Nat Hazards (2010) 52:481–499
DOI 10.1007/s11069-009-9391-2

ORIGINAL PAPER

Assessment of lightning-related damage and disruption in Canada

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Received: 9 February 2009 / Accepted: 24 March 2009 / Published online: 17 April 2009

Abstract This article assesses the extent and costs of lightning-related damage and disruption in Canada. Lightning routinely damages property and disrupts economic and social activities. Affected sectors include health; property and casualty insurance; forestry; electricity generation, transmission, and distribution; agriculture; telecommunications; transportation; and tourism and recreation—the first four sectors are the most important in terms of contributing to overall impacts and costs. Secondary data and extrapolations from U.S. studies were used to develop cost estimates for the health, property, forestry, and electricity sectors. Aggregated, annual lightning-related damage and disruption costs in Canada range from CA$600 million to CA$1 billion. Forestry and electricity damages accounted for over 85% of the total. The estimates are both preliminary and conservative. In terms of continued research, additional or more refined studies using Canadian empirical data are warranted for the insurance and electricity sectors. Detailed insurance claim or outage data would permit analysis at the storm level and potentially discern finer-scaled risk patterns. Further effort is also required to evaluate risk or damage prevention measures, particularly those that relate to expanded or enriched use of the Canadian Lightning Detection Network data by both public and private sector clients. Both the degree of adoption and efficacy or cost-effectiveness should be investigated.

Keywords Lightning · Damage · Cost · Disruption · Casualty · Thunderstorm · Canada

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1 Introduction

Lightning is one of the most pervasive atmospheric hazards. On average approximately 10–14 cloud-to-ground (CG) lightning flashes strike the globe each second (Mackerras et al. 1998), discharging electricity into or through the earth and various surface features including forests, buildings, vehicles, and people. While the global distribution of lightning is concentrated in the tropics and subtropics, the hazard is also common during the summer season in mid- and high-latitude nations such as Canada where annual CG flash rates exceed 2 km^{-1} in the heavily populated regions of southern Ontario (Burrows et al. 2002). Acknowledging this risk, Environment Canada, like many other national weather services, issues warnings to alert the public of the development and imminent arrival of severe thunderstorms and the potential for intense CG lightning. Investments in local, regional, national, and global detection networks and prediction systems—for example, the Canadian Lightning Detection Network[1]—by public and private sector interests further demonstrates the general significance of lightning, however, evidence of the extent of the damage, disruption, and economic costs of this hazard seems to be lacking.

A review of Canadian and international academic and government literature revealed three general types of lightning impact: human casualties, property damage, and losses associated with the interruption of electricity and other critical services (Mills et al. 2009). Affected sectors included health; property and casualty insurance; forestry; electricity generation, transmission, and distribution; agriculture; telecommunications; transportation; and tourism and recreation. Based on the volume of literature, the first four sectors made the greatest contribution to overall impacts and costs. Impacts were usually reported in terms of physical indicators such as the number of people killed or injured, damage report counts, electricity outage frequency and duration, number of insurance claims, and number of lightning-ignited forest fires.

Very few studies have estimated direct lightning-related damage costs or cost savings associated with preventive measures and no formal economic analyses of indirect costs or non-market costs attributable to lightning damage were uncovered in the literature review (Mills et al. 2009). Aside from a few references for the U.S. electricity sector (Diels et al. 1997; Keener 1997; Mitsche 1989), cost estimates were limited to those contained within national hazards assessments and regional-scale property damage analyses; these are summarized in Table 1. While lightning was occasionally treated as a distinct hazard in the former type of assessment, normally it was included in a broader category like thunderstorms (e.g., Changnon 2001). As well, much of this research was based on national or international disaster or catastrophe event databases where entries must exceed a relatively high (sometimes greater than US$5 million) damage, insured loss, or casualty count for inclusion (e.g., EM-DAT,[2] Canadian Disaster Database,[3] SHELDUS[4]). Lightning strike events rarely achieve these thresholds and thus are often poorly represented in the aggregate damage estimates (Mills 2005). Kithil (n.d., 1997) provided the most comprehensive collection of damage estimates and his annual average U.S. loss figure of up to $5 billion appears to be referenced most frequently in multi-hazard assessments. However, with few exceptions (e.g., Holle et al. 1996; Curran et al. 1997, 2000; Stallins 2002), the

[1] http://www.weatheroffice.gc.ca/lightning/index_e.html.

[2] EM-DAT http://www.em-dat.net/.

[3] Canadian Disaster Database http://www.ps-sp.gc.ca/res/em/cdd/index-en.asp.

[4] Spatial Hazards Events and Losses Database http://www.cas.sc.edu/geog/hrl/SHELDUS.html.

Table 1 Summary of published estimates of lightning-related insured and uninsured property damage

Author	Timeframe	Location	Scope	Estimated lightning impact[a]	Data sources
Aguado et al. (2000)	1950–1999	Navarra, Spain	Property damage (all sectors)	Estimated costs of 270 M pesetas (>US$1.5 M) over study period	Media reports and stakeholder survey
Curran et al. (1997, 2000)	1959–1994	United States (state-level)	Property damage (all sectors)	19,814 damage reports over period Over 50% costing between $5,000 and $50,000 Average annual damage of $32 M (1992–1994)	US NOAA Storm Data
Ferrett and Ojala (1992)	1959–1987	Michigan	Property damage (all sectors)	645 lightning strike events caused property damage over the 29-year study period with 173 of these events producing $50,000 or more in damage	US NOAA Storm Data
Holle et al. (1996)	1987–1993	Colorado, Utah, Wyoming	Property damage (insured personal and commercial)	One claim per 52–57 CG flashes 4.7, 1.4, and 3.9 claims per 10,000 population for Colorado, Utah and Wyoming, respectively $7 M average annual 3-state loss (including $150/claim deductible) Average annual U.S. loss of $332 M	Colorado Chapter of Chartered Property and Casualty Underwriters and a large member insurer
Holle et al. (2005)	1890–1894, 1990–1994	United States	Property damage (all sectors)	Tremendous shift in types of damages from 1890s to 1990s, with much reduced farm and animal impacts (from ∼52% to ∼9% of reports) and much higher impacts to dwellings and utilities (from ∼20% to ∼49% of reports)	US NOAA Storm Data Kretzer, H.F. 1895. *Lightning Record: A Book of Reference and Information*. Vol I, 106 pp
Hornstein (1961, 1962)	1939–1958	Canada	Property fire loss	CA$1.5 M average annual property fire loss (1,771 fires)	Dominion Fire Commissioner
			Forestry (fire loss)	CA$3.5 M average annual cost related to forest loss and fire suppression	Provincial Forest Fire statistics

Table 1 continued

Author	Timeframe	Location	Scope	Estimated lightning impact[a]	Data sources
Insurance Information Institute (2007)	2004–2006	United States	Property damage (homeowner insured losses)	266,500 average annual claims $812.4 M average annual losses $3,048 average loss per claim	Participating insurers
Kithil (n.d., 1997) with figures also cited by Best's Review (1998), McGraw (2003), Kunkel et al. (1999)	1980s–2006	United States	Property damage and disruption (all sectors)	$2–5B in annual losses (interpretation of sector statistics from 1980s to 2006: fire-related, insurance, storage/processing, aviation, electrical infrastructure, and electrical components)	References to published estimates Personal and/or written communications with industry representatives
Lopez et al. (1995)	1950–1991	Colorado	Property damage (all sectors)	331 damage reports over period Average of 7.9 damage reports per year	US NOAA Storm Data
Mileti (1999)	1975–1994	United States	Property damage (all sectors)	Average annual loss between $20 and 200 M	US NOAA Storm Data
Stallins (2002)	1996–2000	Georgia	Property damage (insured)	19,582 claims and $22.9 M insured losses over 5-year period for one Georgia insurer ($1,100 per claim)	Large Georgian insurer claims database
				$91.6 M insured losses if results extrapolated statewide using relative market share	US NOAA Storm Data

[a] Costs reported in $US unless noted otherwise

assumptions and rigour of the underlying impact analyses were questionable or simply difficult to ascertain.

In summary, very little research exists that documents the type and amount of physical and economic damage attributable to lightning, particularly at the national scale. Such baseline risk information could be used to help evaluate the effectiveness of monitoring and warnings and associated short- and longer-term responses (i.e., immediate emergency response through education programs). The current study aims to partly address this knowledge gap by developing a preliminary estimate of economic damages associated with lightning strikes in Canada. A combination of media, expert opinion, and industry data sources are described and analyzed to discern direct and indirect impacts for several sensitive economic sectors in Canada. The article concludes with a general discussion and summary of results and recommendations for future applications and research.

2 Development of damage estimates for Canada

The empirical study consisted of two components that drew upon different sources of impact data: (1) analysis of Canadian media reports of lightning-related damage and disruption and (2) development of specific impact and cost estimates for the most-affected sectors as identified through the literature review and media report analysis. For both components, damage or disruption costs were the primary metric sought and used to evaluate the extent of lightning-related impact. All cost estimates have been converted to 2007 Canadian dollars (CA$) using the all-item Consumer Price Index (CPI) (Statistics Canada 2007a) unless noted otherwise in the text.

2.1 Analysis of Canadian media reports

Media reports were a primary source of data used in the lightning-related injury study conducted by the authors (Mills et al. 2008). Since many instances of property damage were uncovered in the search for injury events, it was decided to utilize media accounts in the current study. Such data also forms the basis of several national hazard impact databases, including *Storm Data* published in the United States by NOAA and used in several analyses of lightning damage noted in the literature review (see Table 1). A more detailed rationale for their use is described in Mills et al. (2008).

An online media search was performed using both individual newspaper search engines as well as media conglomerate and global search engines (Factiva and LexusNexus). Over 460 searchable archives covering major daily Canadian newspapers as well as numerous community newspapers were accessed to obtain stories documenting impacts of lightning strikes. In total, 371 unique reports of damage (events) were uncovered for the period 1994–2006. The media reports provided detailed samples of a broad range of damage and disruption types, however, they were less helpful in characterizing the extent or quantifying the magnitude of impacts and costs. Three categories of impact were evident from the reports:

(1) Physical damage from direct or indirect strikes and fires to homes and sheds, churches, schools, hospitals/extended care facilities, commercial buildings, recreational buildings, sailboats, lighthouses, water treatment plants, agricultural buildings and contents, livestock, hay/straw bales, forests, pastures, oil and natural gas pipelines, oil storage facilities/tanks, traffic signals, vehicles, communication towers and systems, electrical transformers/stations, and hydroelectric plants;

(2) Electricity and to a lesser extent communication service interruptions affecting a variety of customers and forcing, among other things, a nuclear power plant shutdown, traffic signal failures, and alarm system failures; and
(3) Evacuations, evacuation alerts, and suppression activities related to forest fires.

Cumulative costs exceeded $17.5 million over the 1994–2006 period; about 900 buildings and 700 power transformers were damaged or destroyed by lightning and accompanying fires; and in excess of 3.3 million people are estimated to have been affected by power outages. The results are strongly influenced by a few large-impact events and incomplete reporting. For instance, 700 buildings were reported damaged or destroyed in only two lightning events; removing these events reduces the annual average from 69 to 15. Similarly, over half of the total cost is attributable to a single lightning event for which ere $10 million was expended to suppress forest fires. In terms of reporting, information concerning damage costs and the number of people affected by power outages was discernible for only about 10 and 50% of reports, respectively. As well, the total number of damage or disruption reports (371) was only 2.5 times greater than those for human casualties (148) as analyzed in Mills et al. (2008). These observations support findings from U.S. studies that damage incidents are severely underreported by media (Holle et al. 1996; Curran et al. 1997, 2000). At best, media reports obtained in the current study provide a qualitative and complementary source of information to the sector-specific empirical estimates developed in subsequent sections of the article.

2.2 Compilation of sector-specific impact estimates

While limited or incomplete in terms of quantifying costs and impacts, the media reports did reveal major impact areas and verified the general importance of lightning to particular sectors, including: health (injury burden), insured and uninsured personal and commercial property damage and disruption, forestry (wildfire management), and electricity transmission and distribution. A variety of secondary data and methods were applied to derive impact and ultimately cost estimates for each sector. These are explained in detail in subsequent sections. While not fully comprehensive, the authors believe that the final summary estimate accounts for a majority of the costs incurred as a result of lightning strikes in Canada.

2.2.1 Health (injury burden)

Mills et al. (2008) estimated that, on average, 9–10 deaths and 92–164 injuries are attributable to lightning each year in Canada. Based on data for the Province of Ontario, it is estimated that 19–33 of the injuries require hospitalization while the remainder (73–131) are treated in an emergency room and later released without being admitted to hospital (Mills et al. 2008). While casualty statistics stand on their own in terms of motivating policy or action to reduce impacts, the economic burden associated with casualties is often significant and should not be overlooked when aggregating or comparing costs across sectors.

A sample of literature concerning the value of a statistical life (VSL)[5] and the costs of injuries was consulted in order to develop a rough estimate of the social costs of lightning casualties. Studies have assessed VSL and injury costs based on contingent valuation

[5] VSLs should not be confused with the value of a specific individual person (i.e., priceless).

(willingness-to-pay or -accept), human capital, and revealed preference approaches (e.g., Alberini 2005; Health Canada 2002; Hirth et al. 2000; Viscusi 2004; Viscusi and Aldy 2003). The lowest values generally come from studies that have adopted human capital methods where only discounted future earnings losses of those killed or injured are considered. Estimates from contingent valuation (e.g., based on an individual's willingness to pay to reduce or accept compensation for the risk of being killed or injured) and revealed preference (e.g., observed wage–risk relationships) analyses tend to produce much larger figures and are more representative of the broad costs to society. In addition to the costs of the human consequences, there are also time and material costs associated with emergency response (i.e., ambulance and fire) and healthcare (Vodden et al. 1994).

Specific VSL and illness burden estimates range widely, in part because of methodological and contextual differences among studies (i.e., the nature of risk being measured, the degree of change in risk, and the characteristics of the population measured) (DSS Management Consultants Inc. 2000).[6] For the current project, lightning-related casualty cost estimates were derived from two Canadian studies that dealt with both injuries and fatalities but used different methodologies (Angus et al. 1998; Vodden et al. 1994). Angus et al. (1998) evaluated the economic impact of unintentional injury in Canada using a cost-of-illness approach that valued both direct (i.e., treatment-related) and indirect (i.e., lost productivity) costs. In principle, indirect costs include those related to impaired quality of life, pain, suffering, etc., however, for the purposes of their study, only lost productivity estimates developed using a human capital approach were incorporated (Angus et al. 1998). Lightning-related injuries typically would fall in either the *fire* or *other* classes defined in the study. Lacking specific data for lightning injuries, the authors chose to apply figures from both of these classes as well as a *total* case estimate to determine lightning-related costs. Costs per casualty defined by Angus et al. (1998) were multiplied by the low and high average annual mortality and injury counts (and hospitalization/ER breakdown) provided by Mills et al. (2008) to determine aggregate costs, ranging from $3.6 to $4.8 million, as presented in Table 2.

Vodden et al. (1994) assessed the social costs of motor vehicle collisions in Ontario. Costs associated with human consequences were determined using a willingness-to-pay approach that measures the value an individual places on reducing the risk of being killed or injured. Time and material costs attributable to emergency response and healthcare were added to determine the total social cost of collisions (Vodden et al. 1994). Costs per injury for four classes of severity were then multiplied by corresponding lightning-related injury counts developed by Mills et al. (2008). Total annual average costs, as shown in Table 3 and ranging from $70.3 to $79.3 million, are more than an order of magnitude greater than those determined through the previous application and reflect the large WTP-based social values adopted by Vodden et al. (1994).

2.2.2 *Property damage*

Information from annual reports of provincial fire authorities and the Council of Canadian Fire Marshals and Fire Commissioners (CCFMFC) was obtained to estimate the extent of lightning-related fire damage to commercial, industrial, institutional, and residential property (CCFMFC 2006). The data pertain to all incident responses by local government fire departments and include variables for injuries and fatalities in addition to property damage, all stratified by the source of ignition (igniting object). Within this category,

[6] Hirth et al. (2000) and Viscusi and Aldy (2003) discuss and provide a range of VSL estimates.

Table 2 Lightning-related costs based on injury estimates derived from Angus et al. (1998)

Costs	Based on *Fires* injury Class estimate		Based on *Other* injury Class estimate		Based on *Total* (all cases) Estimate	
	Low	High	Low	High	Low	High
Direct						
Hospitalized	$478,170	$852,391	$468,805	$835,697	$686,616	$1,223,969
Non-hospitalized	n/a	n/a	n/a	n/a	n/a	n/a
Indirect						
Morbidity	$155,918	$277,940	$109,660	$195,481	$116,677	$207,989
Mortality	$3,135,669	$3,484,076	$2,588,270	$2,875,855	$2,065,186	$2,294,651
Total (1995$)	$3,769,757	$4,614,408	$3,166,735	$3,907,032	$2,868,479	$3,726,609
Inflated total (2007$)	$4,795,246	$5,869,668	$4,028,184	$4,969,805	$3,648,793	$4,740,360

Source Angus et al. (1998), Tables III-1, 8, 15–17, 21

Table 3 Lightning-related costs based on social cost estimates derived from Vodden et al. (1994)

Injury severity	Low estimate	High estimate
Fatality	$47,971,176	$53,301,310
Major injury (requiring admission to hospital)	$1,108,635	$1,976,263
Minor injury (emergency room treatment/ not admitted)	$173,793	$309,805
Minimal (injured but did not go to ER)	n/a	n/a
Total (1990$)	$49,253,607	$55,587,378
Inflated total (2007$)	$70,256,488	$79,291,126

Source Vodden et al. (1994, p. 33)

lightning is classified as the only example of "no igniting object." Losses are estimated by the reporting fire agency and encompass only physical damage to structures and contents therein (i.e., not loss of business). Standardized reporting protocols and coding for all variables are documented in CCFMFC (2002).

Over the 1990–2002 period, CCFMFC member fire agencies responded to an average of 816 lightning-ignited fires each year causing $16.4 million in annual losses. If only the most recent 1998–2002 period is considered, then about 390 fires produce $14.9 million of losses each year. Lightning generally accounts for around 1% of all fires and slightly <1% of all fire losses, though these figures vary by year and province. When inflated, the average reported loss for a lightning-ignited fire was about $20,114.

Insurance claim data is likely one of the best sources of information for evaluating the impacts of lightning (Mills et al. 2009). While claim information is much more comprehensive than media sources and offers the benefit of consistent reporting, it can also be very difficult to obtain, especially for large regions, provinces or entire countries given the multitude of insurance agencies. Insurance data were not available within the timeframe of the current study, however, attempts were made to extrapolate a Canadian estimate from three U.S. studies (Holle et al. 1996; Stallins 2002; Insurance Information Institute 2007).

Prior to developing a cost estimate, it was necessary to establish baseline lightning-related insurance claim rates for Canada. Tables 4 and 5 identify the baseline results of each study that was used to develop Canadian insurance claim rates as a function of

Table 4 Lightning-related insurance claim studies used to derive per capita Canadian estimates

Study	Location	Claims/year	Population[d]	Claims/ 10,000 people
Holle et al. (1996)[a]	Colorado	5,188	3,294,394	15.7
	Utah	774	1,722,850	4.5
	Wyoming	793	453,588	17.5
	3-state average	6,755	5,470,832	12.3
Stallins (2002)[b]	Georgia (low)	15,666	8,186,453	19.1
	Georgia (high)	19,582	8,186,453	23.9
Insurance Information Institute (2007)[c]	United States	266,567	292,173,345	9.1

[a] Based on commercial and homeowner claims; claims were reported in paper as 4.7, 1.4, and 3.9 per 10,000; 1990 population data

[b] Based on commercial, homeowner, and farmowner claims; low scenario based on results in paper, high scenario derived by removing 1 year from claim data (1998) in which virtually no claims reported; 2000 population data

[c] Based on homeowners insurance data; 2004–2006 average population data

[d] All population data obtained/derived from U.S. Census Bureau figures (USCB 2007)

Table 5 Lightning-related insurance claim studies used to derive Canadian estimates based on CG flash counts

Study	Location	Claims/year	CG flashes/year	CG flashes/claim
Holle et al. (1996)[a]	Denver, CO	2,401	123,663	52
	United States	307,000	17,600,000	57
Stallins (2002)[b]	Georgia (low)	15,666	911,104	58
	Georgia (high)	19,582	911,104	47
Insurance Information Institute (2007)[c]	United States	266,567	27,255,605	102

[a] Based on commercial and homeowner claims; Denver area CG flash data for 1983; U.S. CG flash value from average 1989–1993 NLDN data; given lightning detection efficiency improvements one would expect higher numbers of flashes per claim today than determined in the study

[b] Based on commercial, homeowner, and farmowner claims; low claim scenario based on results in paper, high scenario derived by removing 1 year from claim data (1998) in which virtually no claims reported; CG flash value determined for current study based on 2000–2004 flash density (Vaisala 2006)

[c] Based on homeowners insurance data; CG flash value determined for current study based on 2000–2004 flash density (Vaisala 2006)

population (per capita rate) or CG flash occurrence (CG flashes per claim). It was assumed from the original literature that these claims did not cover fire losses and thus could be added to other sector estimates in the final aggregation. In recognition of the uncertainty associated with transferring results from one region to another, the extreme low and high estimates from Table 4 (4.5–23.9 claims/10,000 population) and Table 5 (47–102 CG flashes/claim) were extracted for application in the Canadian analysis.

It is unreasonable to expect per capita results from Utah (low claims per capita estimate) and Georgia (high claims per capita estimate) to be transferred to Canadian provinces without correcting for CG lightning flash density. Similarly, the potency of CG lightning expressed as flashes per claim across the United States (low CG flashes per claim estimate) or Georgia (high CG flashes per claim estimate) should be corrected for population density.

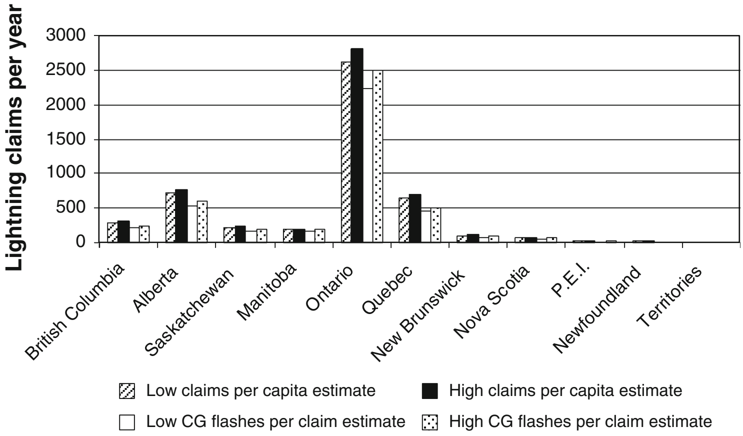

Fig. 1 Adjusted annual lightning-related insurance claim estimates by province

Accordingly, low and high per capita rates were adjusted by the relative 2000–2004 average annual CG flash density (derived from Vaisala 2006) between the source study region (Utah or Georgia) and each province. Relative population densities between the source study region (U.S. or Georgia) and each province were used to adjust the rates of CG flashes per insurance claim.

The provincial results of this adjustment are summarized in Fig. 1. When summed, Canada-wide estimates range from 3,900 to 5,250 lightning-related claims per year. These figures include those derived from both the adjusted per capita and adjusted CG flash rates and are surprisingly consistent. The general pattern at the provincial level reflects the combined influence of lightning frequency and population, with Ontario accounting for over 50% of estimated claims. Although beyond the scope of the current study, it would be interesting to analyze results at a finer scale given the expanse of many provinces and the concentration of population across “U.S. state-size” southern regions (e.g., Ontario and Quebec) or within a few large cities (e.g., B.C., Alberta, Saskatchewan, and Manitoba).

In order to assess the losses associated with lightning claims, cost estimates were developed based on values reported by Holle et al. (1996), Stallins (2002) and Insurance Information Institute (2007). Baseline costs per claim, corrected for currency and inflation, were applied to the adjusted Canadian claim estimates. Annual lightning-related insurance claim losses amount to $6–21 million dollars. Application of an average home insurance deductible of $500 would add from $2 to 2.6 million to the low and high scenarios, respectively. The figures that are based on the Insurance Information Institute (2007) study, which was completed using the most current data (2003–2006), are likely more reflective of actual losses. They account for considerable recent growth in losses per claim that is attributable to increased household investment in a greater number of higher-valued consumer electronics.

2.2.3 Forest fires

The social costs of forest fires include those related to protection and suppression, property damage to buildings and other infrastructure, lost productive timber, amenity and recreation, and existence values of forests (Mills et al. 2009). Due to the limited availability of data, only the first two in this list are treated in the empirical analysis.

Two primary sources of data were consulted for the study: the Canadian Interagency Forest Fire Centre (CIFFC 2007) and the National Forestry Database Program (NFDP 2007a). The NFDP provided annual provincial and national summary statistics on fire frequency, cause, hectares burned, response category, and property losses for both the intensive and limited protection zones. These data were used to establish the number of fires and area burned that could be attributed to lightning and formed the basis of apportioning costs. During the 1990–2005 timeframe lightning accounted for about 46% of forest fires and 85% of the total area burned. The discrepancy between fire frequency and area burned is explained by the disproportionate number of large fires (i.e., >200 ha) that are caused by lightning. Such fires account for 98% of the total area burned (CFS 2007; Weber and Stocks 1998).

Cost data, including property (interface) damage and expenditures related to pre-suppression and suppression activities were obtained from CIFFC annual national and agency reports (CIFFC 2007). Other losses, including forest resource and improvement values, were inconsistently reported and thus were not applied in the current study. Pre-suppression costs are those incurred through fire management activities prior to the occurrence of a fire. The activities include the organization, training, and management of a fire fighting force and procurement, maintenance and inspection of improvements, equipment, and supplies to insure effective fire suppression (CIFFC 2002, p. 36). Suppression costs result from all activities related to controlling and extinguishing a fire once it has been detected (CIFFC 2002, p. 19). Relatively complete provincial level data were available for the years 2002 and 2004–2006 while data for federally managed National Parks were available for 2002, 2003, and 2005.

Annual provincial expenditures on pre-suppression and suppression activities for the years 2002, 2004–2006 are presented in Fig. 2. Data concerning the relative contribution of lightning-ignited fires to the total number of forest fires that were actioned and area burned were used to allocate a portion of these costs to lightning-related incidents. Over 90% of fires reported in the NFDP over the 2002–2005 year period occurred in the intensive protection zone and were fully actioned. The intensive protection zone includes *forested lands of high value and areas where a risk to human life exists* while limited protection zone includes *remote forested lands or other areas of low value where intensive forest protection cannot be justified economically* (NFDP 2007b). A full response fire involves a *full, dedicated attempt to control the fire as soon as possible, consistent with resource*

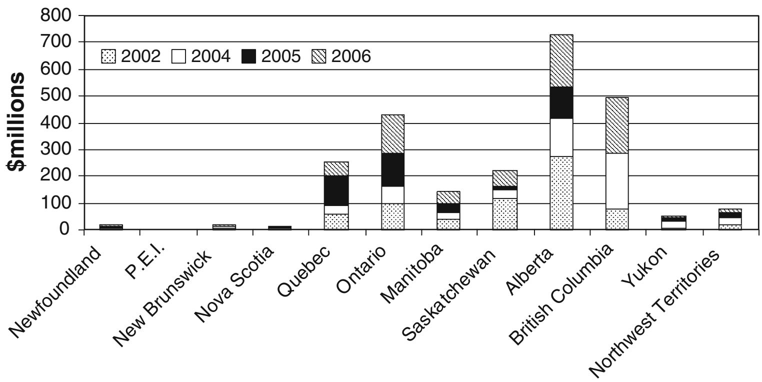

Fig. 2 Annual pre-suppression and suppression costs by province, 2002–2006 (CIFFC 2007)

availability and values at risk, while a modified response fire is controlled *in a limited way such that only isolated values threatened by a fire are protected, or attempt to monitor a fire only until it goes out naturally* (NFDP 2007b). Slight variations to these definitions are noted in CIFFC (2002). Lightning accounted for 47% of all actioned fires in Canada over the 2002–2005 period and the same portion (47%) of actioned fires within the important intensive protection zone. In terms of area burned, 65% of the area that received full or modified response was related to lightning-ignited fires. About 67% of the intensive protection area burned that received action was associated with lightning. Given that the level of preparedness and effort expended to fight fires is likely a function of both fire frequency and fire size (i.e., area burned), the minimum and maximum proportions (i.e., factors of 0.47 and 0.67) were used to assign national costs to lightning incidents. Property damage was apportioned in an identical way for the same years. The inflated total Canadian average annual expenditure of about $620 million fits squarely within the estimated range of $400–800 million cited by NRCan (2004) with lightning estimated to account for between $290 and 415 million of the total.

2.2.4 Electricity transmission and distribution

Mills et al. (2009) observed that lightning is an important variable in the management and operation of electricity infrastructure, in particular the transmission and distribution systems that provide power to residential, commercial, institutional, and industrial customers. Forced outages and impacts to power quality affect these customers as well as the income of electric utilities. In order to derive an estimate of the costs of lightning-related outages and quality events in Canada, information concerning the duration of outages in Canada was combined with cost data originally developed for the U.S. Given the limited scope of this study and availability of data, it was not possible to develop a similarly robust power quality estimate.

Much of the outage cost analysis was based on work by Lawton et al. (2003) as interpreted and applied in an analysis of the cost of power interruptions to U.S. electricity consumers by LaCommare and Eto (2004). Customer damage functions were developed by Lawton et al. (2003) using data from 24 studies and over 60,000 customer survey responses covering residential, commercial, and industrial sectors in the U.S. Direct costing survey methods, whereby respondents are asked to identify net costs across multiple outage scenarios, were adopted in the commercial and industrial studies. Willingness-to-pay or willingness-to-accept approaches, in which customers are asked how much they are prepared to pay to avoid an outage scenario (or receive a credit remuneration for the costs/inconvenience), were used in the residential studies. The damage function models, developed using Tobit regression procedures for each customer class, estimate the average customer loss per event based on several predictors that account for the influence of outage duration, time-of-day, day-of-week, season, region, household income, and number of employees (size factor). The general form of the models, as defined in LaCommare and Eto (2004), is specified as follows:

$$Y = \mathrm{Exp}[\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots \beta_n X_n + \varepsilon] + e$$

where Y is the outage cost for a particular customer class (residential, commercial, and industrial), β_0 is the y-axis intercept, X_n is the independent variable, β_n is the regression coefficient for each parameter, and ε and e are model error terms.

The specific regression coefficients for each parameter are defined in Table 6.

Table 6 Summary of select Tobit regression parameters used to predict electricity outage costs (LaCommare and Eto 2004, p. 23)

Predictor	Customer sector regression coefficients		
	Residential	Commercial	Industrial
Intercept	0.2503	6.48005	7.7954
Duration (h)	0.2211	0.38489	0.5753
Duration (h) squared	−0.0098	−0.02248	−0.0338
Number of employees	–	0.001882	0.0007
Annual electricity consumption (kWh for C&I, MWh for Res.)	0.0065	1.7E-06	2.52E-08
Interaction term (duration * kWh)	–	9.46E-08	−1.8E-09
Morning (1,0)	−0.0928	−0.6032	−0.5624
Night (1,0)	−0.1943	−0.91339	−1.3857
Weekend (1,0)	−0.0134	−0.52041	−0.7149
Winter (1,0)	0.1275	0.37674	0.8992
Household income (log $)	0.0681	–	–
Southeast region (1,0)	0.2015	–	–
West (1,0)	−0.1150	–	–
Southwest (1,0)	0.5256	–	–

– Denotes not applicable

Source LaCommare and Eto 2004, p. 23

Data were obtained to develop inputs for each of the model parameters, including average annual electricity consumption for each customer type, number of electricity customers broken down by sector, household income, average number of employees for commercial and industrial sectors, and average lightning-related outage duration. Average consumption data for Ontario were obtained from McCracken and Rylska (2005) whose study on the societal costs of excavation-related underground electrical distribution network failures also adapted costing information from Lawton et al. (2003). Ontario annual consumption per customer values for residential (11,283 kWh), small-medium commercial and industrial (24,395 kWh), and large commercial and industrial (250,000 kWh) customers were assumed to be representative across Canada. For the purposes of the analysis, the latter two figures were also assumed to represent commercial and industrial values, respectively.

The breakdown of customers by use-sector was developed in two steps. First, the estimated total 2005 electricity demand for the Canadian residential sector (153 TWh) (NRCan 2006) was divided by average residential customer use (11,283 kWh) to produce an estimate of 13.6 million customers. This figure closely matches the total number of dwellings in Canada in 2006 (also 13.6 million) (Statistics Canada 2007b), which lends confidence to the residential consumption figure. The second step involved estimating the number of commercial and industrial customers as a proportion of residential customers using the relative distributions found in the U.S. in 2001 (LaCommare and Eto 2004; Energy Information Administration 2007). The number of commercial and industrial customers in the U.S. represents about 13% and 1% of the residential total, respectively. By applying these factors to the Canadian residential estimate, the authors produce an estimate of 1.78 million commercial and 0.18 million industrial customers in Canada.

Household (family) income and employment data were obtained from Statistics Canada (2007c, d). Average income for all families for 2005 was converted to U.S. currency before being entered into the model. Average employee estimates were determined using 2006 *employment by enterprise size interval* information for sectors representing the commercial (retail trade) and industrial (manufacturing) customer categories. The resulting commercial and industrial figures were 18 and 37 employees, respectively.

The duration parameter is the most influential variable of the models. LaCommare and Eto (2004) used System Average Interruption Duration Index (SAIDI) values from over 180 U.S. utilities to establish an average duration of sustained outages (outliers were trimmed) from which total costs were modeled. The SAIDI statistic is calculated by dividing the sum of sustained outage durations for all customers by the total number of customers served. Canadian Electricity Association data summarized by McCracken and Rylska (2005) reveal that lightning was the cause of over 3.1 million customer-hour interruptions each year in Canada over the 1993–2003 period.[7] About 59.1 million customer-hour interruptions per year resulted from all causes (McCracken and Rylska 2005). For the current application, the average annual sum of lightning-related interruptions was divided by the sum of all residential, commercial, and industrial customers (estimated previously) to develop a lightning-related SAIDI score of about 0.2 h (12 min). In addition to sustained outage costs, LaCommare and Eto (2004) also evaluated momentary outages (i.e., duration of zero in model) and incorporated related costs into their national assessment. Their analysis used Momentary Average Interruption Frequency Index (MAIFI) data from U.S. utilities, which is calculated by dividing the total number of customer momentary (<5 min) interruptions by the total number of customers served. Lacking equivalent data throughout Canada,[8] the authors simply scaled a MAIFI estimate from the lightning-related SAIDI using the proportion of U.S. SAIDI to MAIFI values adopted in LaCommare and Eto (2004). This choice is likely somewhat conservative. An average lightning MAIFI value of 0.22 (2000–2005) determined using data for one large Canadian utility, Toronto Hydro, was about 20% greater than the chosen factor.

The various inputs were entered into the model to produce estimates of the average costs per customer per power outage/interruption for residential, commercial, and industrial categories. A combined estimate for each use category was developed by applying the model for six potential time periods in which lightning outages may be expected to occur (i.e., summer × weekday/weekend × morning/afternoon/night). Results were weighted by the relative number of hours in each respective period as in LaCommare and Eto (2004). All of the regional parameters were set to zero which by default represents the northern U.S. region (assumed to be most similar to Canada).

Lightning-caused sustained outages are estimated to cost Canadian customers about \$83 million each year while momentary outages cost an additional \$273 million. The commercial sector accounts for about 73% of total costs with the industrial and residential sectors contributing 24% and 3%, respectively. These proportions are very similar (within 1–2%) of baseline costs assessed for the U.S. (LaCommare and Eto 2004) and reflect the combined influence of average costs per outage per customer and the total number of customers in each class.

The previous analysis permitted examination of another type of cost noted in the literature review. Utilities lose revenue from customers when lightning outages occur. Using

[7] Based on data for 31 Canadian CEA-member utilities (i.e., figure is likely greater).

[8] Some aggregate data are available from the Canadian Electricity Association but costs were deemed too high for this study.

Table 7 Combined annual estimates of lightning-related damage and disruption costs for Canada

Sector	Key impact/cost	Estimated annual costs/losses[a]	
		Low	High
Health	Lightning-related injuries and fatalities	$3,648,793	$79,291,126
Property	Lightning-ignited municipal fires	$14,858,541	$16,414,436
	Insured losses and deductibles	$7,906,521	$23,540,272
Forestry	Forest fire suppression and pre-suppression	$306,981,081	$437,611,328
Electricity	Sustained and momentary outage costs to customers	$266,940,187	$444,900,311
	Lost revenue	$16,187	$16,187
Total		$600,351,310	$1,001,773,660

[a] Low and high estimates taken from previous tables; electricity low and high values determined by subtracting and adding 25% to estimates

the average outage duration applied in the customer cost analysis (0.2 h), average demand data (McCracken and Rylska 2005), and electricity pricing information (NRCan 2006), revenue losses are estimated to total about $16,000. Even if these figures are in error by a few orders of magnitude, they are dwarfed by the customer losses associated with sustained and momentary outages.

2.2.5 An initial aggregate estimate

By combining the range of low and high estimates from each of the four sector analyses, one produces an overall annual lightning-related damage and disruption figure between $600 million and $1 billion (Table 7). While this figure is incomplete, the authors believe that it includes the major contributions to lightning-related costs.

3 Discussion

This study provided an initial assessment of lightning-related impacts and costs for Canada totaling between $0.6 and 1 billion each year. Care must always be taken when interpreting these estimates, not the least of which because of uncertainties that arise from the degree of incompleteness, potential double-counting, transferability of U.S.-based relationships, variable treatments of costs (direct, indirect, social costs, etc.), assumption concerning the Canada-wide applicability of results, and the general use of multiple data sources over variable timeframes. Lacking resources to produce original data explicitly for the particular objectives of this project, the authors relied upon readily available data and impact relationships drawn from studies completed in the U.S. The specific sources of information, references, and steps used to develop the estimates for each sector are defined such that others can repeat and improve upon these initial results.

Overall, the authors believe that the estimates are conservative. In part, this is because impacts and costs for several sectors are not included in the analysis. The authors considered deriving lightning-related impact and cost estimates for other Canadian sectors including transportation (aviation) and tourism and recreation (golfing). In the case of aviation, where convective disturbances are estimated to cost the U.S. industry up to $2 billion annually (Weber et al. 1998), cause-of-delay and frequency of ground operation interruptions information for Canada were not readily available. Extrapolating from the U.S. estimate would prove difficult given radically different networks and issues with respect to discerning the proportion of U.S. delays and thus costs that are due to lightning as opposed to other aspects of convective weather. Similarly for golfing, where lightning may reduce the potential revenue of a course/operation, it proved very difficult with available sample data to distinguish between the effects of lightning and rainfall on the number of daily rounds played. By not including these and other sectors where even less information was found (e.g., telecommunications), or other impacts to those sectors that were included (e.g., power quality events on electricity customers, utility transformer or surge protection and repair/replacement expenditure, and costs of lost timber value due to fires), the study errors on the conservative side.

Despite the caveats noted above, the estimated impact of lightning in terms of damage and disruption to Canadians is very large and likely much greater than that attributed to other forms of hazardous weather (i.e., tornadoes, hail and hurricanes) over the long-term. The key point here is *likely*—the lack of suitable data and comparable analyses across multiple types of acute and chronic natural hazards in Canada prevents a firm conclusion from being made. Nevertheless, with this very basic lightning impact information in hand it is possible to begin evaluating where the introduction of new preventive measures and technologies may yield potential cost savings. This includes further development of the CLDN and related information products, services, and forecasts. While evidence of substantial innovation and investment in lightning protection and detection was apparent for the electricity sector and wildfire management agencies (Mills et al. 2009), the empirical analysis suggests that, at the macro scale, residual costs or impacts may still warrant further investment. Potential benefits may also be realized by the property and casualty insurance sector. Finally, it goes without saying that society will be better off if the number of lightning-related injuries and fatalities can be reduced. The authors hope that this research, together with the previous study (Mills et al. 2008), will help raise awareness of the importance of lightning in Canada and lead to measurable improvements in safety and reductions in costs.

In terms of continued research, additional or more refined studies using Canadian empirical data are warranted for the insurance and electricity sectors. Detailed insurance claim or outage data would permit analysis at the storm level and potentially discern finer-scaled risk patterns. Further effort is also required to evaluate risk or damage prevention measures, particularly those that relate to expanded or enriched use of the CLDN data by both public and private sector clients. Both the degree of adoption and efficacy or cost-effectiveness should be investigated.

Acknowledgments The authors wish to thank Ron Holle *Vaisala Inc*. and Bob Kochtubajda *Environment Canada* for reviewing elements of this research. Constructive comments from the anonymous reviewers are also greatly appreciated.

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