Climate Change and Transportation: Potential Interactions and Impacts

By **Brian Mills and Jean Andrey**

Introduction

The purpose of this paper is to illustrate several potential interactions between anthropogenic climate change and transportation based on published literature and the opinions of the authors. Although the content is synthesized primarily from Canadian research (Andrey and Mills 2003, Andrey *et al.* 1999), most of the transportation-climate relationships are equally relevant to the American context.

Unfortunately, the available peer-reviewed literature addressing this subject is very limited. For example, the most recent IPCC (Working Group II) synthesis of impacts, adaptation and vulnerability (McCarthy *et al.* 2001) devotes less than one of over 1000 pages to potential transportation-related impacts and sensitivities. Although there is no comprehensive, quantitative assessment of the various transport-sector costs and opportunities associated with the current, let alone changed, climate, there are several qualitative summaries describing the vulnerabilities of transport-related activities to climate variability and change (e.g., Andrey and Mills 2003, Queensland Transport *et al.* n.d., Andrey and Snow 1998, Moreno *et al.* 1995, Lonergan *et al.* 1993, Jackson 1990, IBI Group 1990). In addition, a few quantitative impact analyses of climate change on selected transportation infrastructure and operations have been published (e.g., Millerd 1996, McCulloch *et al.* 2001). However, the bulk of literature relevant to climate change deals with current weather and climate sensitivities of transport systems.

A general framework to guide discussion is presented in Figure 1. Weather and climate, as represented by several indicators (elements, such as precipitation, temperature, etc.) in Figure 1, contribute to several hazards or sensitivities within the transportation sector (such as landslides, reduced visibility, etc.). The statistics of these variables may be affected by anthropogenic climate change. Weather and climate factors directly affect the planning, design, construction and maintenance of transportation infrastructure in several ways—they also indirectly affect the demand for transportation services. Costs and benefits, measured in terms of safety, mobility, economic efficiency, and externalities, accrue as the operation of transportation facilities and services meets these demands and adjusts to weather and climate hazards. The remainder of the paper explores some of the climate-transportation interactions conceptualized in Figure 1.

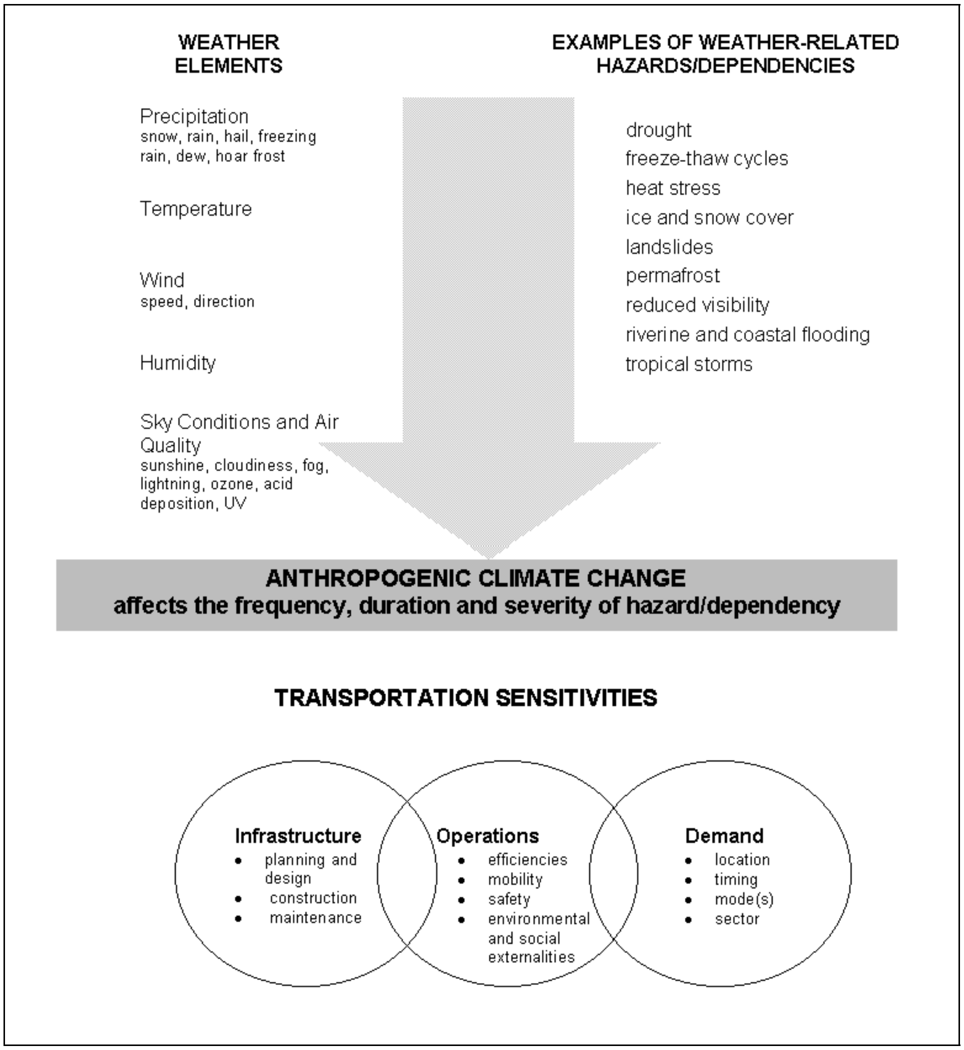

Figure 1. *Aspects of transportation that may be sensitive to changes in climate. The diagram conceptualizes how weather elements (precipitation, temperature, etc.) contribute to hazards (landslides, reduced visibility, etc.), which in turn affect transportation infrastructure, operations, and demand.*

Infrastructure

Roads, railways, airport runways, shipping terminals, canals, and bridges are examples of the facilities and structures that are required to provide transportation services that enable the movement of passengers and freight. Weather and climate affect the planning, design, construction, maintenance and performance of infrastructure throughout its service life. Infrastructure is built to withstand a wide variety of weather and environmental conditions—the prospect of anthropogenic climate change means that certain assumptions about future atmospheric conditions may be wrong, possibly resulting in premature deterioration or failure of infrastructure. Current climate modeling research suggests that many transportation-sensitive aspects of climate change will be realized over a long time frame. Fortunately the service life is sufficiently short for many types of transportation infrastructure (i.e., less than 25 years) to facilitate cost-effective replacement using improved designs. In other cases, such as bridges and port facilities, expected changes in climate may occur considerably earlier during the expected service life, possibly forcing expensive reconstruction, retrofit or relocation.

Temperature-Related Sensitivities

Temperature-related sensitivities include extreme heat and cold, freeze-thaw cycles, permafrost degradation and reduced ice cover.

Extreme heat and cold

It is likely that climate change will increase the frequency and severity of hot days while the number of extremely cold days will be reduced across much of North America (Houghton *et al.* 2001). The following pavement impacts might become more common as extreme heat conditions become more severe and frequent:

- pavement softening and traffic-related rutting,
- buckling of pavement (especially older, jointed concrete), and
- flushing or bleeding of asphalt from older or poorly constructed pavements.

This will generally lead to increased maintenance costs wherever pavement thermal tolerances are exceeded—the last issue is also a safety concern. On the positive side, fewer extremely cold days and 'warmer' minimum temperature thresholds may reduce thermal cracking of pavement during winter and offset some of the increased summer maintenance costs, at least in Canada and the northern U.S. Buckling of jointed concrete pavement is not a large issue in Canada given its limited use, but may be much more important in parts of the U.S.

Railway track is also subject to buckling from extreme heat—possibly a contributing factor to a July 29, 2002 serious rail incident in Maryland presently under investigation by the Transportation Safety Board (Associated Press 2002). While heat-related impacts may become more frequent, Canadian information suggests that cold temperatures and winter conditions are responsible for a much greater proportion of track, switch, and railcar damage (Andrey and Mills 2003).

Freeze-thaw cycles

Increased frequencies of freeze-thaw cycles have been related to premature deterioration of road and runway pavements, primarily where subgrades are composed of fine-grained, saturated material—conditions that are conducive to frost heaving and thaw weakening (Haas *et al.* 1999). Preliminary research reported in Andrey and Mills (2003) suggests that freeze-thaw cycles, defined using a 0°C (32°F) daily air temperature threshold, may actually become less common under climate change in several cities in southern Canada.

Permafrost degradation

Permafrost degradation and related increases in the active (seasonally unfrozen) permafrost layer may compromise the stability of paved airport runways and all-season road and rail bases in the Canadian (and likely Alaskan) north. Sensitivities are especially high where permafrost temperatures are warmer than -2°C (28°F) and where the ice content of frozen ground is high (Natural Resources Canada 2002).

Reduced ice cover

Another northern issue is the future viability of winter ice roads—a cheaper means of transportation than air for many communities not serviced by all-season roads. Warmer temperatures will reduce both the length of the ice season and thickness/strength of ice, a factor limiting the weight of vehicles (Lonergan *et al.* 1993). These impacts may be offset somewhat by a longer ice-free season that may allow greater use of boats and barges.

Construction season length/quality

Although infrastructure expansion will likely be driven by non-climate factors (economics, population growth, etc.), warmer temperatures could translate into a longer potential construction season and improved cost efficiencies. Extreme heat and unfavourable working conditions for employees and certain types of construction activities may offset such gains. For example, high temperature, low humidity and high wind are factors that reduce the setting times and strength of concrete (Almusallam 2001).

Sea-level Rise and Storm Surge

Sea-level rise ranging from a global mean of 9-88 cm (approx. 4-35 in) is also a likely outcome of global climate change and will be exacerbated (reduced) where land is naturally subsiding (rebounding) (Houghton *et al.* 2001). Combined with acute storm surges related to tropical (hurricanes) or mid-latitude (e.g., nor'easters) storms, gradual changes in sea level may be expected to damage or render inaccessible low-lying coastal infrastructure including road and railway beds, port and airport facilities, tunnels and underground rail/subway/transit corridors. Detailed studies of vulnerable infrastructure have been completed for the New York City metropolitan region (Klaus *et al.*, n.d.) and parts of Atlantic Canada (McCulloch *et al.* 2001, Martec Ltd. 1987, Stokoe *et al.* 1988). Both regions have experienced damaging coastal flooding over the past decade. The vulnerability is significantly higher in the U.S. than in Canada, owing primarily to much greater levels of investment, including several major airports, along the American East and Gulf coastlines.

Precipitation-related Sensitivities

The impacts of climate change on future precipitation patterns are much less certain than for temperature, due in part to the highly variable nature of precipitation and the inability of global climate models to resolve certain precipitation processes. Increased precipitation may affect the frequency of land slides and slope failures that could damage road and rail infrastructure and force greater levels of maintenance. This is likely to be most problematic in mountainous regions, such as the continental divide (Evans and Clague 1997).

Riverine and urban stormwater flooding may exacerbate impacts related to sea-level rise and may also affect inland regions (road and rail infrastructure within flood plains including bridges, bridge foundations, culverts, etc.). The 1993 summer floods along the Mississippi River provide the most vivid image of this future scenario, although even local urban flooding can cause significant damage to transportation infrastructure (see Changnon 1999).

Precipitation and moisture are also important factors that contribute to the weathering of transportation infrastructure. Premature deterioration of bridges, parking garages and other concrete structures may be magnified where climate change induces more frequent precipitation events, especially in areas (e.g., northeastern U.S. and southeastern Canada) where acid deposition is a problem (Smith *et al.* 1998; Auld 1999).

Transportation Operations

The impact of climate change on transportation system operations extends from current weather-relationships and adjustments that are known to affect safety, mobility, and economic efficiency. Certain externalized environmental issues stemming from transportation operations may also be indirectly influenced by climate change.

Safety

Weather is identified as a contributing factor in approximately 10 train derailments, 10-15 aircraft accidents, over 100 shipping accidents, and tens of thousands of road collisions that occur in Canada each year (Andrey and Mills 2003). In 2000, about 300,000 injury road collisions in the U.S. occurred during rain, snow, sleet or other adverse weather condition (U.S. Department of Transportation 2001). Although a detailed analysis has not been completed, and assuming all other factors remain constant, it is expected that milder winter conditions would improve the safety record for rail, air and ship modes in Canada (Andrey and Mills 2003). In absolute terms, road collisions are by far the most important safety concern. Precipitation generally increases collision risk from 50-100 percent; and research for several Canadian cities reported injury risk increases of about 45 percent (Andrey *et al.* 2001a, 2003). Injury risk was similar for snowfall and rainfall events, relative to normal seasonal driving conditions (Andrey *et* *al.* 2003). Should these relative sensitivities remain intact over the next several decades, shifts from snowfall to rainfall as suggested by many climate change modeling studies (Houghton *et al.* 2001) may have minimal impact on casualty rates, contrary to the benefits reported in past studies (IBI Group 1990). Where precipitation events become more frequent, one might expect injury risk to increase.

Mobility

All modes of transportation currently experience weather-related service disruptions, particularly during winter. Commercial passenger flight cancellations and diversions are estimated to cost $US 40,000 and $US 150,000 per flight, respectively (Environmental and Societal Impacts Group 1997). Temporarily reduced speeds for rail service during extremely cold conditions and prolonged heat waves, and road or rail closures due to winter storms, flooding, land slides and forest fires are other examples of weather-related impacts on mobility (Andrey and Mills 2003). Associated costs, although variable from year to year, certainly amount to millions of dollars. Any reduction in the intensity or frequency of winter storms or weather extremes would likely translate into a mobility benefit for transportation operators and the public at large.

Another possible benefit of a warmed climate would be the improved potential for navigation, for example in the Beaufort Sea area. A greater extent of open water in the summer, coupled with a longer open-water season and thinner first-year sea ice, may extend the Arctic shipping season (McGillivray *et al.* 1993, Goos and Wall 1994).

Efficiencies

There is general consensus that climate change will result in a reduction of Great Lakes water levels and connecting channel flows (Mortsch *et al.* 2000, National Assessment Synthesis Team 2001). Several investigations of the implications of reduced water levels for shipping activities in the Great Lakes (Lindeberg *et al.* 2000, Millerd 1996, Bergeron 1995, Slivitzky 1993, Marchand *et al.* 1988) have reached similar conclusions—shipping costs for the principal commodities (iron ore, grain, coal, limestone) are likely to increase substantially because of the need to make more trips to transport the same amount of cargo, even considering the prospect of an extended ice-free navigation season. This would present a serious challenge to an industry that is already in decline due to both changing patterns of transport demand and competition from other freight modes. Similar impacts could affect commercial navigation along the Mississippi River system, as supported by observations from recent droughts (Changnon 1989, National Assessment Synthesis Team 2001).

Reduced spending on snow and ice control has been identified as a major benefit of global warming to the transportation sector (IBI Group 1990). Annual winter road maintenance expenditures by government agencies in the U.S. and Canada are approximately $US 2 billion and $CDN 1 billion, respectively (The Weather Team 1998, Jones 2003). Less snowfall and days with snow are also likely to result in savings because of some reduction in salt corrosion-related damage to vehicles and steel-reinforced concrete structures (e.g., bridges, parking garages). Empirical relationships between temperature and historic rates of salt use (Andrey *et al.* 2001b, McCabe 1995, Cornford and Thornes 1996) tentatively suggest that a warming of 3-4°C could decrease salt and sand use by between 20 and 70 percent resulting in substantial savings annually. For other modes, considerable benefits will likely be realized for rail companies and airport facilities where snow removal and de-icing are necessary. Reduced sea ice coverage and thickness would lower ice-breaking costs in Atlantic Canada and possibly facilitate the use of Arctic waters as an alternative shipping route to the Panama Canal (Andrey and Mills 2003, Maxwell 1997, McGillivray *et al.* 1993).

The effects of temperature on the fuel efficiency of motorized transport have also been subject to discussion in climate impact assessments (IBI Group 1990, Titus 1992). Surface warming may lead to slight increases in fuel consumption for aircraft, related to lower engine efficiency, and for road vehicles, related to the increased use of air conditioning and the offsetting impact of reduced use of snow tires and defrosting systems (Andrey and Mills 2003). Higher or more frequent extreme temperatures associated with climate change may, in conjunction with aircraft type (rated cargo and passenger capacity, engine size and efficiency), runway length, destination elevation and location (requirements for additional fuel storage) and other factors, reduce aircraft cargo carrying capacities.

Environmental Externalities

As with the economic and mobility benefits, not all of the costs of operating transportation systems are limited to the transportation sector. Among other things, transportation activities produce air pollution and residual road salt loadings that affect human health and the environment (WGAQOG 1999, Environment Canada and Health Canada 2001). Both of these issues may in turn be indirectly affected by climate change. Benefits may be realized where warmer temperatures, as noted previously, reduce the loadings of road salt, glycols and other de-icing chemicals into the environment. Conversely, transportation-related activities are major sources of NO_x, VOCs, CO, and particulate matter. The surface and upper air conditions (warm temperatures; stagnant anticyclonic air masses) that promote the occurrence of high concentrations of these pollutants may become more frequent and of longer duration under certain climate change scenarios; however, the magnitude and direction of this impact may be highly variable spatially and requires additional research (Patz *et al.* 2000).

Transportation Demand

Very little if any information exists that addresses the possible consequences of climate change for transportation demand. It seems intuitive however to consider the effects of global warming on the sources (location, sector, timing) of specific demands for freight and passenger services and the implications for various modes of transportation. A few demand adjustments might occur directly in response to climate change impacts on transportation—such as a shift from shipping to rail and truck in the Great Lakes-St. Lawrence region. Other, more important shifts may occur indirectly as a result of adaptation to climate change in other sectors—most notably in natural resource sectors like agriculture, energy, and forestry, and in tourism. For instance, should the spatial pattern of agricultural production change in response to drought or extended growing seasons, it seems reasonable to expect new demands for transportation to arise and others to wane. Similarly for energy, climate change may permit the cheaper development of new fossil fuel resources in the Arctic thus increasing demand for supplies and the bulk shipment of petroleum; increased shipping activity in the Arctic may also generate greater needs for safety-related services and increase the probability of hazardous spills (Maxwell 1997, McGillivray *et al.* 1993). The greatest potential shift, however, will likely result from international commitments to reduce greenhouse gas emissions and associated investment in renewable energy sources. In the extreme case, widespread adoption of renewables and new fuels (e.g., hydrogen) could dramatically transform the transportation sector—creating both new opportunities and challenges.

Conclusions: What We've Learned and What We Need to Know

This paper has provided a sample of possible interactions between aspects of transportation and anthropogenic climate change. Several of these sensitivities are summarized in Figure 2, classified by the amount of research that has been completed, as well as the confidence in expected changes to particular climate variables (as interpreted from IPCC, Houghton *et al*. 2001). The published research provides a general account of several significant vulnerabilities within the transportation sector to climate change—all are based on the assumption that contemporary sensitivities can be extrapolated in a linear fashion into the future. Confidence in sensitivities related to temperature and sea-level rise is much higher than for precipitation-related impacts, as per Houghton *et al.* (2001). The most significant vulnerabilities that have been studied include: various types of coastal infrastructure that are threatened by sea-level rise and storm surge flooding (U.S. East and Gulf Coasts, Atlantic Canada); Great Lakes shipping; northern ice roads; and roads and air strips built on permafrost. Unfortunately, relatively little research has been published on the implications of extreme heat—an issue that may be very important for transportation interests in the U.S.

Confidence in Expected Changes in Climate Variables*	**Transportation Sensitivities: Amount of Completed Research**	
	A few studies	***No significant climate change research***
HIGH CONFIDENCE *Mean temperature* *Sea-level rise*	- East and Gulf Coast infrastructure (sea-level rise and storm surge) - Reliable northwest passage through Arctic (ice cover) - Northern infrastructure (permafrost degradation and ice roads)	
MODERATE CONFIDENCE *Extreme temperature* *Mean precipitation*	- Great Lakes - St. Lawrence shipping	- Winter maintenance costs for surface and air transport - Fuel efficiencies and payloads for motorized transport - Extreme temperature and freeze-thaw related impacts on infrastructure design and maintenance - Construction season length/quality
LOW CONFIDENCE *Storm frequency/severity* *Extreme local precipitation*	- Landslide/avalanche impacts on mobility and maintenance - Inland urban infrastructure (flooding)	- Health and safety - Mobility - Property damage due to weather-related incidents and severe storms (excluding coastal infrastructure) - Bridges and other structures spanning inland lakes, rivers (flooding) - Transportation demand and competition

*refers to agreement among global climate models as per IPCC (Houghton *et al*. 2001)

Figure 2. *Possible implications of climate change for Canadian and U.S. transportation.*

Based strictly on available evidence and compared to the many political, economic and technological factors affecting the evolution of transportation systems—including international agreements to limit greenhouse gas emissions—the potential impacts of climate change on transportation seem to be largely manageable. This conclusion may be premature given that very little research has been conducted on chronic impacts to pavements or rails; safety; or the potential benefits of climate change. More generally, insufficient attention has been paid to the dynamic and complex nature of transportation demand, intermodal competition and the implications of these for industry adjustments to climate change impacts.

Thus, many gaps exist in our understanding of climate change impacts, available adaptation strategies, and their various costs. Several recommendations for research are listed below. In addressing these general needs, the emphasis should be placed on developing research projects that focus in-depth on important activities and sensitivities rather than on conducting exhaustive and comprehensive studies of the entire transportation industry.

- Greater attention must be given to road transportation. North Americans are becoming increasingly reliant on road transport, and have invested over $1 trillion in road infrastructure. Studies should initially focus on estimating the vulnerability of roads to changes in freeze-thaw cycle frequency, extreme heat and cold.

- There is a need to assess the significance of extreme weather events and weather variability in the design, cost, mobility and safety of North American transportation systems. Many of the benefits attributed to potential climate change are based on the assumption that climate variability will remain similar to the present climate. There is a need to test this hypothesis against a variety of measures (cost, mobility, safety, etc.) and for previously unexamined impacts (e.g., potential increased frequency of severe summer weather and effects on aviation).

- A more thorough evaluation of existing adaptive measures and their relative ability to defer infrastructure upgrades, reduce operational costs, and maintain or improve mobility and safety is required.

- Analyses of mitigation (greenhouse gas emissions reduction) options and adjustments to reduce the impacts of climate change must be integrated so as to identify and work toward a transportation future that is more sustainable from an environmental perspective and more resilient to weather hazards.

- An improved understanding of the implications of climate change for transport demand is needed.

- Since most of the factors (e.g., technology, land use policy, economics) affecting the evolution of transport systems are external to climate, it is important to consider how changes in these factors affect societal vulnerability to climate and climate change.

- The above-mentioned research must be conducted in closer working relationships with transportation stakeholders. Several 'myths' surrounding climate change impacts that evolved from 'arms-length' investigations and were highlighted in subsequent studies were discounted after consulting managers of transportation activities. Involving stakeholders will also provide the best opportunity for weather and climate-related issues to become acknowledged in legislation, standards and policies.

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References

Almusallan, A.A. 2001. Effect of environmental conditions on the properties of fresh and hardened concrete, *Cement and Concrete Composites*, 23:353-361.

Andrey, J. and B. Mills 2003. Climate change and the Canadian transportation system: vulnerabilities and adaptations, chapter 9 in J. Andrey and C.K. Knapper (eds) *Weather and Road Transportation*, Department of Geography Publication Series, Monograph 55. University of Waterloo, Waterloo, Canada.

Andrey, J., B. Mills, M. Leahy and J. Suggett 2003. Weather as a Chronic Hazard for Road Transportation in Canadian Cities, *Natural Hazards*, in press.

Andrey, J., J. Suggett, B. Mills, and M. Leahy 2001a. Weather-related road accident risks in mid-sized Canadian cities. *Proceedings of the 12th Canadian Multidisciplinary Road Safety Conference*, University of Western Ontario, London, ON, June 10-13, 2001.

Andrey, J., J. Li and B. Mills 2001b. A winter index for benchmarking winter road maintenance operations on Ontario highways, *80th Annual Meeting Preprint CD-ROM,* proceedings of the Transportation Research Board annual meeting, January 7-11, 2001, Washington, D.C.

Andrey, J., B. Mills, B. Jones, R. Haas and W. Hamlin. 1999. *Adaptation to Climate Change in the Canadian Transportation Sector*. Report submitted to Natural Resources Canada, Adaptation Liaison Office, Ottawa.

Associated Press 2002. Dozens hurt in U.S. train derailment, Toronto Star, July 30, 2002.

Auld, H. 1999. Adaptation to the impacts of atmospheric change on the economy and infrastructure of the Toronto-Niagara Region, in B.N. Mills and L. Craig (eds.) *Atmospheric Change in the Toronto-Niagara Region: Towards and Integrated Understanding of Science, Impacts and Responses*. Proceedings of a workshop held May 27-28, 1998 at the University of Toronto. Environmental Adaptation Research Group, Waterloo, Ontario, pp. 103-121.

Changnon, S.A. 1989. The 1988 drought, barges, and diversion, *Bulletin of the American Meteorological Society*, 70(9):1092-1104.

Changnon, S.A. 1999. Record flood-producing rainstorms of 17–18 July 1996 in the Chicago Metropolitan Area. Part III: impacts and responses to the flash flooding, *Journal of Applied Meteorology*, 38(3):273–280.

Cornford, D. and J.E. Thornes 1996. A comparison between spatial winter indices and expenditures on winter road maintenance in Scotland, *International Journal of Climatology*, 16:339-357.

Environment Canada and Health Canada 2001. Priority Substances List Assessment Report – Road Salts. Prepared under the *Canadian Environmental Protection Act, 1999*. http://www.ec.gc.ca/substances/ese/eng/psap/final/roadsalts.cfm. Accessed June 2002.

Evans, S.G. and J.J. Clague 1997. The impacts of climate change on catastrophic geomorphic processes in the mountains of British Columbia, Yukon and Alberta, in *Responding to Global Climate Change in British Columbia and Yukon, Vol. 1, Canada Country Study: Climate Impacts and Adaptation*. E. Taylor and B. Taylor (eds.). British Columbia Ministry of Environment, Lands and Parks and Environment Canada, Vancouver, British Columbia, pp. 7-1 and 7-16.

Goos, T. and G. Wall 1994. Impacts of Climate Change on Resource Management of the North, *Climate Change Digest,* CCD94-02. Environment Canada, Downsview, Ontario. 7 pp.

Haas, R., N. Li, and S. Tighe 1999. *Roughness Trends at C-SHRP LTPP Sites*. Ottawa: Roads and Transportation Assoc. of Canada, Final Project Report, 97 pp.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Da, K. Maskell, and C.A. Johnson (eds.) 2001. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. http://www.grida.no/climate/ ipcc_tar/wg1/index.htm. Accessed July 2002.

IBI Group 1990. The Implications of Long-term Climatic Changes on Transportation in Canada, *Climate Change Digest,* CCD90-02. Environment Canada, Downsview.

Jackson, C.I. 1990. Chapter 9, Transportation, in *Global Warming: Implications for Canadian Policy*. Report to Atmospheric Environment Service, Environment Canada, Downsview, Ontario, pp. 94-103.

Jones, B. 2003. The cost of safety and mobility in Canada: winter road maintenance, chapter 4 in J. Andrey and C.K. Knapper (eds) *Weather and Road Transportation*, Department of Geography Publication Series, Monograph 55. University of Waterloo, Waterloo, Canada.

Klaus, J., N. Edelblum and J. Arnold (undated). Risk increase to infrastructure due to sea-level rise. Sectoral Report. Climate Change and a Global City: An Assessment of the Metropolitan East Coast (MEC) Region. http://metroeast_climate.ciesin.columbia.edu/reports/infrastructure.pdf. Accessed August 2002.

Lindeberg, J.D. and G.M. Albercook 2000. Climate change and Great Lakes shipping/boating, in P. Sousounis and J.M. Bisanz (Eds.) *Preparing for a Changing Climate - Potential Consequences of Climate Variability and Change, Great Lakes*. Prepared for the U.S. Global Change Research Program, pp.39-42.

Lonergan, S., R. DiFrancesco and M. Woo 1993. Climate Change and Transportation in Northern Canada: An Integrated Impact Assessment, *Climatic Change,* 24:331-351.

Marchand, D., M. Sanderson, D. howe and C. Alpaugh 1988. Climatic change and Great Lakes levels: the impact on shipping, *Climatic Change*, 12:107-133.

Martec Ltd. 1987. Effects of One Metre Rise in Mean Sea-level at Saint John, New Brunswick and the Lower Reaches of the Saint John River, *Climate Change Digest Series* CCD 87-04, Environment Canada, Downsview, Ontario, 8 pp.

Maxwell, B. 1997. *Responding to Global Climate Change in Canada's Arctic, Volume II of the Canada Country Study: Climate Impacts and Adaptation*. Environment Canada, Downsview, Ontario. 82 pp.

McCabe, C. 1995. *Winter Disruption in Metropolitan Toronto: Climate Change and the Effects on Snow Maintenance Programs*. Unpublished BES Thesis, Department of Geography, University of Waterloo, 60 pp.

McCarthy, James J., Osvaldo F. Canziani, Neil A. Leary, David J. Dokken and Kasey S. White (Eds.) 2001: *Climate Change 2001: Impacts, Adaptation & Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK.

McCulloch, M.M., Forbes, D.L., Shaw, R.W. 2002. *Coastal impacts of climate change and sea-level rise on Prince Edward Island*. Geological Survey of Canada, Open File 4261, 62 p. and 11 supporting documents.

McGillivray, D.G., T.A. Agnew, G.A. McKay, G.R. Pilkington, and M.C. Hill 1993. Impacts of Climatic Change on the Beaufort Sea-ice Regime: Implications for the Arctic Petroleum Industry, *Climate Change Digest* CCD93-01, Environment Canada, Downsview, Ontario, 19 pp.

Moreno, R.A., Skea, J., Gacuhi, A., Greene, D.L., Moomaw, W., Okita, T. Riedacker, A., Lien, T.V., Ball, R., Breed, W.S., and Hillsman, E. 1996. Industry, Energy and Transportation: Impacts and Adaptation, in R.T. Watson, M.C. Zinyowera and R.H. Moss (Eds.), *Climate*

Change 1995 Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp. 364-398.

Mortsch, L.D., H. Hengeveld, M. Lister, B. Lofgren, F. Quinn, M. Slivitzky, and L. Wenger 2000. Climate change impacts on the hydrology of the Great Lakes-St. Lawrence system, *Canadian Water Resources Journal*, 25(2):153-179.

National Assessment Synthesis Team 2001. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change,* Report for the US Global Change Research Program, Cambridge University Press,Cambridge UK, 620 pp.

Natural Resources Canada 2002. *Permafrost and Climate Change*. http://sts.gsc.nrcan.gc.ca/permafrost/climate.htm. Accessed July 2002.

Patz, J.A., M.A. McGeehin, S.M. Bernard, K.L. Ebi, P.R. Epstein, A. Grambsch, D.J. Gubler, P. Reiter, I. Romieu, J.B. Rose, J.M. Samet, and J. Trtanj. 2000. The Potential Health Impacts of Climate Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the U.S. National Assessment, *Environmental Health Perspectives*, 108(4): 367-376.

Queensland Transport, CSIRO Atmospheric Research and PPK Infrastructure & Environment Pty. Ltd. (undated). *The Effect of Climate Change on Transport Infrastructure in Regional Queensland*. Synthesis Report, 18 pp.

Smith, J., B. Lavender, H. Auld, D. Broadhurst and T. Bullock 1998. *Adapting to Climate Variability and Change in Ontario – Canada Country Study: Climate Impacts and Adaptation Volume 4*. Environment Canada, Downsview, Ontario, 117 pp.

Stokoe, P., M. Leblanc, P. Lane, S. Belford, D. Carey, M. Manzer and D. DeWolfe 1988. *Socio-Economic Assessment of the Physical and Ecological Impacts of Climate Change on the Marine Environment of the Atlantic Region of Canada – Phase 1*. Dalhousie University, Halifax, Nova Scotia, 141 pp.

The Weather Team 1998. Weather Information for Surface Transportation. Revised May 15, 1998 draft White Paper on Needs, Issues and Actions. Office of Safety and Traffic Operations, Federal Highway Administration, U.S. Department of Transportation. http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/8_v01!.pdf. Accessed July 2001.

Titus, J.G. 1992. The Costs of Climate Change to the United States, in S.K. Majumdar, L.S. Kalkstein, B. Yarnal, E.W. Miller, and L.M. Rosenfeld (Eds.) 1991. *Global Climate Change:Implications, Challenges and Mitigation Measures*, Philadelphia, pp. 385-409.

U.S. Department of Transportation 2001. *Traffic Safety Facts 2000: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System*. National Highway Traffic Safety Administration, National Center for Statistics and Analysis, Washington, DC.

WGAQOG 1999: *National Ambient Air Quality Objectives For Particulate Matter – Part 1: Science Assessment Document*. CEPA/FPAC Working Group on Air Quality Objectives and Guidelines. Health Canada and Environment Canada, Ottawa. http://www.hc-sc.gc.ca/bch. Accessed June 2002.

The opinions expressed in the following paper are those of the authors and do not necessarily represent the views of the Government of Canada or of the University of Waterloo.

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