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The potential impact of climate change on Great Lakes international shipping

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Abstract The higher temperatures of climate change may result in a fall in Great Lakes water levels. For vessels carrying imports into and exports out of the Great Lakes lower lake levels will lead to restrictions on vessel drafts and reductions in vessel cargos, increasing the number of trips and the cost of moving cargo. Estimates of these impacts are derived from simulations of a recent year's international cargo movements, comparing a base case with no climate change to various climate change scenarios. The impacts vary from a 5% increase in vessel variable operating costs for a climate change scenario representing the possible climate in 2030 to over 22% for a scenario representing a doubling of atmospheric carbon dioxide. Impacts vary by commodity and route. For years of naturally occurring low water the impacts are up to 13% higher for even the most moderate climate change scenario. Climate change may also result in a shorter time of ice cover leading to an extension of the navigation season. Climate change is also expected to increase the threat of damage from aquatic invasive species, possibly leading to further requirements for ships to undertake preventive measures.

1 Introduction

This study examines the potential impacts of the lower water levels for the Great Lakes that may result from global climate change on Great Lakes international commercial navigation. International shipping is here defined as shipping by water to or from an American or Canadian Great Lakes port and a port in a country other than the United States or Canada. Cargo originating in or destined for the Great Lakes which moves to or comes from another country after being transhipped at a port in the lower St. Lawrence River or Gulf of St. Lawrence is included.

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The possible significant impacts of global climate change for Great Lakes international commercial navigation are lower water levels and shorter times of ice cover. Since commercial ships in the Great Lakes often operate with minimal underkeel clearances, as low as 0.3 m, lower water levels will mean that these ships may have to reduce the weight of cargo they carry in order to maintain sufficient underkeel clearance. Transporting a given tonnage of a commodity will require additional trips, increasing shipping costs. This impact is estimated by simulating a typical annual pattern of cargo movements under various possible climate change and water level conditions. The second impact, a reduced time of ice cover, could result in an extension of the navigation season as currently, because of ice formation, the locks in the Great Lakes–St. Lawrence River system are closed for at least 2 months a year. This impact is discussed in terms of the adjustments season extension may require.[1] A secondary impact is through climate change = s effect on invasive species and the resulting preventive measures which may be required by ships.

After overviews of international commercial navigation on the Great Lakes and potential effects of climate change on the Great Lakes the impacts on commercial navigation are examined in detail. Possible means of adaptation, alternative transportation modes, and qualifications to the analysis are also discussed.

2 International commercial navigation in the Great Lakes

The Great Lakes–St. Lawrence River system provides a strategically located, convenient, efficient, and environmentally sound means of transporting commodities between ports in a heavily industrialized part of North America and to and from overseas markets. Using this system of lakes, rivers, and canals vessels can travel 3,700 km inland from the Gulf of St. Lawrence, up the St. Lawrence River, through the Great Lakes, to the head of Lake Superior. Ports located as far west as the midwestern states of Wisconsin and Minnesota and in northwestern Ontario can be directly accessed from the Atlantic Ocean and can ship by water to the world = s oceans. The present system was completed in 1959 with the opening of the St. Lawrence Seaway, a joint Canada–United States project, which allowed larger ships to travel between Lake Ontario and Montreal. Other obstacles to navigation between the Great Lakes had been overcome earlier by the construction of locks between Lakes Superior and Huron and the construction of the Welland Canal between Lakes Erie and Ontario.

International commercial navigation is transported by both domestically registered (Canada and the United States) and internationally registered (all other countries) ships. The domestically registered ships carrying export or import shipments from or to Canada and the United States mainly operate between the Great Lakes and the lower St. Lawrence River and the Gulf of St. Lawrence. Typically they are loaded at a port in the Great Lakes, travel out of the Lakes, and unload at a transhipment port such as Montreal or a port further east. Their cargo is then loaded onto an ocean-going ship for shipment to an overseas market. Some shipments by domestically registered vessels are the reverse, loading an imported commodity at a lower St. Lawrence River port and unloading in the Great Lakes.

[1] See Millerd (2007) for further information on this project.

All vessels carrying import or export cargo to or from the Great Lakes are limited in size by the dimensions of the St. Lawrence Seaway locks between Montreal and Lake Ontario. The Seaway locks can accommodate vessels up to 740 ft in length and 78 ft wide. The maximum allowable draft is 26.5 ft. Most of the American and Canadian Great Lakes vessels carrying export or import cargoes were built specifically for operation in the Great Lakes and Seaway. They are operated to take advantage of maximum water depths in ports and connecting channels; their usable capacity declines with even small decreases in water depths. If a lake vessel has to reduce its draft by 3 ft, its cargo capacity is reduced by 15%. Under-keel clearances in harbours and connecting channels are often minimal.

Internationally registered ships participate in two flows of cargo. Some only move commodities from or to transhipment points in the lower St Lawrence River and Gulf of St. Lawrence and, never entering the Seaway, have few restrictions on their size and draft. The water depths and dock facilities at transhipment ports in the lower St Lawrence River and Gulf of St. Lawrence allow the use of larger ships then those entering the Seaway.

Other internationally registered vessels come into the Great Lakes to deliver commodities from overseas and take on export shipments; they are constrained by the dimensions of the Seaway locks and the limited water depths in the canals and many Great Lakes ports. With water depth limitations in the Great Lakes–St. Lawrence system the weights of cargoes carried by these vessels may be limited, often resulting in the topping-up of export cargoes in the lower St. Lawrence River or Gulf of St. Lawrence after vessels have left the Seaway. Many of these vessels were built for trading into the Great Lakes and make regular trips into the lakes. Others are chartered for single trips into the lakes. Some international vessels are the maximum allowable Seaway length and width, similar to the dimensions of lake ships. More recently built ships have a lower length to width ratio with a length less than the maximum possible in the Seaway but still the maximum allowable Seaway width. These newer ships are better able to withstand the stresses on their hull during ocean voyages and are more easily accommodated at overseas ports.[2]

3 Climate change and the Great Lakes

Climate change will likely be manifested in the the Great Lakes area by higher temperatures, possibly causing increased evaporation and evapotranspiration, lower runoff into rivers and lakes, higher lake temperatures; and reduced ice formation with shorter periods of ice cover. Rainstorms may be more intense and, due to higher temperatures, more precipitation may fall as rain rather than snow. A number of authors report that overland evapotranspiration may increase and total runoff to the lakes may be lower due to the higher temperatures. Also, runoff may peak earlier due to a lower snowpack, changing the seasonal distribution of water levels. Overall, the average steady-state supply of water to the lakes may decrease, resulting

[2]Phillippe Rodenburg, Manager, Operations, Fednav International Ltd., Montreal, QC, telephone interview by author, 23 January 2007; National Research Council of the National Academies (2008) p. 65.

in lower lake levels and lower connecting channel flows. Any increases in precipitation are not expected to be sufficient to overcome the increased evaporation and evapotranspiration. (Chao 1999; Croley 1990; Easterling and Karl 2001; Hartmann 1990a, b; Mortsch and Quinn 1996) This study examines the implications of lower water levels in the Great Lakes, but some predict that Great Lakes water levels may not fall or may even rise as a result of climate change. Manabe et al. (2004) and Milly et al. (2005) after modeling future world-wide changes in water availability due to climate change predict that run-off will increase in high latitude northern areas, resulting in higher levels for the Great Lakes. The Manabe et al. (2004) simulations show an increase in the flow of the St. Lawrence River. Kutzbach et al. (2005) report on simulations from eight climate change models using two greenhouse gas emission scenarios. Averaging the model results shows that the Great Lakes will experience increased moisture but the actual change in the annual water balance was in doubt due to variations between models in precipitation and evaporation. Lofgren (2004), using a regional climate model based on simple conservation laws, found both increases and decreases in net supplies to the Lake Superior drainage basin, depending on the time period considered. Angel and Kunkel (2009) examined the results of a large number of runs from a variety of global climate models and found a wide range of lake levels predicted. Lofgren and Wilbarger (2009) suggest that the regional hydrologic models used in forecasting lower water levels predict too great an increase in evapotranspiration, thus raising the question of the suitability of these models.

There is evidence that the climate of the Great Lakes is already changing. Kling et al. (2005) report that winters are shorter, average annual temperatures are rising, and the duration of lake ice cover is decreasing as air and water temperatures rise. An assessment report states that over the last 30 years the maximum amount of ice forming on each of the five lakes each year is decreasing. (State of the Lakes Ecosystem Conference 2006) A recent study from the University of Minnesota Duluth reports that since the late 1970s Lake Superior has warmed more rapidly than the air temperature due to the shorter duration of ice cover and increased heat storage. (Austin and Colman 2007) Sellinger et al. (2008) examined long term water level data for Lakes Michigan and Huron, finding a lake level decline starting about 1973 and, although not certain the decline is due to global climate change, suggest that future planning include the possibility of permanently lower lake levels. McBean and Motice (2008), after examining 70 years of Great Lakes meteorological and hydrological data, conclude that some of the hydrologic changes occurring in some of the Great Lakes may be due to climate change.

4 Previous work

Several previous studies report on the impact of climate change on shipping costs. Marchand et al. (1988) used output from the Goddard Institute of Space Studies general circulation model with which the atmospheric concentration of carbon dioxide was doubled and the climate allowed to stabilize at a new level in the future. Output from the general circulation model provided input into a hydrologic model developed by the US Army Corps of Engineers. Lake levels were forecast to be

0.2 to 1.6 m lower. With no change in tonnages shipped or in the composition of the fleet, average annual costs for Canadian Great Lakes shipping were estimated to increase by 5%. Higher cost increases, up to 33%, were found when larger vessels were used, coal shipments increased, and the consumptive uses of water, which further reduced lake levels, increased.[3] Chao (1999) used a variety of steady state and transient general circulation models linked to a hydrologic model to determine future water levels and flows. In all cases water levels declined, resulting in increases in shipping costs, up to 35% for the US and up to 20% for Canada.

More recently Schwartz et al. (2004) assessed the potential impact of lower water levels on the Lake Huron community of Goderich, Ontario. With an arbitrary 1 m drop in water levels vessel capacity would be reduced by 30%. Alternatively, dredging could be undertaken at a cost of up to $7 million. Millerd (2005) used water levels projected by a hydrologic model receiving input from a general circulation model to estimate the impact of climate change on annual vessel variable operating costs for shipments between Canadian ports and between Canadian and American ports. A doubling of the atmospheric concentration of carbon dioxide is projected, using the CCCma GCM1 general circulation model and IS92a emissions scenario, to lower average water levels by 0.23 to 1.62 m and increase variable vessel operating costs by 29%. The CCCma 2050 general circulation model using the IS92a emissions scenario, with a gradual 1% increase in carbon dioxide, results in a 13% increase in annual vessel variable operating costs by 2050, due to water level declines of 0.31 to 1.01 m. The impacts vary by commodity and route. If water levels are already low the impacts will be even greater.

5 The impact of lower water levels on international commercial navigation

The impact of lower water levels on commercial navigation is estimated by simulating international cargo movements in a recent year, 2001, first, with no climate change effects but allowing for seasonal and annual changes in water levels, then with various magnitudes of climate change, still allowing for seasonal and annual changes in water levels. The vessel variable transportation costs for the base case with no climate change are compared with the costs for the climate change cases to estimate the costs imposed by the lower water levels due to climate change. In this section the data used and its sources are reviewed, the climate change scenarios described, the methodology outlined, and the results presented.

5.1 Data used

The simulation requires data on cargo shipped by origin, destination, and commodity; vessel characteristics, including their capacity at various water depths and changes in draft and cargo tonnage capacity with changes in water depths; vessel variable operating costs for vessel movements between each origin and destination; Seaway fees and port tolls; base case water depths encountered between and at each origin and destination; and water depths under various climate change scenarios. Each data requirement and source is discussed below.

[3]Consumptive uses of water are not now projected to have a significant impact on water levels.

5.1.1 Tonnages shipped

Cargo movements by port and commodity for 2001 were obtained from Statistics Canada and the Institute for Water Resources of the US Army Corps of Engineers. Merging the data required the use of a common commodity classification. Canadian data used the Standard Classification of Transported Goods; American data were transformed to this classification system.[4] Shipment data for 2001 were used as Canadian origin–destination–commodity data had previously been compiled and the 2001 shipment pattern was representative of recent years. An evaluation of the use of 2001 data may be found below.

The international cargo movements considered here are those from or to an American port or a Canadian port and a country other than the United States or Canada. The data set consists of 116 origin–destination–commodity combinations. These international cargo movements are all exports or imports but exports and imports between the United States and Canada are not considered. Unfortunately the American data do not provide the country of origin or destination for international shipments. Thus all shipments were assumed to move to or from the Gulf of St. Lawrence.

International shipments are a significant part but not all the commercial navigation traffic in the Great Lakes–St. Lawrence system. Large volumes of freight also move between Canadian ports, between American ports, and between Canadian and American ports.[5] International shipments are a large proportion of the traffic on the Seaway. In 2001, 49.2% of the cargo passing through the Montreal–Lake Ontario section of the Seaway was estimated to be international cargo. Another indication of the importance of international shipments is that 50.7% of the transits of the Montreal–Lake Ontario section of the Seaway were vessels not registered in either Canada or the US. Additionally, many domestically registered vessels would be carrying international cargo to or from a transhipment point. International shipments travel considerable distances in the Great Lakes–St. Lawrence Seaway system. These cargos are usually destined for or originating on the upper or western lakes, moving between the lakes and ocean through the Seaway. In contrast most shipments between Canadian and/or US ports are relatively short hauls but do account for considerable tonnage. In 2001 25% of the total tonnage shipped on the system was iron ore, primarily moved on the upper lakes; 21% was sand, stone and other non-metallic minerals moved on the upper lakes; and 10% was coal loaded at a Lake Erie port primarily for the short movement across Lake Erie. The result is that, on a simple tonnage bases, international shipments represent 10.6% of the total tonnage moved in the Great Lakes in 2001, although on a ton-mile basis international shipments would be a much higher proportion.

Table 1 presents a grouping of similar origin–destination–commodity combinations used in the analysis. The export of grains and other agricultural products takes

[4]The transformation of American data to the Standard Classification of Transported Goods (SGTC) structure was done for computational efficiency as the custom-written computer programs used the SGTC coding system. Since only broad groupings of commodities were used there was no impact of this reclassification.

[5]Millerd (2005) presents an analysis of the impact of lower water levels on shipments between Canadian ports and between Canadian and American ports.

Table 1 Exports and imports to and from outside Canada and the United States, 2001

Commodity group and route	Country of origin or destination	Metric tonnes	% of total exports & imports
Grains and agricultural	Can.	2,222,235	13.66
products exported directly overseas	U.S.	2,727,768	16.76
Grains and agricultural products	Can.	3,805,869	23.39
exported, shipped to lower St. Lawrence River for transhipment	U.S.	2,145,535	13.19
Other exports, incl. petroleum products, forest	Can.	436,444	2.68
Other exports, incl. forestry products, base metals	U.S.	146,098	0.90
Imports of base metals and articles of	Can.	886,065	5.45
base metal	U.S.	2,161,978	13.29
Other imports, incl. sugar, petroleum products	Can.	1,102,111	6.77
Other imports, incl. forestry products, metallic ores	U.S.	637,024	3.92
Total exports and imports		16,271,127	100.00
Total exports and imports, by country	Can.	8,452,724	51.95
	U.S.	7,818,403	48.05

Sources: Statistics Canada and Institute for Water Resources, US Army Corps of Engineers

place either through ocean going ships loading in Great Lakes ports and moving directly to overseas ports or through grain shipped by lake freighter to ports in the lower St. Lawrence River or Gulf of St. Lawrence for transhipment to ocean going ships. Ocean going ships which take on grain in the Great Lakes may also load additional grain in the lower St. Lawrence River and Gulf of St. Lawrence.

Two-thirds of the export and import tonnage transported in the Great Lakes is grain and other agricultural products for export. The major imports are base metals and articles of base metal, such as flat-rolled products of iron or steel and bars, rods, angles, shapes, sections, and wire of iron or steel. A variety of other imports make up 10.7% of international shipments. On a tonnage basis, exports are 70.6% of the total international cargo, imports are 29.4 per cent. The total tonnage of exports and imports is slightly greater for Canada than the United States.

5.1.2 Vessel characteristics

Lake vessels and ocean vessels are used for international shipments in the Great Lakes. As mentioned above lake vessels move grain and other agricultural products from Great Lakes ports to the lower St. Lawrence River and Gulf of St. Lawrence for transhipment. Ocean vessels move a variety of commodities into and out of the Great Lakes. For the commodity flows in Table 1 bulk carrying lake vessels (lakers) are assumed to move all grain and agricultural products to the lower St. Lawrence for transhipment and ocean-going vessels are assumed to move all other commodities. This is a typical allocation of cargoes by vessel type in the Great Lakes–St. Lawrence River system.

Both lake and ocean ships have possibilities for moving cargo in both directions, into and out of the Great Lakes. Many ocean ships bring imported iron and steel products into the lakes and take out export grain. Lake ships moving export grain out of the lakes to the lower St. Lawrence River or Gulf of St. Lawrence will often take on a cargo of iron ore at a Gulf of St. Lawrence port for delivery to a Great Lakes steel mill, shipments which are not considered to be imports here and are thus not included in the analysis.

To determine vessel immersion factors, the change in vessel draft with a change in tonnage carried, and daily vessel variable operating cost data were obtained for a representative lake vessel and a representative ocean-going vessel.[6] Vessel variable operating costs include crew wages and subsistence, fuel, stores and supplies, and normal maintenance and repairs. Vessels in the Great Lakes–St. Lawrence River system are often loaded so that they operate with minimal under-keel clearances, the minimum allowable clearance being 1 ft or 0.3 m. Lower water levels which reduce water depths may force vessels to reduce the amount of cargo they can carry.

5.1.3 Travel times, fees and tolls

Sailing distances between ports were obtained from Greenwood (2002), by measuring distances on navigation charts published by the Canadian Hydrographic Service, and from Canadian Hydrographic Service sailing directions. Fees and tolls are those of the St. Lawrence Seaway. (www.greatlakes-seaway.com, 10 January 2007)

5.1.4 Port and channel depths

Water depths at potential route constraint points, connecting channels, locks, the Seaway, and ports were provided by Greenwood (2002), the St. Lawrence Seaway Management Corporation, navigation charts, sailing directions, and Schulze et al. (1981). Various world-wide web internet sites provided additional port information.

5.2 Water level scenarios

5.2.1 Benchmark

Estimates of the impact of climate change require a benchmark, the water levels which would occur without climate change, against which any changes in water levels due to climate change can be compared. The benchmark, labelled the Basis of Comparison (BOC), takes into account naturally occurring annual and seasonal variations in water levels, providing an indication of the water levels that would occur without climate change. The BOC is established by linking the annual and seasonal variation over the 90-year period, 1900 to 1989, with the current set of regulation plans, structures, channels, and diversions to estimate a set of water levels that would have occurred each month of the 90-year period from 1900 to 1989 if all current regulation plans, structures, channels, and diversions had been in effect over that period. The hydrologic conditions that occurred over these 90 years are applied to

[6] Information on vessel characteristics is from Greenwood (2002), Seaway Marine Transport, and Fednav International Ltd. Operating costs are from US Army Corps of Engineers, Detroit District (2002) and industry sources. The representative lake vessel does not have self-unloading gear as this is the type of vessel most commonly used for shipping grain.

current water management procedures and structures to derive a set of monthly water levels for each of the 90 years for various locations on the Great Lakes and St. Lawrence River.

5.2.2 Climate change scenarios

Estimates of the impact of climate change on the Great Lakes–St. Lawrence River system were developed by using the output from General Circulation Models (GCMs) to develop climate change scenarios which provided input for hydrologic models of the Great Lakes. The atmospheric conditions created by climate change are used to project the resulting hydrologic situations. The General Circulation Models are numerical representations of the atmosphere and its phenomena which simulate weather and climate conditions for all or for regions of the Earth. Increases in the atmospheric concentrations of greenhouse gases, a cause of climate change, are introduced into a GCM and the resulting climate conditions noted. Greenhouse gases, primarily CO_2, may be gradually increased and the changing climate observed, a transient model, or instantaneously increased and the model run until the climate is in equilibrium, an equilibrium model. Sulphate and other aerosols, which provide a cooling effect, the opposite of greenhouse gases, may also be introduced. The resulting temperature and precipitation data can then be used to derive changes in hydrologic conditions, including evaporation, evapotranspiration, runoff, and lake levels.

For the analyses reported here several projections of water levels, termed water level scenarios, are used. Mortsch et al. (2000) have estimated the impacts on water levels of climate change on the Great Lakes using climate change scenarios developed from several GCMs. This study uses the following three scenarios, labelled by the GCM used in their development:

CCCma 2030: Canadian Centre for Climate Modelling and Analysis, a time slice from a transient run

CCCma 2050: Canadian Centre for Climate Modelling and Analysis, a time slice from a transient run

CCC GCM1: Canadian Climate Centre, General Circulation Model 1, an equilibrium doubling of CO_2 run

The transient scenarios (CCCma 2030 and CCCma 2050) are developed from different time periods within the same global climate change model run that simulates the response of the climate system to a gradual increase in greenhouse gases and sulphate aerosols. The period 1961–1990 is the base climate. Greenhouse gases and aerosols increase at past rates up to 1990. After 1990 the IS92a emission scenario, where emissions increase by 1% a year until 2100, was used as an estimate of future emissions.[7] The year 2030 represents an average of 2021 to 2040; 2050 represents an average of 2041 to 2060. Climate change is the difference between the base and 2030 and the base and 2050. A drier and warmer climate is indicated with runoff and outflow decreasing and evapotranspiration and lake evaporation increasing, resulting in lower lake levels. (Mortsch et al. 2000, pp. 156, 171–2) For the CCC GCM1

[7]Environment Canada (2007)

scenario, the atmospheric concentration of CO_2 is doubled and the climate allowed to stabilize at a new level. The cooling effect of sulphate aerosols is not considered. Water levels are lowered with less yearly runoff for all the lakes. (Mortsch et al. 2000, pp. 155, 171)

For the benchmark BOC, monthly water levels at various locations in the Great Lakes - St. Lawrence River system were provided by Environment Canada for the 1900 to 1989 period. These levels were modified by Environment Canada to provide water levels for each of the three climate change scenarios. Table 2 indicates the average change in water levels at selected locations for each of the climate change scenarios, compared to the Basis of Comparison. Except for Lake Superior the impacts are greatest for doubling the atmospheric concentration of CO_2 and least for the earlier transient scenario. The BOC data are levels above a datum in the Gulf of St. Lawrence, not depths.

5.3 Estimated impact of lower water levels

The potential impacts of lower water levels were estimated by computing the average annual vessel variable operating costs for Great Lakes international commercial navigation under the BOC and for each of the climate change water level scenarios, using a simulation program, and then comparing the costs for each of the climate change scenarios to the costs for the BOC. For the BOC and each climate change scenario the 2001 pattern and volume of international shipments is applied to the water levels generated by the scenario and the average annual vessel variable operating costs of moving the various commodities computed. The differences in vessel variable operating costs between the BOC and the climate change scenarios are the estimated impacts of lower water levels. Annual shipments are evenly allocated over the navigation season to account for changes in seasonal maximum allowable vessel drafts and seasonal changes in water levels.

The computer simulation minimizes the vessel variable operating costs of moving the internationally traded commodities under each water level scenario, subject to the following constraints:

- Weight and volume of cargo to be shipped, by commodity, route, and season. The vessel variable operating costs for each scenario must include all commodities shipped during the example season of 2001.

Table 2 Average change in water levels, by climate change scenario

Location	Basis of comparison average annual level, metres	Average annual decrease from Basis of Comparison, metres		
		CCCma 2030	CCCma 2050	CCC GCM1
Lake Superior	183.34	0.22	0.31	0.23
Lakes Michigan and Huron	176.44	0.72	1.01	1.62
Lake Erie	174.18	0.60	0.83	1.36
Lake Ontario	74.84	0.35	0.53	1.30
Montreal Harbour	6.49	0.45	0.62	1.41

Levels based on International Great Lakes Datum 1985. Source: Environment Canada

- Vessel capacity, the maximum load the vessel can carry with no other constraints. This cannot be exceeded.
- Season of the year. For vessel safety the maximum allowable draft and capacity is greatest in the summer and lowest in the winter as the most severe weather is expected in the winter.
- Time required for loading, unloading, and travel.
- Minimum water depths encountered on a route. For each route the water levels and depths at the origin and destination ports, the connecting channels, and the locks and Seaway are examined to determine the minimum depth. The minimum depth encountered on the route for each voyage is then a determinant of the amount the vessel can carry on that route and during that season. Required under-keel clearances are always maintained.

Given the total weight of a commodity to be shipped between an origin–destination pair of ports and the available capacity for the type of vessel used, the total number of voyages required for each commodity and each origin–destination pair is computed for each of the years from 1900 to 1989. The length of each voyage, the number of vessel-days required, is a function of the number of days required for loading and unloading and for travel between the origin and destination ports, taking into account delays at locks and channels and speed restrictions. The total vessel-days required for each origin–destination–commodity combination is determined by multiplying the length of the voyage in days by the number of voyages required.

Origin–destination–commodity combination vessel variable operating costs are determined by multiplying total vessel-days by daily vessel variable operating costs, defined above. The total vessel variable operating cost for a commodity is the sum of the costs for all origin–destination pairs involving that commodity. The vessel variable operating cost for a scenario is the sum of these costs across all commodities. Variable costs other than those for the daily operation of the vessel, fixed costs, and profits are not included.

The total vessel variable operating costs by commodity and scenario are computed for each of the 90 years, 1900 to 1989, of water level data and annual averages computed. The average annual vessel variable operating costs for each climate change scenario are compared and contrasted with the average annual vessel variable operating costs for the benchmark Basis of Comparison.

Over the 90 years for which costs are calculated for each scenario the only variable is hydrologic conditions. A fixed pattern of shipments and current daily vessel variable operating costs are used in computing total costs for each of the 90 years. The cost calculations for each year use the hydrologic conditions for that year but shipments and daily vessel variable operating costs are the same for all years. Thus the average for 1900 to 1989 indicates the costs for average hydrologic conditions.

The percentage increases in vessel variable operating costs for each of the climate change scenarios are presented in Table 3. The table shows the annual average vessel variable operating costs for the BOC and the percentage increase in average annual vessel variable operating cost over the 1900–1989 period for each of the three climate change scenarios, by commodity group and route. As expected the overall increase in cost is greatest for the doubling of CO_2 scenario, the scenario with the greatest water level decreases; less for the 2050 transient scenario; and least for the 2030 scenario, the scenario with the smallest decreases in water levels. But even with the 2030 scenario total vessel variable operating costs are estimated to increase by

Table 3 Climate change scenario average annual cost comparisons with the basis of comparison

Commodity group and route	Country	BOC average annual costs, $ Can.	% increase in average annual costs over BOC, by climate change scenario		
			CCCma 2030	CCCma 2050	CCC GCM1
Grains and agricultural products exported directly overseas	Can.	17,619,824	5.31	9.76	23.47
	U.S.	23,622,519	4.95	9.30	22.62
Grains and ag. products exported, to lower St. L. R. for transhipment	Can.	35,657,559	5.63	10.53	26.73
	U.S.	20,355,006	4.15	7.96	21.71
Other exports	Can.	3,492,575	7.36	12.16	25.56
	U.S.	1,323,207	6.29	10.94	24.47
Imports of base metals and articles of base metal	Can.	5,856,075	3.35	5.48	14.97
	U.S.	19,711,794	3.50	6.44	16.55
Other imports	Can.	5,686,766	1.89	3.56	13.30
	U.S.	5,735,336	5.90	9.82	21.84
Total exports and imports		139,060,660	4.77	8.78	22.14

approximately 5%.[8] The doubling of CO_2 scenario would result in a cost increase of 22%.

The annual average increases vary by commodity group depending on the total amount shipped, the distances shipped, and allowable vessel loads. The other exports group has percent increases in cost greater than the overall average while the base metal imports group shows percent increases in cost below the average.

The variation by commodity group in the average annual cost data for the BOC reflects the variation in tonnage shipped for each commodity group, as presented in Table 1. The implication of this is that the absolute burden of the cost increases due to climate change will not be uniformly distributed between commodity groups. The large shipments of grains and other agricultural products mean that these commodity groups together bear approximately three-quarters of the dollar value of cost increases.

The results presented are the costs using current prices as of the example year, 2001, for a future year when the full impact of a climate change scenario has occurred. The costs are not the present value of the future impacts of a climate change scenario. The impact of climate change will not occur immediately; it may be gradual with an

[8]Due to natural annual and seasonal variation in levels the low levels estimated for 2030 have been experienced in the past and the shipping industry appears to react as predicted. Under the headline A Shallow Waters Lighten Loads ≅ a business publication recently reported:

> A Record low water levels for this season on the Upper Great Lakes are creating concern for commercial shipping lines.… [The] president of the Lake Carriers Association estimates that 75 percent of their ships are carrying less cargo than they could if they had appropriate water levels.… Lightening loads leads to a big inefficiency in the system. It requires more trips using more fuel, manpower and time. ≅ (Northern Ontario Business, 6 November 2006).

increasing effect over time or it may occur more quickly with rapid changes in water levels, especially if a significant climate threshold is reached.

5.4 Historically low and high water years

The natural variation in hydrologic conditions is considerable over the 1900 to 1989 period. Years with naturally determined high water levels allow vessels to carry greater loads and are generally favourable to commercial navigation; years with naturally determined low water levels limit vessel capacities and are unfavourable to shipping. The possible water level decreases due to climate change will compound the effects of naturally occurring low water levels.

The impact of natural variation was examined by comparing years with abnormally low water levels and years with abnormally high levels with the BOC for each of the water level change scenarios. The lowest and highest years are not the same for all lakes and locations; 1964 was the lowest year for Lakes Michigan, Huron, and Erie and Montreal Harbour; 1965 was the lowest year for Lake Ontario. For the highest years, 1986 was the highest year for Lakes Michigan, Huron and Erie, 1987 for Lake Ontario, and 1973 for Montreal Harbour.

Table 4 presents comparisons of the highest and lowest average level years with the 1900 to 1989 average annual vessel variable operating costs, by scenario. The percentage differences indicate the extent to which naturally occurring low water levels compound and naturally occurring high water levels offset the effects of climate change. As expected the cost increasing impact of climate change would be even greater in naturally occurring low water years. For a low water year similar to 1964 the 2030 scenario generates a 13% further increase in cost over the average decrease in cost for the 2030 scenario. The 2050 and doubling of CO_2 scenarios result in even greater cost increases over the average increases for these scenarios.

In the naturally occurring high water years the cost increasing impacts of climate change are ameliorated by higher water levels, with one exception. A high water year similar to 1986, for example, would result in the cost increase due to climate change being 5% less under the 2030 scenario. Under the 2050 and doubling of CO_2 scenarios there are even further offsetting effects for the high water years. The exception is the BOC for 1973, a year of high water levels for Montreal harbour but not necessarily everywhere in the Great Lakes–St. Lawrence River system. Some areas other than Montreal harbour experienced low water levels resulting in an overall small increase in cost for the BOC in 1973.

Table 4 Cost comparisons for historically low and high water years

Year		% change in vessel variable vessel operating cost, for low and high water years, by climate change scenario			
		BOC	CCCma 2030	CCCma 2050	CCC GCM1
Low water level years	1964	5.19	13.34	15.49	18.12
(increase in cost)	1965	2.08	9.10	10.90	12.88
High water level years	1973	1.22	−1.47	−4.41	−6.22
(decrease in cost)	1986	−0.64	−4.89	−8.17	−14.21
	1987	−0.52	−1.89	−4.69	−5.26

6 Adaptation

This estimation assumes that vessel operators, shippers, and water management authorities take no adaptation, remedial, or avoidance measures other than reducing vessel loads. The model does not allow for reductions in total amounts shipped, shifts to alternative modes, or suspension of shipments for routes when low water levels make shipping uneconomic. Such actions are difficult to predict.

Although in the short run, with no change in the fleet or facilities, vessel loads are reduced with the consequent increases in the number of trips and shipping costs estimated here, in the long run further adaptation may occur. If average water levels were to permanently drop or be lower for a significant part of most navigation seasons, cost-effective remedial measures would be carried out. Lake regulation policies could be used to offset lower water levels, diversions into the Great Lakes could be increased, and diversions out of the lakes decreased. But opportunities for influencing lake levels are limited. Only Lakes Superior and Ontario have outlet control structures which can hold back or release water. Also, if water levels and flows change drastically, water regulation plans may not be able to achieve acceptable water level and flow targets.

Harbours and connecting channels could be dredged, although many will have contaminated material which is costly to handle or rock bottoms requiring drilling and blasting. Vessels specially designed for more efficient operation with lower water levels could be constructed and dock facilities adapted for lower water levels (de Loe et al. 2001; Quinn 2001).

Vessel operators have adapted in the past. Larger vessels were built when the Seaway was opened and when an even larger lock was opened between Lakes Superior and Michigan-Huron.

Various changes in vessel operation could also be used to avoid or minimize low water situations. Shipments could be rerouted to ports less affected by low water levels. Part of a vessel = s cargo could be unloaded at a deep water port and the remainder unloaded at a port with shallower water. Similarly, a vessel could begin loading at a shallow water port and continue loading at a deeper water port. Many ocean going vessels now handle their outgoing grain cargos in this way, part loading in the lakes and finishing loading at the deep water ports on the St. Lawrence River and Gulf of St. Lawrence. One technique used by self-unloading lake vessels, which have a long conveyor boom for unloading, is to hold the vessel off the dock where shallow water may be present and bridge the gap by swinging the end of the boom over the dock.

7 Alternative modes and routes

For many commodities alternative modes and routes are available and could become more competitive as the cost of Great Lakes water transport increases. Grain exports are a prime example of this. Grain shipments can avoid the Great Lakes–St. Lawrence River system by shipping by rail to lower St. Lawrence River ports, western Canadian ports, the port of Churchill, Manitoba, or, possibly in combination with barge transportation, Gulf of Mexico ports. Barge transportation to Gulf of Mexico ports, however, could also be affected by water level changes due to climate change.

The cost of shipping grain by various routes was estimated by Sparks Companies in a 2000 report for Transport Canada, using energy costs at that time. They present the following cost comparisons for shipping a tonne of wheat from Winnipeg to Egypt, one of the example overseas markets used:

Route	$Can/tonne	% above lowest
Rail to Thunder Bay, ocean-going vessel (lowest cost)	69.06	–
Rail to Churchill, ocean-going vessel	70.76	2.5
Rail to T. Bay. laker to lower St. L., ocean-going vessel	73.70	6.7
Rail to Quebec city, ocean-going vessel	77.40	12.1
Rail to New Orleans, ocean-going vessel	79.34	14.9
Rail and barge to New Orleans, ocean-going vessel	87.64	22.6

Shipments out of Thunder Bay on ocean-going vessels were the lowest cost in 1999, the time of the study. Ocean going vessels have several cost advantages; they are usually foreign-registered, allowing them to use lower cost foreign crews and pay lower taxes and capital costs. Most of these vessels bring cargo into the Great Lakes and thus can offer attractive rates on their return journey. Also, with an ocean-going ship there is no need to tranship all the cargo in the lower St. Lawrence River, as with a laker, thus avoiding some elevator costs. The route through Churchill, Manitoba on Hudson = s Bay is shown as attractive economically but has capacity limitations and, currently, a shorter shipping season, July to November, than Thunder Bay with its late March to late December season.

8 Qualifications

Any analysis of this type is subject to a number of qualifications. Some arise from the assumptions used in the simulations, others because of possible future changes.

8.1 Assumptions

8.1.1 Use of 2001 data

The analysis is based on the 2001 pattern and volume of shipments of exports from and imports to the Great Lakes. The validity of using 2001 data may be assessed by comparing 2001 with other recent years. Ideally export and import shipments for 2001 should be compared with export and import shipments for other recent years but, since considerable export grain, from both Canada and the United States, is transhipped at a Canadian port on the lower St. Lawrence River or in the Gulf of St. Lawrence, all shipments destined for export cannot be identified without detailed data for all years, data which is not readily available for years other than 2001. Table 5 gives total transits and tonnage shipped through the Montreal–Lake Ontario section of the Seaway, for both international and domestic trade. The year 2001 appears to be representative of recent years, with total tonnage just 4.7% below the 2000–2007 average.

Table 5 Montreal–Lake Ontario, transits and cargo, 2000–2007

Year	Transits	Cargo, tonnes
2000	2,977	35,406,212
2001	2,588	30,277,824
2002	2,612	30,002,292
2003	2,579	28,900,440
2004	2,683	30,800,380
2005	2,695	31,273,322
2006	2,953	35,546,000
2007	2,878	31,959,000
Average 2000–2007	2,746	31,770,000

Source: St. Lawrence Seaway

8.1.2 Operational efficiencies

The costs presented here are estimates only and are primarily presented for comparison purposes. They are underestimates of actual costs as certain operational efficiencies are assumed which may not always be possible during actual operations. The analysis is based on the operating costs for a series of one-way voyages, hauling the current volumes, and operating within the current navigation season. The costs of return or positioning trips are not included since some return trips are made with revenue-producing cargo. When lower water levels necessitate additional voyages to move a given amount of cargo between an origin and destination additional empty return or positioning trips may also be necessary, another cost of lower water levels. Not including these additional trips without cargo leads to an underestimate of the impacts of lower water levels.

The additional costs of the empty return or positioning trips could possibly be estimated by developing a model which includes minimizing the amount of travel by vessels with no cargo then estimating the costs of all trips, including those with cargo and those without cargo. Additional constraints for this minimization would be introduced by the timing of cargo flows, fleet sizes, and vessel operating procedures. For example, not all vessels handle all cargoes, a constraint on minimizing the travel of vessels with no cargo. The simulations assume vessels are always loaded to their available capacity, which, for reasons other than water depths, may not always occur.

The study accounts for seasonal variations in water levels by evenly spreading the tonnages shipped over the period of the year, March to December, when navigation is open and over which seasonal variations in water levels will occur. Vessel operators, however, may not similarly allocate shipments over the navigation season, but instead take advantage of seasonally high water levels by scheduling additional shipments during high water periods.

Capital costs of vessels are not included, only those costs which vary as the result of the number of days operated are presented. If additional trips are required fleet additions may be necessary but, as discussed below, the current fleet could handle additional voyages if an extended navigation season is allowed by reduced ice cover.

The estimates presented are estimates of the vessel variable operating costs of transporting various commodities. The prices vessel operators charge to shippers will depend on this cost but will also be influenced by the volume shipped, the possibility of a back haul, the availability of competitive modes, and other contract conditions. The impact of higher costs may not always be reflected in higher prices to shippers.

8.2 Other potential impacts of climate change

Climate change may also have other impacts on commercial navigation. Extreme weather events may become more intense and frequent, forcing vessels to delay voyages and vessels may be forced to control engine exhaust emissions or buy emission credits under a cap and trade system, an additional expense.

Environmental considerations may make the transport of other cargoes into, out of, and between the Great Lakes more attractive. The use of water transportation to ship cargo, particularly containers, in and out of the lakes has several environmental benefits, including reduced energy consumption and emissions compared to truck or train use, reduced traffic congestion with less need to build and repair the highway infrastructure, and improved use of water transportation systems, which have significant room for traffic expansion. Currently, there are several proposals for shipping containers between Great Lakes and overseas ports.

Climate change may also affect other modes and routes and the demand for and supply of those commodities now shipped on the Great Lakes. For example, the total production of grain and the location of its production may change, affecting the demand for grain transportation. Individual routes may become more or less attractive. With less ice in the north, the port of Churchill, Manitoba, may become more active, taking traffic from the Great Lakes. A limited amount of grain is now shipped from Churchill but the port's capacity could be increased and the rail line to Churchill improved.

Climate change and the resulting lower water levels in the Great Lakes could reduce the flow of the St. Lawrence River thus reducing levels and depths in Montreal and deep water ports further down the river. Considerable traffic, particularly containers, moves to and from Montreal which could be adversely affected by climate change and similarly, but to a lesser extent, for ports further down the St. Lawrence River. The results presented here are only for shipments to and from Great Lakes ports.

8.3 Future traffic patterns

Freight traffic patterns could be considerably different in the future for a variety of reasons. Relative shipping costs for alternative modes and routes may change for reasons other than climate change. The normal evolution of firms and industries will likely result in changes in the transportation of bulk commodities. Markets for agricultural products may grow or diminish, sources of raw materials may change, and technological developments may alter the inputs required by various industries. General economic growth should increase the demand for water transport.

9 Reduced ice cover and season extension

The second impact of climate change examined here is the effect of reduced ice cover on the Great Lakes and connecting channels leading to the possibility of extending the navigation season. The current situation is reviewed, the potential for season extension examined, and the implications of season extension discussed.

9.1 Current navigation season

Currently the Seaway locks between Montreal and Lake Ontario, the Welland Canal between Lakes Erie and Ontario, and the Soo locks between Lakes Superior and Huron are closed for over 2 months every winter. Ice conditions make use of the locks difficult, time is required for lock maintenance, and winter navigation in restricted channels presents environmental problems.[9]

The opening and closing dates for the St. Lawrence Seaway, both the Montreal–Lake Ontario section and the Welland Canal are flexible, set according to ice conditions, the demand for service, and maintenance requirements. The opening also depends on the availability of ice breaking services which are usually needed immediately before the opening and for a short period afterwards. Opening and closing dates are announced by the Seaway 5 to 6 weeks in advance although vessel operators and shippers know the approximate dates from past practice. In 2008 the Welland Canal opened March 20 and closed December 30, a record length of time open. The Montreal–Lake Ontario section opened March 22 and closed December 29, tying the record for the longest time open.

The Soo locks have fixed opening and closing dates, opening on March 25 and closing on January 15, dates which are published in the US Federal Register. (US Army Corps of Engineers 1996) Some flexibility is possible on the closing date depending on the demand for service and ice conditions. But a short extension in 2004 was not successful as a ship became stuck in ice. From 1974 to 1979 the Soo Locks were open year-round but, because of environmental concerns, a fixed closed period was adopted.

9.2 Season extension in the future

Reduced ice cover, a predicted impact of climate change, may allow the navigation season to be extended. The conditions allowing for opening of the navigation season would occur earlier and conditions requiring closing the locks would occur later. Neither the St. Lawrence Seaway nor the Soo Locks have plans to extend the season; season extension will likely evolve as permitted by ice conditions. The length of the Seaway navigation season has been gradually increasing. For the 5 years from 1994 to 1998, the average open period for the Montreal–Lake Ontario section of the Seaway was 274 days; for the 5 years 2004 to 2008 the average open period was 282 days, an increase of 8 days. The Welland Canal was open 12 days longer over the same period.

[9]Information on current and possible future winter closings was obtained through interviews. Sam Babisky, Acting Superintendent, Canadian Coast Guard Regional Operations Centre, Sarnia ON., telephone interview by author, 23 January 2007.

Peter Burgess, Senior Marine Officer/Enforcement Officer, Marine Navigation Technology, The St. Lawrence Seaway Management Corporation, interview by author, Cornwall, ON, 15 November 2006; telephone interview by author, 25 January 2007.

Brian Donahue, Officer in charge, Ice section, United States Coast Guard Ninth District, Cleveland OH., telephone interview by author, 25 January 2007.

Gradual season extension would avoid the navigational and environmental problems associated with past attempts at all-winter navigation, no longer seriously considered. Vessels moving in ice in channels may result in ice scouring channel banks and bottoms disrupting vegetation and aquatic organisms. Shoreline structures may be damaged. Aboriginal groups along the St. Lawrence River have expressed concerns about the impacts of the Seaway, particularly ice-breaking during the beginning of the navigation season. Their concerns include environmental impacts, disruption of wildlife and wildlife habitats, shoreline erosion, and the inability to travel on the ice to hunting and fishing areas. If there is a shorter period of ice cover, however, allowing the navigation season to be lengthened with a decrease in ice breaking, then there will likely be less opposition to a longer season. It appears that any extension of the navigation season will only be publicly acceptable if the period of ice cover is reduced and there is, at least, no increase in ice breaking.[10]

9.3 Lock maintenance

The closed season is used for lock maintenance, mechanical overhauls, and replacement of machinery and other parts. Some period of closure is required every year for regular maintenance and inspection. Maintenance engineers suggest this regular annual maintenance could be done in 1 month, providing no major problem is encountered. Every 3 to 5 years, however, major maintenance, replacement and upgrading of lock machinery, and possibly resurfacing of lock walls is necessary, requiring at least 2 months. Thus, for many years a maintenance closure of 1 month would suffice but every third to fifth year a longer closed period would be required. Maintenance procedures and schedules would have to be rearranged and possibly more outside contractors hired to accommodate the shorter closed periods. Aging of the locks is increasing maintenance requirements. The Montreal–Lake Ontario locks were opened in 1959; the Welland Canal locks were opened in 1932.[11]

If year-round navigation is ever permitted by a drastic reduction in ice over, complete closures for maintenance could be avoided if all locks were twinned. Presently only three of the eight Welland Canal locks are twinned. Plans have

[10] Winter navigation is opposed by a number of environmental groups, including Great Lakes United, an international coalition of environmental organizations, municipalities, unions, and individuals Adedicated to preserving and restoring the Great Lakes - St. Lawrence River ecosystem. ≅ (Great Lakes United 2002, p. 6) In 1984 the organization achieved Aits first major victory by persuading Congress to defeat an Army Corps of Engineers proposal for winter navigation on the Great Lakes. Nine years of feasibility demonstration projects had clearly shown that ice-breaking to keep winter shipping lanes open was not only economically impractical, but also responsible for severe damage to fish and wildlife habitats. ≅ (Great Lakes United 2002, p. 13)

[11] Gerard Abelfo, Manager of Maintenance Projects, St. Lawrence Seaway, telephone interview by author, 23 February 2007.

Al Klein, Area Engineer, Soo Locks, Sault Ste. Marie Area Office (Detroit District, US Army Corps of Engineers), telephone interview by author, 26 January 2007.

Tom Levigne, Director of the Office of Engineering and Maintenance, St. Lawrence Seaway Development Corporation, telephone interview by author, 22 February 2007.

Wayne Schloop, Locks and Dams officer, US Army Corps of Engineers, Detroit District. Telephone interview by author, 26 January 2007.

Jim Wheeler, Assistant Director of Maintenance, St. Lawrence Seaway Management Corporation, Niagara region, telephone interview by author, 30 January 2007.

been developed to twin the largest lock between Lakes Superior and Huron and preliminary funding has been allocated to this project.[12]

9.4 Other implications of season extension

The longer annual time of utilization of ships and loading and unloading facilities, less need for stockpiling, and lower ice-breaking costs may offset some of the increased costs due to lower water levels. The additional trips necessary because of lower water levels could possibly be carried out in an extended season without any increase in total fleet size. The longer navigation season with a reduction in ice cover may also influence the pattern of shipments and could result in other traffic being attracted to the system.

The extended season could not only be used for international shipping movements but will also be used by inter-lake and intra-lake shipping. Some of these movements are now occurring when the locks are closed, often with ice-breaker assistance, and will likely expand with a longer ice-free season. One issue may be the suitability of cargo handling equipment if operations take place during colder weather. Some of the current equipment may not be cold weather-capable but could be modified for cold weather operation.

10 Potential impacts of climate change on aquatic invasive species

A continuing issue for international shipping using the Great Lakes–St. Lawrence system is preventing the introduction of aquatic invasive species. These species have imposed severe economic and ecological costs on the Great Lakes. Many, estimated at 50% to 70%, of the aquatic invasive species in the Great Lakes have come from international shipping activities, principally through the discharge of ballast water. To maintain stability, in the past some vessels took on ballast water before leaving a foreign port and discharged this ballast water, possibly containing invasive species, in the Great Lakes when loading cargo.[13]

Besides the impacts on water levels, climate change, by its broad impact on the environment, will affect the indigenous and invasive species found in the Great Lakes. Climate change is generally expected to encourage the spread and abundance of invasive species in several ways. Higher water temperatures may alter the length and timing of reproductive and growing seasons, likely positively affecting invasive species. Warm water species, including warm water invasive species, are expected to be enhanced, becoming more competitive with cold water and cool water species. If minimum winter temperatures are no longer as severe there will likely be fewer winter kills of thermally ill-adapted invasive species. Conversely, other invasive species, better suited to a colder environment, may not be able to survive. The

[12] In June 2009 $1.9 million was allocated for the building of coffer dams. (US Army Corps of Engineers, Detroit District, News Release, June 9, 2009 http://www.lre.usace.army.mil Accessed 28 September 2009.)

[13] See National Research Council of the National Academies (2008) for a discussion of the problem and possible solutions. The report states that 55 to 70 percent of the aquatic invasive species in the Great lakes have entered through the discharge of ballast water.

lower water levels associated with climate change may also be of advantage to some invasive species. (Beeton 2002; Casselman 2002; Mills et al. 2005; Rahel and Olden 2008; Taylor et al. 2006)

With the past record of commercial vessels introducing many aquatic invasive species into the Great Lakes and the possibility that climate change will increase the spread and damage from further invasions, the ballast water activities of commercial vessels entering the Great Lakes–St. Lawrence system have become increasingly subject to control and monitoring. Replacing fresh ballast water with salt water has been found to be effective in reducing the abundance of freshwater organisms. Thus, before entering the system, those ships without ballast water on board are now required to flush their ballast tanks with salt water; those with ballast water on board are to carry out ballast water exchange with salt water. Beyond this, a recent report of the National Research Council of the National Academies (2008) recommends that the United States and Canada adopt and enforce uniform regulations, a surveillance program to monitor the presence of new aquatic invasive species in the Great Lakes be established, and that, with experience and technological change, improved regulations, preventive measures, and treatment methods be adopted.

11 Summary

The potential impacts of climate change on Great Lakes international shipping are examined. The expected higher temperatures of climate change are predicted to increase evaporation, lower runoff, reduce ice formation, and raise surface water temperatures in the Great Lakes, possibly resulting in a fall in lake levels. Increases in precipitation will not be sufficient to completely offset the reduction in lake levels.

For international commercial navigation in the Great Lakes the impact of lower lake levels will be felt through restrictions in vessel drafts and reductions in vessel cargos, thus increasing the number of trips and the total costs to move a given tonnage of cargo. Estimates of these impacts are derived from simulations of international cargo movements from and to the Great Lakes. Four water level scenarios are used, a base case with only seasonal and annual variation in water levels and three climate change scenarios, each representing different degrees of climate change. The simulation minimizes the variable vessel operating cost of transport subject to a number of constraints, including the depth of water available. In the climate change scenarios water depths are reduced thus restricting vessel loads and increasing costs over the base case.

The impacts of climate change on variable vessel operating costs vary from approximately 5% for a climate change scenario representing the possible climate in 2030 to over 22% for a climate change scenario representing a doubling of atmospheric carbon dioxide. The relative increases in cost vary by commodity and route. When years of naturally occurring low water are examined, the impacts are up to 13% higher for even the most moderate climate change scenario. For years of naturally occurring high water climate change impacts are reduced.

Several qualifications apply to the results of the simulations. The analysis is based on 1 year' s pattern of shipments which, with shifting demand and supply conditions, will likely change in the future. No adaptation, remedial, or avoidance measures are included. No doubt, with lower water levels a variety of adaptation measures would be instituted to lessen the impacts of lower water levels. The analysis is based on the characteristics of typical lake and ocean going vessels, representing the majority of vessels used. To the extent larger and smaller vessels are used, the impacts of lower water levels will vary.

Climate change may also result in a shorter time of ice cover leading to the possibility of extending the navigation season. Seaway and lock managers now have no plans to extend the season but a longer season may evolve if allowed by ice conditions. The Seaway sets opening and closing dates on the basis of both ice conditions and the demand for service and has been gradually lengthening the season. The closed time of over 2 months during the winter is now used for lock maintenance. Reducing the time required for maintenance would facilitate a longer navigation season.

Climate change is also expected to increase the threat of ecological and economic damage from aquatic invasive species. Commercial vessels, responsible for many of the aquatic invasive species in the Great Lakes, are now required to undertake measures to prevent the introduction of further aquatic invasive species. With experience and technological change further preventive measures may be required.

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