each year's estimated savings. Assuming an elasticity of demand for transportation services equal to -1.0 and a 10-percent increase in transportation services' costs in the absence of weather information implies a 5-percent downward correction to the estimates in Section II. If the elasticity of supply of transportation services is less than infinite, it can be shown that the preceding correction exceeds the correct adjustment, thereby leading to an underestimate of the value of weather information.

Craft (1995) reports annual budgets of the entire Army Signal Service for 1882 and years thereafter and estimates the resource costs during the earlier years by using data on direct weather appropriations and assuming similar ratios of costs as exist in the complete budgets.[21] Included in these budgets are the construction and maintenance of telegraph lines in the West, as well as the provision of communication services to the Army. The *Annual Report of the Department of Marine and Fisheries* (Canada Department of Marine and Fisheries) lists the expenditures of the Canadian Meteorological Service. Both Canada and the United States wired current meteorological data to the other country's forecasting office. By 1880, combined United States and Canadian meteorological service budgets stabilized at about 1 million dollars.

Given the preceding adjustments, the 1880 present value of weather expenditures and loss reductions is calculated using a 4-percent nominal interest rate which approximates the rate of return on high quality bonds during the 1870's and 1880's (Sidney Homer, 1963 pp. 309–16). The estimated minimum bound on the social rate of return to all weather information expenditures of the U.S. Army Signal Service and Canadian Meteorological Service from 1870 through the first half of fiscal year 1888 is 64 percent.[22] This estimated rate of return and those in footnote 22 include neither the value of weather information on the Atlantic seaboard nor in any other context in the United States or Canada other than transportation on the Great Lakes from 1873 to 1887. Note that the estimated savings due to storm warnings also do not include any of the reduced shipping losses in either the fall of 1871 or 1872. The Signal Service already operated the warning system in the largest ports on the Great Lakes during this time, but the absence of consistent data on losses, wind miles, and Great Lakes tonnage prevents the inclusion of these years in the rate-of-return calculations.

V. Conclusion

Two distinct empirical data sources have offered evidence that the United States Army Signal Service storm-warning service during the 1870's and 1880's on the Great Lakes provided valuable information to shippers. An es-

[21] During the early 1870's, Western Union and various agents of the U.S. government disagreed on the appropriate fees for telegraphy service. The government claimed that the Postal Telegraph Bill of 1866 permitted the Postmaster General to establish telegraphy rates for weather observations. Given Western Union's repeated requests for the government's entire telegraphy business, the telegraphy rates must have exceeded marginal cost. (See the Western Union Letterbooks at the Smithsonian Institution, 1866–1880.)

[22] The corresponding rate-of-return calculation for the linear specification in column (XI) of Table 3 yields 126 percent. One might argue that this is a priori an underestimate of the value of weather information on the Great Lakes, as no variation of weather services at the largest ports occurs in the sample data. Had the semilog estimates in column (VI) been used in the present value discounting procedure, the minimum social rate-of-return calculation would yield 114 percent. See Craft (1995) for the derivation of costs for a Great Lakes weather network of equal forecast accuracy. When estimating the cost of a weather network solely designed for the Great Lakes, the corresponding minimum rate of return rises to 390 percent using the conservative estimates in column (V).

Finally, recall that the point estimate of a semilog specification becomes the median estimate, not the expected value, when the antilogarithm is taken. Since the expected value equals $\exp(\mu + \frac{1}{2}s^2)$, the larger the standard error of the estimate, the greater are the expected losses in the absence of a storm-warning network. Multiplying the storm-warning station coefficient times the number of stations and taking the antilog gives a ratio effect on storm losses. This procedure effectively assumes $s = 0$ and yields rates of return for columns (V) and (VI) of 27 percent and 93 percent, respectively.

timate of the decreased fall grain cargo premium for grain leaving Chicago is consistent with annual total Great Lakes cargo and hull loss reductions ranging from 1 to $4^1/_2$ million dollars, depending on the year. Early federal weather information services were a valuable investment which provided a high social rate of return, even ignoring reduced shipping losses on the Atlantic seaboard and all other uses of the Canadian and United States national weather networks. The marginal storm-warning display station reduced Great Lakes cargo and hull losses by approximately 1 percent in any given year.

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