Environment Canada / Environnement Canada

ADAPTATION AND IMPACTS RESEARCH DIVISION (AIRD)
Environment Canada

FLASH BACK: A REVIEW OF LIGHTNING-RELATED DAMAGE AND DISRUPTION LITERATURE

By:
Brian Mills, Daniel Unrau, Laurel Pentelow
and Kelsey Spring

OCCASIONAL PAPER 16

2009

FLASH BACK: A REVIEW OF LIGHTNING-RELATED DAMAGE AND DISRUPTION LITERATURE♦

Brian Mills[1], Daniel Unrau[1,2], Laurel Pentelow[1,2] and Kelsey Spring[3]

[1]Environment Canada, Adaptation & Impacts Research Division, Waterloo, ON
[2]University of Waterloo, Faculty of Environment, Waterloo, ON
[3]Environment Canada, Canadian Lightning Detection Network, Richmond, BC

ABSTRACT: This paper reviews and summarizes research completed to assess the extent and costs of lightning-related damage and disruption. 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. Based on available literature, the first four sectors are the most important in terms of contributing to overall impacts and costs. Very little information exists that documents the amount of damage attributable to lightning in Canada, a finding that substantiates the need for additional Canadian empirical research, including on-going efforts by the authors to develop an aggregate picture of lightning impacts and costs across multiple sectors.

Keywords: lightning, damage, cost, disruption, casualty, thunderstorm, Canada

INTRODUCTION

Approximately 14,000 warnings for severe weather are issued each year by Environment Canada (MSC 2003). From April through October, most of these warnings are issued to alert the public of the development and imminent arrival of severe thunderstorms and the potential for damaging winds, heavy rainfall, large hail, and intense cloud-to-ground (CG) lightning. While the physical characteristics and climatology of lightning are relatively well-known, much less effort has been devoted to understanding the impacts of this common hazard. In response to this apparent dearth of

♦ A peer-reviewed synthesis of this paper (and empirical analysis) has been published as: Mills, B., D. Unrau, L. Pentelow, and K. Spring. Assessment of lightning-related damage and disruption in Canada, *Natural Hazards*, DOI:10.1007/s11069-009-9391-2.

information, especially for Canada, Environment Canada and university partners have undertaken an assessment of the impacts of lightning. The first phase of activity established an updated estimate and profile of lightning-related casualties (Mills et al. 2008). The current paper reviews published research examining the impact of lightning in terms of property damage, service interruptions and associated economic implications.

Emphasis was placed on North American research obtained through traditional library journal search engines (e.g., Web of Science, Scholar's Portal) and general internet searches focused on combinations of the term "lightning" with damage, impact, cost, prevention, and a range of sensitive economic sectors (e.g., electricity generation, transmission, and distribution). The review was intended to provide general understanding of damage mechanisms, quantified estimates of economic and social costs or other measures of physical impact, data sources and analysis methods. Discussion throughout the remainder of the paper is organized by impacted sector or activity: human health; general property damage; forest fire management; power generation, transmission and distribution; agriculture; transportation and pipelines; telecommunications; tourism and recreation; and other impacts. A brief summary section concludes the discussion, establishing the contextual and methodological stage for an empirical analysis of direct and indirect impacts across several sensitive economic sectors in Canada reported in Mills et al. (n.d.).

HUMAN HEALTH

Human casualties were discussed extensively in Mills et al. (2008) who estimated that 9-10 deaths and 92-164 injuries are attributable to lightning each year in Canada. The literature review from that publication also provides an inventory and interpretation of estimates for other countries (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. That said, no references were found that examined the costs of lightning-related mortality and morbidity, somewhat surprising given the inclusion of this direct cost element in other hazard studies (e.g., air quality; DSS Management Consultants Inc. 2000). However, many studies have assessed the value of a statistical life (VSL) and injury costs based on contingent valuation (willingness-to-pay or –accept), human capital, and revealed preference approaches (e.g., Albernini 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, fire) and healthcare (Vodden et al. 1994).

GENERAL PROPERTY DAMAGE: INSURED AND UNINSURED LOSSES

Property damage is a frequently examined aspect of lightning impact. It has also been an important concern of the insurance industry for over a century—an observation supported by the titles of early insurance companies which contained explicit references to lightning (e.g., Virginia Assessment and Cooperative Fire, Lightning and Storms Insurance companies; Valgren 1925). Lightning strikes to power facilities, vehicles, livestock, forests, dwellings, and other public or private buildings and structures may cause immediate damage to assets. Physical damage to concrete structures and masonry has been documented, but is relatively uncommon (Blumenstein 2006; Erlin 2007). More often property damage results from either lightning-ignited fires or lightning-caused power surges through electrical, communication or other utility lines that affect equipment and the electronic contents of homes and businesses.

Several researchers, mostly within the natural hazards and applied climatology fields, have sought to understand the impact of a large spectrum of weather and climate-related events that cause insured and uninsured property damage (e.g., Changnon et al. 2001; Changnon 2003; Kunkel et al. 1999; Dore 2003; Cutter and Emrich 2005; Mileti 1999). Lightning is occasionally treated as a distinct hazard in such assessments but normally it is included in a broader category like thunderstorms (e.g., Changnon 2001). Much of this research is based on national or international disaster or catastrophe event databases where entries must exceed a relatively high (often greater than US$5 million) damage, insured loss, or casualty count for inclusion (e.g., EM-DAT , Canadian Disaster Database , SHELDUS). Lightning strike events rarely achieve these thresholds and thus are often poorly represented in the aggregate damage estimates (Mills 2005).

Table 1 identifies general lightning-related property damage analyses and references that were uncovered through the literature review. The list is composed of estimates derived from analyses or interpretations of actual damage data from multiple sectors as opposed to more theoretical or conceptual risk models (e.g., Mazzetti and Flisowski 2000). Although there is some degree of overlap, research focused on individual sectors (e.g., damage to power generation facilities) is reported in subsequent sections. References were excluded if supporting documentation for statements was not provided or could not be verified (e.g., Briët 2004). The bulk of the work included in Table 1 was conducted in the United States, most often relying on the U.S. National Oceanic and Atmospheric Administration (NOAA) Storm Data database which uses a combination of media references and reports from law enforcement agencies, local government officials and others in documenting weather-related fatalities, injuries and property damage (NOAA 2007). Household and commercial property and casualty insurance claim data were also used in a few studies, either alone or in combination with NOAA Storm Data. Proprietary constraints often restrict the use of insurance data such that only samples or partial coverage (i.e., records from one company) are usually available.

Kithil (n.d., 1997) provides 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 broader hazard assessments. However, the most rigorous studies have been completed by Holle et al.

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 270M pesetas (>US$1.5M) 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-$50,000 • Average annual damage of $32M (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 • $7M average annual 3-state loss (including $150/claim deductible) • Average annual U.S. loss of $332M	Colorado Chapter of Chartered Property and Casualty Underwriters and a large member insurer
Holle et al (2005)	1890-94, 1990-94	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 Forestry (fire loss)	• CA$1.5M average annual property fire loss (1,771 fires) • CA$3.5M average annual cost related to forest loss and fire suppression	Dominion Fire Commissioner Provincial Forest Fire statistics

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

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 • $812.4M 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, 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 $20-200M	US NOAA Storm Data
Stallins (2002)	1996-2000	Georgia	Property damage (insured)	• 19,582 claims and $22.9M insured losses over 5-year period for one Georgia insurer ($1,100 per claim) • $91.6M insured losses if results extrapolated statewide using relative market share	Large Georgian insurer claims database US NOAA Storm Data

[a] costs reported in $US unless noted otherwise

(1996), Curran et al. (1997, 2000) and Stallins (2002). The following general points have emerged from their work and are consistent with the results of other studies referenced in Table 1:

- Lightning is one of the most common sources of weather-related property damage, whether measured in absolute terms or normalized for population or cloud-to-ground (CG) lightning flash density.
- NOAA Storm Data consistently and significantly underreport the number of damaging events and the value of damage when compared with insurance claim data. Presumably this underestimation applies to all media report-based damage data sets.
- While the frequency of damage appears to follow the same diurnal and seasonal pattern apparent for casualties, additional research is necessary to characterize and explain the relative roles of population density, household consumer trends (e.g., prevalence of consumer electronics), and CG flash density in influencing the observed geographic and longer-term temporal variation in property damage.

FOREST FIRE MANAGEMENT

Forest fire, also commonly known as wildfire, is a natural and important part of the ecology of a forest (Podur et al. 2003). Nevertheless, forest fires may impact hydrology, water quality, air quality, and forest ecosystems. Where fires interface with people and settlements, they may cause injuries, damage property, force evacuations, close roads and railway lines, interrupt power and energy supplies, and necessitate substantial investments in fire suppression activities (Hardy 2005). Lightning is a well-established and recognized ignition source for forest fires (e.g., Gisborne 1926). Long continuous current (LCC), high multiplicity, and positive polarity CG strikes are generally thought to account for most lightning-caused fires (Wotton and Martell 2005; Latham and Williams 2001). However, other research has shown little evidence of a relationship between the latter two factors and forest fires (Hall and Brown 2006). Studies have examined the relative significance of lightning as compared to anthropogenic ignition sources on the frequency and spatial extent of forest fires. Canadian figures for the 1959-1997 period indicate that more than 70 percent of large (>200ha) fires and 85 percent of the average annual 1.8 million ha burned are attributable to lightning (Stocks et al. 2002). Lightning accounts for a smaller proportion of fires less than 200 ha in size, however, these only make up a few percent of the total area burned each year (Weber and Stocks 1998). Variations in the potency of lightning have recently been observed in Ontario (Podur et al. 2003), Western Canada (Wierzchowski et al. 2002), and Northwest Territories (Kochtubajda et al. 2006). In a study of the Central Cordilleran area, Wierzchowski et al. (2002) determined that one fire occurred for every 50 and 1400 lightning discharges in British Columbia and Alberta sections, respectively. Differences are attributable in part to elevation, vegetation, fuel and lightning characteristics (Podur et al. 2003; Wierzchowski et al. 2002; Wotton and Martell 2005).

The general costs and economics of forest fires and fire prevention have also received treatment in the literature. While no studies were found that explicitly evaluated the aggregate costs of lightning-ignited fires, research has been undertaken on individual fires or exceptional fire seasons (e.g., Kelowna, B.C., Filmon 2004; Chisholm, AB, CFRC 2001), summary statistics of provincial/state and national suppression costs (e.g., NRCan 2004; Johnston 2006), and specific forest use impacts (e.g., parks, Starbuck et al. 2006). Fire management costs in Canada typically range from $400-800 million each year (NRCan 2004). The value of timber lost to fire is substantial and in extreme fire years can equal or exceed the value that is harvested commercially (NRCan 2004). Where fires occur at the wildland-urban interface, significant costs can result from forced evacuations and property damage to homes, other buildings, and transportation or energy infrastructure.

Some work has been completed to quantify impacts for tourism and recreation and health sectors. If parks and other recreation areas are shut down over large areas because of fire, economic impacts associated with reduced visitation can cost tens of millions of dollars (Starbuck et al. 2006). Rittmaster et al. (2006) estimated one-day health impacts of $9-12 million for the 2001 Chisholm forest fire whose smoke plume affected the large urban area of Edmonton, Alberta. These costs were comparable to those incurred for fire suppression ($10 million) and about half of the value of lost timber ($20 million) as determined by CFRC (2001). Regardless of cost type, it is apparent from studies that provide very detailed accounts of losses and expenditures for specific fires that the form and magnitude of impact are strongly influenced by the individual circumstances of each event (i.e., nature of the fire, forest qualities, and socio-economic considerations) (Lynch 2004).

POWER GENERATION, TRANSMISSION AND DISTRIBUTION

Power utilities, in particular transmission and distribution facilities, bear a significant portion of the overall lightning-related damage burden. Although generation is largely unaffected by the outdoor environment (Billinton and Acharya 2005), studies have noted the impacts of lightning to the safety-related instrumentation and control systems of nuclear power plants (e.g., Trehan 2001; Bernstein et al. 1996) and have provided detailed accounts of lightning damage to wind turbines (Cotton et al. 2000; McNiff 2002; Glushakow 2007).

Most of the literature regarding the power sector, however, relates to the effect of lightning on the transmission and distribution infrastructure of electric utilities. Lightning was a major contributing cause of very significant blackouts, including the July 1977 blackout in New York City that affected 9 million people for up to 26 hours, and a June 1998 blackout that shut down electricity systems in the U.S. Upper Midwest, Ontario, Manitoba and Saskatchewan for upwards of 19 hours (U.S.-Canada Power System Outage Task Force 2004). More commonly though lightning is a nuisance hazard that affects small sections of transmission and distribution networks. Two types of impact are widely cited: 1) physical damage to lines, towers, poles, transformers, insulators, fuses, and surge arrestors which generate repair and replacement costs, and 2) outages and power quality events that result in lost revenue to utilities and various costs to electricity consumers.

Whether or not a particular segment of a transmission or distribution system is affected depends on many factors. For instance, the location and properties of the lightning strike (i.e., direct overvoltage or adjacent strike causing induced overvoltage, current strength); voltage rating and length of power line; construction design and maintenance of towers, poles, transformers and lines (e.g., height, insulation rating, material deterioration); ground resistance (i.e., flashover potential greater if resistance is high); and extent of investment in lightning protection (e.g., surge arresters, overhead shield wires) have all been identified as being important in determining the vulnerability of a network (Carpenter and Auer 1995; Drabkin and Carpenter 2004; Parrish 1991; Rakov 2003; Shen et al. 1999; Koval and Chowdhury 2005; Allan and Billinton 1993; Chisholm et al. 2001; Nakada et al. 1998; Short 1992; Porrino et al. 1997). In general, higher voltage components of the system (i.e., transmission element, substations) are constructed to higher standards and with greater levels of lightning protection than the lower voltage (i.e., distribution) portion.

Reliability statistics are used by electric utilities to track, explain and manage impacts, most often outages, on a particular system. General measures include the annualized number of outages per standard line-length, total customer hour interruptions, percentage or count of total unplanned outages, total duration of outages, total customers affected. Standard industry indices include the System Average Interruption Frequency Index (SAIFI) (average number of interruptions per customer per year) and Customer Average Interruption Frequency Index (CAIFI) (average number of interruptions per customer affected per year) (Allan and Billinton 1993; Keener 1997; McCracken and Rylska 2005; McDaniel et al. 2003; Mitsche 1989; Tarchini and Giminez 2003; Visacro et al. 2005). In general, adverse weather accounts for most of the unplanned sustained and transient line-related outages that are experienced in Canada (Koval 1994). Table 2 summarizes a selection of studies that have identified lightning-specific influences on outages, based on analyses of observed outage data as opposed to modeled or simulated values (e.g., Anderson and Short 1993; Savic 2005; Pyrgioti et al. 2000; Torres 1999; Teixeira and Moura 2006). Lightning consistently appears as a major cause of service interruptions.

Despite the documented significance of lightning, few articles were found that assessed or referenced estimates of the direct or indirect costs of lightning-related outages and utility equipment damage. Diels et al. (1997) note that lightning accounts for about half of all power failures experienced in regions of the U.S. that are subject to thunderstorms and costs the electric utility industry up to US$1 billion annually in damaged equipment and lost revenue. Considering annual estimates of US$50 million (Mitsche 1989) and US$100 million (Keener 1997) for repairing lightning-caused damage and service restoration from the Electric Power Research Institute (ERPI), it appears that much of the impact may reside in lost income (i.e., electricity sales) rather than property damage.

An even greater cost may be that borne by electricity consumers and society-at-large. While not lightning-specific, several researchers have recently examined the economic value of electricity reliability and the costs of power disturbances to consumers in a number of countries including Brazil (Massaud et al. 1994), Canada (Allan and Billinton 1993; Billinton and Wangdee 2003, 2005), Denmark (Baarsma et al. 2005), South Africa (Mushwana 2005), United Kingdom (Allan and Karuiki

Table 2 Selection of published estimates of lightning-related damage (electricity generation, transmission and distribution sector)

Author	Timeframe	Location	Sector(s)	Estimated Lightning Impact	Data Sources
Adler et al. (1994)	1965-1985	Canada and United States	Electricity transmission	• 0.596 line-related forced outages per mile-year (583,712 mile-years of circuit exposure)	1985 Utility survey by IEEE
Chisholm et al. (2001)	1989-1992	Southwestern Ontario	Electricity distribution	• Average system experienced 15 sustained outages per 100km-year (FAIRS data) • Average lightning-related line disturbances per 100km-year for Drayton DS (55) and Cedar Mills (29) based on ELDS	Hydro-One (FAIRS) data ELDS Station Event Recorder data (2 stations in SW Ontario)
Gelineau (2000)	2000	Canada	Electricity transmission and distribution	• 5.9% of customer interruptions were due to lightning	Canadian Electricity Association
Hidayat et al. (2002)	1996-2000	Jakarta, Indonesia	Electricity distribution	• 36.2 line outages per 100 km-year (1,779 km medium-voltage lines)	Regional utilities
Karlsson and Norberg (2001)	Not stated	Sweden	Electricity transmission	• 1.8 outages per 100 km-year (130kv line)	Vattenfall AB (utility)
McCracken and Rylska (2005)	1999-2003	Canada	Electricity transmission and distribution	• 3.1M average annual customer hour interruptions (5-year average) • 5.2% of total average annual customer hour interruptions	Canadian Electricity Association (based on 31 major utilities)
McDaniel et al. (2003)	1997-1999	United States	Electricity transmission and distribution	• Lightning-related outages/flash density (flashes/km^2) statistics: • Detroit Edison (9,583/2.1) (13kv system over 20,000 km^2) • Carolina Power & Light (30,831/3.9) (23kv system over 35,000 km^2) • Florida Power (37,683/9.3) (12kv system over 10,155km^2)	Reliability data from Detroit Edison, Carolina Power and Light, and Florida Power
Parrish (1991)	1986-1988	Florida	Electricity distribution	• Average annual lightning-caused transformer failure rate of 0.25% and transformer fuse operating rate of 0.43% based on 2,448 transformers at 1,789 locations and 154.4km of exposed circuit	Florida Power Corporation

Table 2 Selection of published estimates of lightning-related damage (electricity generation, transmission and distribution sector) cont...

Author	Timeframe	Location	Sector(s)	Estimated Lightning Impact	Data Sources
Shen et al. (1999) and Koval and Chowdhury (2005)	1977-1996	Alberta	Electricity transmission	• Lightning was the primary cause of 10, 5 and 23% of 72kV, 144kV, and 244 kV line-related sustained forced outages, respectively. Mean/median durations for 72kV, 144kV and 240kV line outages caused by lightning were 7.12/1.83, 104.21/1.26, 1.45/0.39 hours, respectively.	Alberta Power Limited
Tarchini and Giminez (2003)	1997-2001	Argentina	Electricity transmission	• 15 line outages per 100 km-year (132kv line)	Empresa Distrihuidora de Electricidad de Mendom
Tolbert et al. (1997)	1960-1992	Tennessee	Electricity distribution	• 57 of 135 recorded outages (42%) over the period and approximately 20-mile network were attributed to lightning	Oak Ridge National Laboratory
Whitehead and Driggans (1990)	1987	Southeast United States	Electricity transmission and distribution	• 65% of 1009 reported transmission line outages in 1987 were lightning-related	Tennessee Valley Authority
Zhu et al. (2006)	1995-2004	United States Unspecified**	Electricity distribution	• Number of lightning-related outages explained by simple linear model N=58.94(flash density/mile2)-27.975 (r-squared, 0.919)	Unspecified utility's power outage data Regional utilities
Zoro and Mefiardhi (2005)	2002-2004	West Java, Indonesia	Electricity distribution	• 88-168 direct and indirect flashovers per 100km-year (4-20kv lines, 260 km of total circuit)	

1999), and the U.S. (Balducci et al. 2002; Caves et al. 1992; CEIDS 2001; Chowdhury et al. 2004; Eto et al. 2001; LaCommare and Eto 2004; Lawton et al. 2003). Disturbances include momentary, temporary and sustained power outages (0-10 percent of voltage for fractions of a second to many hours) and power quality phenomenon (all other deviations from perfect power including voltage sags, surges, transients, and harmonics) (CEIDS 2001; LaCommare and Eto 2004). Such events affect residential, industrial, commercial, and institutional consumers through lost production, labour, lost or damaged electronic data, materials loss or spoilage, equipment damage, backup generation, overhead, and restart costs which are offset to some extent by unused materials and fuel, scrap value of damaged materials, lower energy bills, and unpaid labour (Eto et al. 2001; CEIDS 2001; Balducci et al. 2002). Broader or secondary social costs (e.g., looting and other crime, injuries/deaths related to alternative fuel use and CO poisoning) have also been acknowledged but never included in costing studies (Eto et al. 2001; Balducci et al. 2002).

Several methods have been used to determine costs, including market-based approaches that rely upon observed consumer behaviour (e.g., choice of interruptible and curtailable electricity rates, investment in back-up generation, insurance for utility service interruptions) and survey approaches (e.g., direct costing, contingent valuation) (Koomey et al. 2002). The latter seem to dominate the literature and have produced a wide variety of estimates (or damage/cost functions) for residential, commercial, industrial, and institutional user classes. While few studies have explicitly assessed the costs of power quality impacts on consumers, CEIDS (2001) estimates that power quality events may cost the U.S. economy between $15-24 billion each year. When combined with aggregate outage impacts across all business sectors, it is estimated that power disturbances cost the U.S. economy between $119 billion and $188 billion annually (CEIDS 2001). LaCommare and Eto (2004) provide a smaller base estimate of US$79 billion for outage costs but suggest that two-thirds of the impact are the result of momentary interruptions (less than 5 minutes duration)—important for the current investigation in that many of these short-term events are caused by lightning strikes. Assuming that the Canadian economy is similarly sensitive to that of the U.S., if even a small fraction of such large costs are associated with lightning, then the potential lightning-related impacts could be significant.

An alternative and complementary approach to gauging the impact of lightning-related interruptions to customers is to assess the level of investment in preventive measures and realization of benefits. In the general power disturbance literature, this technique has been used to determine the impact of power quality on consumers (e.g., Clemmensen et al. 1993, as cited in LaCommare and Eto 2004 and Koomey et al. 2002). Although several studies have evaluated the technical efficacy or small-scale feasibility of lightning arresters, alternative pole designs and other protection technologies across a transmission or distribution network (e.g., Karlsson and Norberg 2001; Carpenter and Auer 1995; Tarchini and Gimenez 2003), minimal research was found on the aggregate economic costs and benefits of adoption. Bernstein et al. (1996) provide a series of U.S. utility-specific accounts of savings attributable to data produced through the U.S. National Lightning Detection Network though. While not comparable to a fully quantified valuation and cost-benefit analysis, reported cost savings for 8 utilities amounted to several hundred thousand dollars per year (Bernstein et al. 1996). General areas of cost reduction or benefit interpreted from the paper include: reduced labour-intensive monitoring effort; more accurate and cost-effective pre-positioning of resources (e.g., repair crews) in response to lightning threat compared to deployment based on general forecasts or waiting for customers to identify problems; reduced system down-time; validation of insurance claims for lightning-caused interruptions; reduced time and labour explaining cause of outages to customers; and justification for allocation of additional lightning protection equipment in infrastructure designs (i.e., to higher-prone parts of system).

AGRICULTURE

Lightning-related agricultural losses, such as damage to homes, barns, sheds and other buildings, were included in several of the studies referenced in Table 1 that relied on Storm Data. Holle et al. (2005) note that agricultural losses were the most common form of lightning damage in the late nineteenth century but now account for a much smaller proportion of reported impacts. Livestock mortality in particular has historically been important to insurers (Kopf 1928) with weather in general responsible for about 7 percent of the 3.9 million cattle and calves lost in the U.S. in 2005 (USDA 2007). Linn (1993) observed that lightning accounts for more than 80 percent of accidental livestock losses, presumably in the U.S., and Williams (2000) describes lightning mortality in horses. However, aside from these references, a few isolated and often anecdotal accounts of individual events (e.g., Nunes 2006), and papers describing farm-specific lightning protection measures (e.g., Chamberlain and Hallman n.d.), no contemporary documentation was found in the literature that could be used to define the extent and magnitude of lightning-related impacts to agriculture. Intuitively, and through experiences with other natural hazard events (e.g., Ice Storm 1998; Kerry et al. 1999), power supply interruptions as discussed in the previous section are important and costly to certain operations (e.g., dairy) and often necessitate the purchase of standby generators.

TRANSPORTATION AND PIPELINES

Little research has been conducted on the impacts of lightning on transportation. Much of what exists has been completed in the U.S. and provides evidence of general impact mechanisms but little indication of the frequency, severity or magnitude of impacts let alone costs. Most of the detailed and quantitative research has been completed for aviation with less activity concerned with surface transportation, which for this analysis includes energy supply pipelines.

Concerns about the impact of lightning on aviation, in particular the safety and protection of aircraft and space vehicles, have been expressed in the literature for several decades (e.g., Cobb and Holitza 1968; Plumer et al. 1985). Weather is a contributing factor in about 23 percent of U.S. accidents involving aircraft (Kulsea 2003) and several studies have isolated the impact of lightning. Cherington and Mathys (1995) identified 40 lightning-related aviation entries in the US National Transportation Safety Board accident data over the 1963-1989 period. Ten commercial and 30 private aircraft incidents resulted in 290 fatalities and 74 serious injuries (Cherington and Mathys 1995). Uman and Rakov (2003) reviewed past studies to determine the nature of lightning-aircraft interactions, documenting both direct effects (e.g., holes in metal skin, puncturing or splintering of non-metallic structures, welding or roughening of moveable hinges and bearings, exterior antenna and light damage, fuel ignition) and induced voltage impacts that affect many aircraft electronic systems (e.g., VHF communication set, compass, instrument landing system). Based on a meta-analysis of commercial aircraft strike data (1950-1974) they estimated an exposure of 1 strike for every 3000 hours or about once per year for each commercial aircraft though impacts of strikes are often minimal and are only very rarely catastrophic (Uman and Rakov 2003). This observation is also supported by Weber et al. (1998) who noted that only 11 percent of lightning strikes to aircraft in the United States require repair or replacement of equipment. Damage incidence is much lower for newer aircraft with avionics or full High-Intensity Radiated Fields (HIRF) protection (O'Loughlin and Skinner 2004) thus one would expect impacts to diminish over time as fleet stocks are replaced.

While one account of lightning damage to airport infrastructure was found in the literature (Gopalan 2005), the greater significance of lightning for aviation is its impact on ground operations, flight delays, diversions, and cancellations. Weather-related accident damage and injuries, delays, and unexpected operating costs amount to $3 billion annually in the U.S. (Kulsea 2003). In assessing the utility of a new lightning mapping sensor, Weber et al. (1998) suggest that $2 billion per year in operating costs and passenger delays are associated with thunderstorms. This figure, based on U.S. Federal Aviation Administration information, has also been attributed, perhaps incorrectly, to lightning alone (NOAA 2006). Research by Evans et al. (2004) suggest that, given the complexity of aviation systems, it is very difficult to determine and allocate delay costs related to convective weather, let alone an aspect of it such as lightning. Post et al. (2002) utilized lightning data to develop an enroute weather severity index that can be applied to determine travel delays associated with convective weather—and ultimately costs (Kettunen et al. 2005). In additional to providing information on the impacts of convective weather, such studies, along with those of Evans et al. (2004), are important for assessing the potential benefits and costs of various planned improvements to aviation systems.

Surface transportation, including road, rail, and marine modes, along with pipelines, that account for most of the economic value of the transport sector, is also affected by lightning. Although no research has been conducted to determine the overall economic significance of lightning, a recent survey of U.S. surface transportation representatives to assess their weather information needs (OFCM 2002) identified the following lightning-related impacts:

- potential for injuries to maintenance and operations personnel (small boat marine, aviation ground operations, rural/urban light rail transit);
- potential equipment damage (pipelines);
- occasional damage to towers and antennae disrupting communications (State police);
- restrictions on certain hazardous operations such as refueling or maintenance;
- signal and track sensor malfunctions/outages from lightning strikes to switches or electrical boxes causing delays, stops, or traffic congestion (long-haul rail, rural/urban light rail transit); and
- sensor damage and disruption of monitoring data flow and communications from sensors and control facilities (pipelines).

Several studies have examined the general impacts noted above and the efficacy of lightning protection for rail or light rail systems in greater detail (Morris and Dinallo 1996; Lucca and Buffarini 2000; Heilig et al. 2002; Pham et al. 2003; Theethayi et al. 2007). For the road sector, measures to mitigate lightning-caused damage to traffic sensor and data communication surge protection infrastructure in Florida were assessed by Harvey and Mussa (2003). Some simulation research has also been completed to examine impacts on and preventive measures for pipelines (e.g., Metwally and Heidler 2005). Overall though, research on the impacts of lightning on surface transportation interests seems lacking which likely suggests that existing lightning protection technology and operating rules and standards are effective at mitigating impacts at acceptable cost levels for most users.

TELECOMMUNICATIONS

The telecommunications sector has expanded rapidly over the past two decades. Approximately 64 fixed telephone lines, 53 mobile cell subscribers, 87 computers, 68 Internet users and 24 broadband Internet subscribers existed for every 100 inhabitants in Canada in 2005 (ITU 2007). Expansion in telecommunications, as measured by these and other indicators, is positively correlated with economic growth (Correa 2006). Despite the increasing importance of telecommunications, no published information was found that described the aggregate impact of lightning on telecommunications infrastructure, operations, and services. However, several studies generally note and discuss various means to reduce the vulnerability of systems and infrastructure to direct strikes or, more commonly, induced voltages and associated electromagnetic damage or interference (Barreto 2002; Kijima 1999; Baker and Ahmad 1999; ITU 1997; Janklovics 1997; Shintaku et al. 1998; Woodward 1991). For instance, Kijima (1999) described 3 cases of lightning damage to telecommunications installations (private branch exchange, digital switch, and transmission equipment elements) and simulated countermeasures for each event. Baker and Ahmad (1999), Janklovics (1997) and Shintaku et al. (1998) also used models to simulate potential damage or the efficacy of protective measures such as lightning rods, grounding systems, surge by-pass with arresters, and insulation.

TOURISM AND RECREATION

Tourism and recreation activities that take place outdoors are exposed to lightning. Although businesses and facilities may be subject to direct damage from lightning strikes or affected by lightning-related power or telecommunication outages, the published literature pertains almost exclusively to the protection of active participants and spectators. Several studies have shown that a large and growing proportion of lightning-related casualties involve those engaged in recreation activities such as hiking, camping, boating or golfing (e.g., Holle et al. 2005; Makdissi and Brunker 2002; Mills et al. 2008). These risks are acknowledged in various guidelines that have been developed to alert the public of the lightning hazard, threats to safety, and precautions necessary to minimize exposure in a wide range of settings (Zimmerman et al. 2002). Most of the literature obtained for the review dealt with either stadiums (or other events with concentrated gatherings) or golfing[4]. General threats to stadiums and other large event venues from severe storms have been studied by Edwards and Lemon (2002) with more detailed, lightning-specific risks and safety recommendations provided by Walsh et al. (1997, 2000, 2003), Gratz et al. (2004), Gratz and Noble (2006). Lightning safety policies have also been developed for participants in sports and athletics activities (e.g., Makdissi and Brukner 2002; Bennett 1997) which often take place in large event venues during the peak lightning season and time-of-day (Walsh et al. 1997).

The prime golfing season also overlaps peak lightning months which in part explains why a significant number of lightning casualties occur on golf courses (Kithil 2007; Flynn 1995; Waddell 2006). High profile events, such as the 1991 tragedy at Hazeltine National Golf Club during the U.S. Open golf tournament, which killed one man and injured 5 others (Kindred 2002), have encouraged a number of golf facility operators to invest in some level of lightning protection (e.g., mobile or permanent shelters) or detection/alert technology whereby golfers are ordered off a course (e.g., Waddell 2006; Bonner 2005; Mooney 2003). No figures were found that quantified the market penetration of such systems, but cost estimates for individual courses were between US$3,000 (Flynn 1995) and CA$30,000 (Crawford 2001). Such costs may explain why many courses lack such policies or interventions and simply rely on golfers to use common sense in lightning situations (Crawford 2001). As adoption of policies and new technologies increase, liability may become an issue if a failure to provide lightning-proof weather shelters or protection can be proven an act of negligence though, according to research by Flynn (1995), this has not yet occurred in U.S. courts.

Lightning may also affect the tourism and recreation sector through lost revenue due to cancelled events or reduced participation rates (because of safety concerns) and property damage. As noted previously, there is little evidence documenting the extent or magnitude of either type of cost to the industry. Flynn (1995) anecdotally noted that significant lightning activity can close a golf course thus reducing the number of rounds played and associated revenue. Other researchers have examined the impact of weather elements, including precipitation, on participation levels in golfing and other recreation activities (e.g., Scott and Jones 2007) but no quantified estimates of the impact of lightning were found. In terms of property damage, descriptions of particular events are evident (e.g., golf course green, Krider 1977) and U.S. National Golf Foundation figures estimate that lightning damage to trees, irrigation systems or buildings occurs on average 2 times per golf course each year (Crist 1995). Cheng (2002) notes a potential grounding (and therefore damage) issue for the moving components of retractable stadium roofs. Overall, the lack of literature suggests that for most forms of recreation, property damage is not a large concern. Recreational boating may be an exception though. In his review of the US code for lightning protection of boats, Thomson (1991) surveyed 71 owners of small recreational sailboats in southwest Florida that were damaged by lightning. By combining the survey information with general repair records, Thomson (1991) estimated that about 3 percent of all moored sailboats in the region experience lightning-induced damage each year. In

[4] Lightning-ignited forest fires are also a threat to parks (e.g., Heathcott 1999), but this was generally treated in the Forest Fire Management section.

general, sailboats in freshwater experienced the most severe and frequent electronics and hull damage; lightning protection equipment seemed to afford only modest reductions in damage (Thomson 1991).

OTHER IMPACTS

A couple of studies were also discovered that dealt with hazardous material accidents. Rasmussen (1995) extracted and analyzed data from the MHIDAS (SRD)[5] and Facts (TNO)[6] data bases of (global) accident case histories for the period 1941-1991. Lightning accounted for 61 percent of 232 hazardous material accidents where natural events were the cause or a major contributing factor (Rasmussen 1995). At a smaller geographic scale, Ruckart et al. (2004) determined that lightning was a causal factor in over 19 percent of the 110 weather-related acute releases of hazardous substances that were reported to the HSEES system in Texas during 2000-01.

Finally, Keskar (1996) cites and explains lightning-related damages to water and wastewater treatment plants in Florida and Arkansas, respectively, arising in part from improper installation of surge protection equipment. Despite the limited amounts of literature, lightning impacts to water utilities may be relatively common. A survey of community water system managers conducted in South Carolina and the Susquehanna River Basin in 2000 revealed that over 50 percent had experienced lightning events over the past 5 years (Dow et al. 2007). Over 40 percent of system managers in South Carolina and over 20 percent of those in the Susquehanna River Basin expected to be impacted with considerable or catastrophic problems related to lightning during the next 10 years (Dow et al. 2007).

SUMMARY

In summary, three general types of impact were revealed through the literature review: human casualties, property damage, and losses associated with the interruption of electricity and other critical services. Affected sectors include human 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. Impacts were usually reported in terms of physical indicators (i.e., number of people injured, damage report counts, electricity outage frequency and duration, number of insurance claims, etc.) with a smaller set of studies also estimating economic costs. Based on the available though often limited descriptions of analyses, virtually all of the research that was examined reported direct lightning-related damage costs or cost savings associated with preventive measures. No formal economic analyses of indirect costs or non-market costs attributable to lightning damage

[5] Major Hazard Incident Data Service developed by AEA Technology plc on behalf of the Major Hazards Assessment Unit of the United Kingdom Health and Safety Executive (HSE).

[6] Facts (TNO) http://www.factsonline.nl/tabid/178/Default.aspx

were uncovered. Much of the work that has been completed is focused on the U.S., with only a few Canadian studies. In short, this literature review substantiates the need for additional Canadian empirical research, including on-going efforts by the authors to develop an aggregate picture of lightning impacts and costs across multiple sectors (Mills et al., n.d.).

References

Adler RB, Daniel Jr SL, Heising CR, Lauby MG, Ludorf RP, White TS (1994) An IEEE survey of U.S. and Canadian overhead transmission outages at 230kv and above. IEEE Trans Power Deliv 9(1): 21-39

Aguado M, Hermoso B, Yarnov A, Sarries L (2000) An evaluation of lightning's effects and economic costs in Navarra (Spain) from 1950 to 1999, In: Proceedings of the 25th International Conference on Lightning Protection, September 18-22, Rhodes, Greece, pp. 798-801.

Alberini A (2005) What is a Life Worth? Robustness of VSL Values from Contingent Valuation Surveys. Risk Anal 25(4):783-800

Allan R, Billinton R (1993) Power system reliability and its assessment, Part 3: Distribution systems and economic considerations. Power Eng J 7(4):185-192

Allan RN, Kariuki KK (1999) Reliability worth assessments of electrical distribution networks. Qual Reliab Eng Int 15:79-85

Anderson JG, Short TA (2005) Algorithms for calculation of the lightning induced voltages on distribution lines. IEEE Trans Power Deliv 8(3):1217-1225

Angus DE, Cloutier E, Albert T, Chénard D, Shariatmadar A, Pickett W, Hartling L (1998) The Economic Burden of Intentional Injury in Canada. Prepared for Smartrisk in partnership with Health Canada, Ontario Ministry of Health, and the Kingston, Frontenac and Lennox and Addington Health Unit. http://www.smartrisk.ca/ListingContributions.aspx?sd=77&dd=3.

Baarsma BE, Berkhout PB, Hop JP (2005) Valuation of the quality of the electricity grid-Power outages have a price too. Discussion paper no. 41, SEO Economic Research, University of Amsterdam.

Baker AMA, Ahmad HB (1999) EMC aspects in telecommunication buildings struck by lightning, In: Proceedings of the 1999 IEEE Symposium on Electromagnetic Compatibility, pp. 654-659

Balducci PJ, Roop JM, Schienbein LA, DeSteese JG, Weimar MR (2002) Electrical Power Interruption Cost Estimates for Individual Industries, Sectors, and U.S. Economy. Prepared for the U.S. Department of Energy by Pacific Northwest National Laboratory, Richland, WA. Report PNNL-13797.

Barreto RM (2002) EMC and lightning protection for telecommunications systems, ITEM 2002. http://www.interferencetechnology.com/ArchivedArticles/lightning_and_transients/i_02_03.pdf?regid=

Bennett BL (1997) A model lightning safety policy for athletics. J Athlet Train 32(3):251-253

Bernstein R, Samm R, Cummins K, Pyle R, Tuel J (1996) Lightning detection network averts damage and speeds restoration. IEEE Comp Appl Power 9(2):12-17

Best's Review (1998) Annual lightning damage exceeds $5-6 billion. Best's Rev 99(4):98

Billinton R, Acharya J (2005) Consideration of multi-state weather models in reliability evaluation of transmission and distribution systems, 2005 Canadian Conference on Electrical and Computer Engineering, May 1-4, Sasktatoon, SK, pp.619-622.

Billinton R, Wangdee W (2003) Estimating customer outage costs due to a specific failure event, In: IEEE Proceedings of Generation, Transmission and Distribution, 150(6):668-672

Billinton R, Wangdee W (2005). Approximate method for event-based customer interruption cost evaluation. IEEE Trans Power Syst 20(2):1103-1110

Blumenstein L (2006) Lightning damages First Carnegie Pl. Libr J 131(9):18

Bonner J (2005) When Thunder Rolls, Don't Swing a Metal Rod. Poynteronline, Retrieved online at http://www.poynter.org/column.asp?id=65&aid=85037

Briët R (2004) Myths and misconceptions of lightning protection and the dangers of indiscriminately implementing standards for the installation of lightning protection systems, In: Proceedings of the International Symposium on Electromagnetic Compatibility 1:306-308

Carpenter RB, Auer RL (1995) Lightning and surge protection of substations. IEEE Trans Ind Appl 31(1):162-170.

Caves DW, Herriges JA, Windle RJ (1992) The cost of electric power interruptions in the industrial sector: Estimates derived from interruption service programs. Land Econ 68(1):49-61

CEIDS (2001) The Cost of Power Disturbances to Industrial and Digital Economy Companies. Report prepared by Primen for the Consortium for Electric Infrastructure to Support a Digital Society, Electric Power Research Institute, Palo Alto, CA.

CFRC (2001) Chisholm Fire Review Committee Final Report. Submitted to the Minister of Alberta Sustainable Resource Development. 50 pp. http://www.wildfirelessons.net/development/documents/Chisholm%20Final%20Report%202001.pdf.

Chamberlain D, Hallman E (n.d.) Rural Safety and Health: Lightning Protection for Farms. Cornell Cooperative Extension, Cornell Agricultural Health & Safety Program. http://www.cdc.gov/nasd/docs/d001801-d001900/d001825/d001825.pdf.

Changnon SA (2001) Damaging thunderstorm acitivity in the United States. Bull Am Meteorol Soc 82(4):597-608

Changnon SA (2003) Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming. Nat Hazards 29(2):273-290

Changnon SA, Changnon JM, Hewings JD (2001) Losses caused by weather and climate extremes: A national index for the United States. Phys Geogr 22(1):1-27

Cheng A (2002) Lightning plays the stadium. Mech Eng 124(2):60

Cherington M, Mathys K (1995) Deaths and injuries as a result of lightning strikes to aircraft. Aviat Space Environ Med 66(7):687-689

Chisholm WA, Cress SL, Polak J (2001) Lightning-caused distribution outages, In: Proceedings of the 2001 IEEE/PES Transmission and Distribution Conference and Exposition, pp. 1041-1046.

Chowdhury AA, Mielnik TC, Lawton LE, Sullivan MJ, Katz A (2004) Reliability worth assessment in electric power delivery systems. Paper presented at the IEEE Power Engineering Society General Meeting, 2004, pp. 1-7.

Clemmensen J, Bates J, Kraft S (1999) The top 50 equipment suppliers and service providers. Power Qual Assur Mag 10:13-25

Cobb WE, Holitza FJ (1968) A note on lightning strikes to aircraft. Monthly Weather Rev 96(11):807-808

Correa L (2006) The economic impact of telecommunications diffusion on UK productivity growth. Information Economics and Policy 18(4):385-404

Cotton I, McNiff B, Soerenson T, Zischank W, Christiansen P, Hoppe-Kilpper M, Ramakers S, Pettersson P, Muljadi E (2000) Lightning protection for wind turbines, In: Proceedings of the 25th International Conference on Lightning Protection, 18-22 September, Rhodes, Greece, pp. 848-853.

Crawford A (2001) Golf course considers lightning warning device. CBC News, Public Broadcasting Service. http://cbc.ca/news/story/2001/07/26/warningsca010726.html.

Crist GM (1995) The Lightning Hazard: Whose Responsibility? Golf Market Today, January/February.

Curran EB, Holle RL, Lopez RE (1997). Lightning casualties and damages in the United States from 1959 to 1994. NOAA Technical Memorandum, NWS SR-193. http://www.nssl.noaa.gov/papers/techmemos/NWS-SR-193/techmemo-sr193-13.html

Curran EB, Holle RL, Lopez RE (2000). Lightning casualties and damages in the United States from 1959 to 1994. J Climate 13:3448-3464

Cutter SL, Emrich C (2005) Are Natural Hazards and Disaster Losses in the U.S. Increasing? EOS Transactions, American Geophysical Union 86 (41):381-396

Diels J-C, Bernstein R, Stahlkopf KE, Zhao XM (1997) Lightning control with lasers. Scientific American 277(2):50-55

Dore M (2003) Forecasting the conditional probabilities of natural disasters in Canada as a guide for disaster preparedness. Nat Hazards 28(2-3):249-269

Dow K, O'Connor RE, Yarnal B, Carbone GJ, Jocoy CL (2007) Why worry? Community water system managers' perceptions of climate vulnerability. Global Environmental Change 17(2):228-237

Drabkin MM, Carpenter Jr RB (2004) Advances in lightning protection and grounding systems for power systems, In: Proceedings of the Rural Electric Power Conference, May 23-25, Scottsdale, Arizona. Paper A3, 2-4.

DSS Management Consultants Inc. (2000). Phase II: Estimating Health and Economic Damages – Illness Costs of Air Pollution. Prepared for the Ontario Medical Association.

Edwards R, Lemon LR (2002) Proactive or reactive: The severe storm threat to large event venues. 21st Conference on Severe Local Storms, 12-16 August, San Antonio, TX, American Meteorological Society. 4pp.

Energy Information Administration (2007) Number of ultimate customers served by sector, by provider. http://www.eia.doe.gov/cneaf/electricity/epa/epat7p1.html.

Erlin B (2007) A brief look at lightning strikes. Concrete International 29(1):60-63

Eto J, Koomey J, Lehman B, Martin N, Mills E, Webber C, Worrell E (2001) Scoping Study on Trends in the Economic Value of Electricity Reliability to the U.S. Economy. Report LBNL-47911 prepared for U.S. Department of Energy. E.O. Lawrence Berkeley National Laboratory, Berkeley, CA.

Evans JE, Allan S, Robinson M (2004) Quantifying dealy reduction benefits for aviation convective weather decision support systems, In: Proceedings of the 11th Conference on Aviation, Range, and Aerospace Meteorology, Hyannis, MA. 32 pp.

Ferrett RL, Ojala CF (1992) The lightning hazard in Michigan. Michigan Academician 24:427-441

Filmon G (2004) Firestorm 2003: Provincial Review. Government of British Columbia. 100 pp. http://www.2003firestorm.gov.bc.ca/firestormreport/default.htm.

Flynn M (1995) Lightning: A double hit for golf course operators. Marquette Sports Law Journal 6(1):133-51

Gelineau P (2002) Financial implications of stakeholder use of industry data. Electricity 2002, Canadian Electricity Association Annual Review 73(1):13

Gisborne HT (1926) Lightning and forest fires in the Northern Rocky Mountain region. Mon Weather Rev 54(7):281-286

Glushakow B (2007) Effective lightning protection for wind turbine generators. IEEE Transactions on Energy Conservation 22(1):214-222

Gopalan TV (2005) Lightning protection of airport runway. Journal of Performance of Constructed Facilities 19(4):290-294

Gratz J, Nobel E (2006) Lightning safety and large stadiums. Bull Am Meteorol Soc 87(9):1187-1194

Gratz J, Church R, Noble E (2004) Lightning safety and outdoor stadiums. Retrieved June 21, 2007 from http://sciencepolicy.colorado.edu/admin/publication_files/resource-1740-2005.27.pdf

Hall BL, Brown TJ (2006) Climatology of positive polarity flashes and multiplicity and their relation to natural wildfire ignitions, In: Preprints, International Lightning Detection Conference, 24-25 April, Tucson, Arizona. Vaisala, Tucson, AZ. 5 pp.

Hardy CC (2005) Wildland fire hazard and risk: Problems, definitions, and context. Forest Ecology and Management 211(1-2):73-82

Harlan LC, Harlan WR, Parsons PE (1990) The economic impact of injuries: A major source of medical costs. American Journal of Public Health 80(4):453-459

Harvey B, Mussa R (2003) Improving Operation of FDOT Telemetered Traffic Monitoring Sites. Final report prepared for the Florida Department of Transportation. FAMU-FSU College of Engineering, Florida State University, Tallahassee, Florida. FDOT-BC596. http://www.fsutmsonline.net/images/uploads/reports/FDOT_BC596_rpt.pdf.

Health Canada (2002) Economic Burden of Illness in Canada, 1998. Policy Research Division, Strategic Policy Directorate, Population and Public Health Branch, Health Canada, Ottawa. 100pp. http://www.phac-aspc.gc.ca/publicat/ebic-femc98/index.html.

Heathcott M (1999) Lightning and lightning fire: Central Cordillera, Canada. Research Links—A Forum for Natural, Cultural and Social Studies 7(3):1,5,14

Heilig T, Stinger Jr WE, Thomas RS (2002) Tri-met Portland light rail system experience with nuisance tripping of track-to-earth potential relay-A case study, In: Proceedings of the 2002 ASME/IEEE Joint Rail Conference, 23-25 April, Washington, D.C., pp. 131-150

Hidayat S, Haryanto N, Sriyatmo E (2002) Lightning characteristics and performance of distribution system around Jakarta., In: IEEE proceedings of the 2002 Asia-Pacific Transmission and Distribution Conference, 1:540-545

Hirth RA, Chernew ME, Miller E, Fendrick AM, Weissert WG (2000) Willingness to pay for a quality-adjusted life year: In search of a standard. Medical Decision Making 20(3):332-342

Holle RL, Lopez RE, Navarro BC (2005) Deaths, injuries, and damages from lightning in the United States in the 1890's in comparison with the 1990's. J Appl Meteorol 44(10):1563-1573

Holle RL, Lopez RE, Arnold LJ, Endres J (1996) Insured lightning-caused property damage in three Western states. J Appl Meteorol 35(8):1344-1351

Hornstein RA (1961) Lightning Deaths and Damage in Canada. CIR-3452, TEC-349. Meteorological Branch, Department of Transport, Canada. 10pp.

Hornstein RA (1962) Canadian Lightning Deaths and Damage. CIR-3719, TEC-423. Meteorological Branch, Department of Transport, Canada. 5pp.

Insurance Information Institute (2007). Lightning striking again and again: New III study finds increase in lightning claim costs. Press release, http://www.iii.org/media/updates/press.773471/. Accessed July 2007.

ITU (1997) Risk assessment of damages to telecommunication sites due to lightning discharges, ITU-T Recommendation K.39, Series K: Protection Against Interference. Telecommunication Standardization Sector, International Telecommunication Union.

ITU (2007) ICT Statistics: Canada. International Telecommunication Union. http://www.itu.int/ITU-D/icteye/DisplayCountry.aspx?countryId=47.

Janklovics Z (1997) The place and role of power supply in the overvoltage protection and risk assessment of damages to telecommunication sites due to lightning discharges. Telescon '97 - The Second International Telecommunications Energy Special Conference, April 22-24, Budapest, Hungary, pp. 439-446.

Johnston T (2006) CIFFC Canada Report 2006. Canadian Interagency Forest Fire Centre. http://www.ciffc.ca/web/libraries/documents/2006CanadaReport.pdf.

Karlsson D, Norberg P (2001) Earthing of 130 kV power lines-effects on dependability and linecost, In: Proceedings of the 2001 IEEE/PES Transmission and Distribution Conference and Exposition, pp. 609-614.

Keener RNJ (1997) The estimated impact of weather on daily electric utility operations, in R.A. Pielke Jr. (ed), Workshop on the Social and Economic Impacts of Weather. National Center for Atmospheric Research, April 2-4, Boulder, CO. http://sciencepolicy.colorado.edu/socasp/weather1/

Kerry M, Kelk G, Etkin D, Burton I, Kalhock S (1999) Glazed over: Canada copes with the ice storm of 1998, in I. Burton, M. Kerry, S. Kalhok and M. Vandierendonck (eds) Report from the Adaptation Learning Experiment. Environment Canada and Emergency Preparedness Canada. Toronto, Ontario.

Keskar PY (1996) Analysis of lightning-related damages to instrumentation and control systems for water and wastewater plants. ISA Transactions 35:9-15

Kettunen T, Hustache J-C, Fuller I, Howell D, Bonn J, Knorr D (2005) Flight efficiency studies in Europe and the United States, 6th USA/Europe Seminar on ATM Research and Development, June 27-30, Baltimore, Maryland. 10 pp.

Kijima H (1999) Lightning protection for recent telecommunications installations, In: Proceedings of the 1999 IEEE International Symposium on Electromagnetic Compatibility, May 17-21, Tokyo, Japan, pp. 306-309.

Kindred D (2002) The day tragedy struck at Hazeltine – lightning accident at Hazeltine National Golf Club, site of this year's U.S. Open. Golf Digest http://findarticles.com/p/articles/mi_m0HFI/is_8_53/ai_89435667/print

Kithil R (1997) An overview of lightning safety, in R.A. Pielke Jr. (ed), Workshop on the Social and Economic Impacts of Weather. National Center for Atmospheric Research, April 2-4, Boulder, CO. http://sciencepolicy.colorado.edu/socasp/weather1/.

Kithil R (2007). A Lightning Safety Mandate for the Game of Golf. Retrieved May 30, 2007 from http://www.lightningsafety.com/nlsi_pls/golfsafetyrecommend.html

Kithil R (n.d.) Annual USA lightning costs and losses. National Lightning Safety Institute. http://www.lightningsafety.com/nlsi_lls/nlsi_annual_usa_losses.htm.

Kochtubajda B, Flannigan MD, Gyakum JR, Stewart RE, Logan KA, Nguyen T-V (2006) Lightning and fires in the Northwest Territories and responses to future climate change. Arctic 59(2):211-221

Koomey JG, Calwell C, Laitner S, Thornton J, Brown RE, Eto JH, Webber C, Cullicott C (2002) Sorry, wrong number: The use and misuse of numerical facts in analysis and media reporting of energy issues. Annual Review of Energy and the Environment 27:119-158

Kopf EW (1928) Origin, development and practices of livestock insurance. Casualty Actuarial Society Proceedings XIV:291-372

Koval DO, Chowdhury AA (2005) An investigation into extreme-weather-caused transmission line unavailability, In: Proceedings of the IEEE Power Engineering Society General Meeting, June 12-16, San Francisco, CA, pp.1-4.

Koval DO (1994) Frequency of transmission line outages in Canada, Conference record of the 1994 IEEE Industrial Applications Society Annual Meeting, October 2-6, Denver, CO, vol. 3, pp.2201-2208.

Krider EP (1997) On lightning damage to a golf course green. Weatherwise 30:111

Kulesa G (2003) Weather and aviation: How does weather affect the safety and operations of airports and aviation, and how does FAA work to manage weather-related effects, In: Proceedings of the Potential Impacts of Climate Change on Transportation workshop, October 1-2, 2002, Washington, D.C. USDOT Center for Climate Change and Environmental Forecasting and Federal Research Partnership (DOT, DOE, EPA, USGCRP). http://climate.volpe.dot.gov/workshop1002/index.html.

Kunkel KE, Pielke Jr RA, Changnon SA (1999) Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. Bull Am Meteorol Soc 80(6):1077-1098

LaCommare KH, Eto JH (2004) Understanding the Cost of Power Interruptions to U.S. Electricity Consumers. Report LBNL-55718 prepared for the U.S. Department of Energy. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA.

Latham D, Williams E (2001) Lightning and forest fires, chapter 11 in Johnson, E.A. and Miyanishi (eds) Forest Fires: Behaviour and Ecological Effects. Academic Press, New York. pp.375-418.

Lawton L, Sullivan M, Van Liere K, Katz A, Eto J (2003). A Framework and Review of Customer Outage Costs: Integration and Analysis of Electric Utility Outage Cost Surveys. Report LBNL-54365 prepared for the U.S. Department of Energy. Population Research Systems, LLC, and Lawrence Berkeley National Laboratory, Berkeley, CA.

Linn R (1993) Lightning Protection for the Farm. Montguide, MT 8529, B8 (Farm Safety). 4pp.

Lopez RE, Holle RL, Heitkamp TA (1995) Lightning casualties and property damage in Colorado from 1950 to 1991 based on Storm Data. Weather and Forecast 10:114-126

Lucca G, Buffarini GG (2000) Expected number of flashovers on a railway line due to direct lightning strokes, In: Proceedings of the 25th International Conference on Lightning Protection, 18-22 September, Rhodes, Greece, pp. 775-780.

Lynch DL (2004). What do forest fires really cost. Journal of Forestry 102(6):42-49

Makdissi M, Brukner P (2002) Recommendations for lightning protection in sport. Medical Journal of Australia 177:35-37

Massaud AG, Schilling MT, Hernandez JP (1994) Electricity restriction costs, In: IEEE Proceedings—Generation, Transmission, and Distribution 141(4):299-304

Mazzetti C, Flisowski Z (2000) Simplified approach to evaluate the risk of damage due to lightning on structures, In: Proceedings of the 25th International Conference on Lightning Protection, September 18-22, Rhodes, Greece, pp. 763-768.

McCracken MC, Rylska NL (2005) Societal Costs of Damage to Underground Electrical Distribution Networks due to Excavation in Ontario During 2000-03. Background Paper 5 prepared for the Ontario Regional Common Ground Alliance. Informetrica Limited. 33 pp.

McDaniel J, Williams C, Vestal A (2003) Lightning and reliability - a comparison of three utilities. Paper presented at the Rural Electric Power Conference, 2003, 3-6 May, Raleigh-Durham, North Carolina, pp. B1-1-B1-7.

McGraw B (2003) Lightning Protection: New Myths and Old Realities As They Apply to Your Home. The AM Window, general technical info section. http://amwindow.org/tech/htm/lightning.htm. Accessed June 2007.

McNiff B (2002) Wind Turbine Lightning Protection Project, 1999-2001. NREL/SR-500-31115, National Renewable Energy Laboratory, U.S. Department of Energy, Golden, Colorado.

Metwally IA, Heidler F (2005) Mitigation of the produced voltages in AC overhead power-lines/pipelines parallelism during power frequency and lightning conditions. European Transactions on Electric Power 15:351–369

Mileti DS (1999) Disasters by Design. Joseph Henery Press, Washington, D.C.

Mills B, Unrau D, Pentelow L, Spring K (n.d.) Assessment of lightning-related damage and disruption in Canada, Nat Hazards. DOI:10.1007/s11069-009-9391-2.

Mills B, Unrau D, Parkinson C, Jones B, Yessis J, Spring K, Pentelow L. (2008) An assessment of lightning-related fatality and injury risk in Canada, Nat Hazards, 47(2):157-183.

Mills E (2005) Insurance in a climate of change. Science 309(5737):1040-1044

Mitsche J (1989) Reducing lightning damages and outages. IEEE Power Engineering Review 9(3), 3-4

Mooney R (2003) When lightning approaches, let it play through! Golf Facility Report, 3rd Quarter:4-5

Morris ME, Dinallo MA (1996) Electromagnetic effects on transportation systems, Session B, National Traffic Data Acquisition Conference, Albuquerque, New Mexico, May 5-9, pp. 334-340. http://www.itsdocs.fhwa.dot.gov/edldocs/443/sess9b.pdf

MSC (2003) Annual Report 2002-03. Meteorological Service of Canada, Environment Canada, Toronto, Ontario.

Mushwana C (2005) Customer interruption costs (CICs) for network capital investments, In: Proceedings of the IEEE PES 2005 Conference and Exposition in Africa, 11-15 July, Durban, South Africa, pp. 229-233.

Nakada K, Wakai T, Taniguchi H, Kawabata T, Yokoyama S, Yokota T, Asakawa A (1998) Distribution arrester failures caused by lightning current flowing from customer’s structure into distribution lines. IEEE Trans Power Deliv 14(4):1527-1532

NOAA (2006) Economic Statistics for NOAA, Fifth Edition. Program Planning and Integration, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

NOAA (2007) Storm Data. National Climatic Data Center, US National Oceanic and Atmospheric Administration. http://www.ncdc.noaa.gov/oa/climate/sd/.

NRCan (2004) The State of Canada’s Forests, 2003-04. Natural Resources Canada, Ottawa. 93pp.

Nunes J (2006) When the cows didn’t come home. Maclean’s Mag 199(25):41

O’Loughlin JB, Skinner SR (2004) General Aviation Lightning Strike Report and Protection Level Study. Final report prepared for the Federal Aviation Administration, U.S. Department of Transportation. National Institute for Aviation Research, Wichita, Kansas. DOT/FAA/AR-04/13. 32pp.

OFCM (2002) Weather Information for Surface Transportation: National Needs Assessment Report. Office of the Federal Coordinator for Meteorological Services and Supporting Research, NOAA, U.S. Department of Commerce, Silver Spring, MD. FCM R-18-2002.

Parrish DE (1991) Lightning-caused distribution transformer outages on a Florida distribution system. IEEE Trans Power Deliv 6(2), 880-886

Pham KD, Thomas RS, Stinger Jr WE (2003) Operational and Safety Considerations for Light Rail DC Traction Electrification System Design. Transportation Research E-Circular E-C058, 9th National Light Rail Transit Conference, November 16-18, Portland, Oregon, pp.650-658. http://onlinepubs.trb.org/onlinepubs/circulars/ec058/14_02_Pham.pdf

Plumer JA, Rasch NO, Glynn MS (1985) Recent data from the airlines lightning strike reporting project. J Aircraft 22(5):429-433

Podur J, Martell DL, Csillag F (2003) Spatial patterns of lightning-caused forest fires in Ontario, 1976-1998. Ecological Modelling 164:1-20

Porrino A, Alexandri I, Clement M, Finlay GS, Henriksen T, Hoeffelman J, et al. (1997) Protection of MV and LV networks against lightning, Part I: Basic Information. Proceedings of the CIRED 14th International Conference and Exhibition on Electricity Distribution, June 2-5, Birmingham, UK, 2.21:1-7.

Post J, Bonn J, Bennett M, Howell D, Knorr D (2002) The Use of Flight Track and Convective Weather Densities for National Airspace System Efficiency Analysis, 21st IEEE/AIAA Digital Avionics Systems Conference, October 2002, Irvine, CA. 10 pp.

Pyrgioti E, Agoris D, Menemenlis C, Stravropoulos P (2000) Recording lightning acitivity in Patras-Greece and correlation with the outages of distribution lines, In: Proceedings of the 25th International Conference on Lightning Protection, 18-22 September, Rhodes, Greece. Pp. 547-552.

Rakov VA (2003) A review of positive and bipolar lightning discharges, Bull Am Meteorol Soc 84 (6):767-776

Rasmussen K (1995) Natural events and accidents with hazardous materials. J Hazardous Materials 40(1):43-54

Rittmaster R, Adamowicz WL, Amiro B, Pelletier RT (2006) Economic analysis of health effects from forest fires. Canadian Journal of Forest Research 36(4):868-877

Rodetis S (1999) Can your business survive the unexpected? Journal of Accountancy 187(2):27-32

Ruckart PZ, Borders J, Villanacci J, Harris R, Samples-Ruiz M (2004) The role of adverse weather conditions in acute releases of hazardous substances, Texas, 2000-2001, Journal of Hazardous Materials 115(1-3):27-31

Savic MS (2005) Estimation of the surge arrester outage rate caused by lightning overvoltages. IEEE Trans Power Deliv 20(1):116-122

Scott D, Jones B (2007) A regional comparison of the implications of climate change for the golf industry in Canada. Canadian Geographer 51(2):219-232

Shen B, Koval DO, Shen S (1999) Modelling extreme-weather-related transmission line outages, In: Proceedings of the 1999 IEEE Canadian Conference on Electrical and Computer Engineering, May 9-12, Edmonton, Alberta, pp. 1271-1276.

Shintaku M, Kawakubo M, Kishimoto Y, Minakuchi K, Ochiai A (1998) Lightning protection in telecommunication buildings, In: Proceedings of the Twentieth International Telecommunications Energy Conference, October 4-8, San Francisco, CA, pp. 697-702.

Short TA (1992) Lightning protection: Analyzing distribution designs. IEEE Comp Appl Power 5(2):51-55

Stallins JA (2002) An overlooked source of weather-related property damage in the Southeast: Lightning losses for Georgia, 1996-2000. Southeastern Geographer 42(2):349-354

Starbuck CM, Berrensa RP, McKee M (2006) Simulating changes in forest recreation demand and associated economic impacts due to fire and fuels management activities. Forest Policy and Economics 8(1):52-66

Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2002) Large forest fires in Canada, 1959-1997. J Geophys Res 108(D1):8149

Tarchini JA, Giminez W (2003) Line surge arrester selection to improve lightning performance of transmission lines. Paper presented at the IEEE Bologna PowerTech Conference, 23-26 June, Bologna, Italy.

Teixeira C, Coelho J, Machado e Moura A (2006) Study of the backflashover phenomena in overhead transmission lines using the EMTP, In: Proceedings of the Transmission & Distribution Conference and Exposition: Latin America, 2006. TDC '06. IEEE/PES. 6pp.

Theethayi N, Thottappillil R, Yirdaw T, Liu Y, Götschl T, Montano R (2007) Experimental investigation of lightning transients entering a Swedish railway facility. IEEE Trans Power Deliv 22(1):354-363

Thomson EM (1991) A critical assessment of the U.S. code for lightning protection of boats. IEEE Transactions on Electromagnetic Compatibility 33(2):132-138

Tolbert LM, Degenhardt LJ, Cleveland JT (1997) Reliability of lightning resistant overhead distribution lines. IEEE Ind Appl Mag 3(4):17-21

Torres CJ (1999) Line outages calculations for transmission lines. IEEE High Voltage Engineering Symposium, Conference publication 467, volume 2:185-187.

Trehan NK (2001) Consequences of lightning strikes on nuclear power generating stations. 2000 IEEE Nuclear Science Symposium Conference Record 3:27/11-27/15

U.S.-Canada Power System Outage Task Force (2004) Final Report on the August 14th, 2003 Blackout in the United States and Canada: Causes and Recommendations. Governments of the United States and Canada. 124 pp. https://reports.energy.gov/BlackoutFinal-Web.pdf.

Uman MA, Rakov VA (2003) The interaction of lightning with airborne vehicles. Progress in Aerospace Sciences 39:61-81

USDA (2007) Cattle and Calves Nonpredator Death Loss in the United States, 2005. USDA-APHIS-VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO, #N462.0507.

Vaisala (2006) North American average annual cloud-to-ground lightning flash density, 2000-2004. http://www.vaisala.com.

Valgren VN (1925) Farmers' Mutual Fire Insurance Companies. The University Journal of Business 3(2):126-152

Visacro S, Dias RN, de Mesquita CR (2005) Novel approach for determining spots of critical lightning performance along transmission lines. IEEE Trans Power Deliv 20(2):1459-1464

Viscusi WK (2004) The value of life: Estimates with risks by occupation and industry. Economic Inquiry 42(1):29-48

Viscusi WK, Aldy JE (2003) The value of a statistical life: A critical review of market estimates throughout the world. Journal of Risk and Uncertainty 27(1):5-76

Vodden K, Smith D, Meng R, Miller T, Lall A, Beirness DJ, Mayhew D, Simpson HM, Kazakov A, Tasca L (1994) The Social Cost of Motor Vehicle Crashes in Ontario. SRO-94-101. Safety Research Office, Safety Policy Branch, Research and Development Branch, Ontario Ministry of Transportation.

Waddell J (2006) A lightning detector you can carry. http://thesandtrap.com/columns/bag_drop/a_lightning_detector_you_can_carry.

Walsh KM, Bennett B, Cooper MA, Holle RL, Kithil R, López RE, (2000) National athletic trainers' association position statement: Lightning safety for athletics and recreation, J Athl Train 35(4): 471-477

Walsh KM, Bennett B, Cooper MA, Holle RL, Kithil R, López RE (2003) Errata. J Athl Train 38(1):83

Walsh KM, Hanley MJ, Graner SJ, Beam DW, Bazluki J (1997) A survey of lightning policy in selected Division I colleges. J Athl Train 32(3):206-210

Weber ME, Williams ER, Wolfson MM, Goodman SJ (1998) An assessment of the operational utility of a GOES lightning mapping sensor. Project Report NOAA-18, Lincoln Laboratiry, Massachusetts Institute of Technology, Lexington, MA. 108 pp.

Weber MG, Stocks BJ (1998) Forest fires and sustainability in the boreal forests of Canada. Ambio 27(7): 545-550

Whitehead J, Driggans R (1990) TVA's experience with the SUNYA lightning detection network. IEEE Trans Power Deliv 5(4):2054-2062

Wierzchowski J, Heathcott M, Flannigan MD (2002) Lightning and lightning fire, central cordillera, Canada. International Journal of Wildland Fire 11(1):41–51

Williams MA (2000) Lightning strike in horses. Compendium on Continuing Education for the Practicing Veterinarian 22(9):860-867

Woodward J (1991) Case histories: Lightning damage to data and telephone installations. IEEE Colloquium on Experience of Lightning and Surge Damage by Users of Telecommunications Equipment and the Proposed Remedies. 5 pp.

Wotton BM, Martell DL (2005) A lightning fire occurrence model for Ontario. Canadian Journal of Forest Research 35(6):1389-1401

Zhu D, Cheng D, Broadwater RP, Scirbona C (2006) Storm modeling for prediction of power distribution system outages. Electric Power Systems Research 77:973-979

Zimmermann C, Cooper MA, Holle RL (2002) Lightning safety guidelines. Ann Emerg Med 39(6): 660-664

Zoro R, Mefiardhi R (2005) Lightning performance on overhead distribution lines: Field observation at West Java – Indonesia, In: Proceedings of the 7th International Power Conference, IPEC 2005, pp. 1-6.

Occasional Paper 1: *November 2004, Climate Change and the Adaptation Deficit, Ian Burton*

Occasional Paper 2: *January 2005, Mainstreaming Adaptation and Impacts Science into Solutions, Don C. MacIver*

Occasional Paper 3: *January 2005, Cities and Communities: The Changing Climate and Increasing Vulnerability of Infrastructure, Heather Auld and Don MacIver*

Occasional Paper 4: *January 2005, Climate Change: Building the Adaptive Capacity, Adam Fenech, Don MacIver, Heather Auld, Robin Bing Rong and Yongyuan Yin*

Occasional Paper 5: *May 2005, The Americas: Building the Adaptative Capacity to Global Environmental Change, Adam Fenech, Mary Murphy, Don MacIver, Heather Auld and Robin Bing Rong*

Occasional Paper 6: *August 2005, Biometeorology and Adaptation: An Overview, Don MacIver, Heather Auld, Natty Urquizo and Marianne Karsh*

Occasional Paper 7: *Influences on the Sugar Maple Industry in North America, Don C. MacIver, Marianne Karsh, Neil Comer, Joan Klaassen, Heather Auld, and Adam Fenech*

Occasional Paper 8: *Climate-Based Predictions Of Forest Biodiversity Using Smithsonian's Global Earth Observing Network, Marianne Karsh, Don C. MacIver, Adam Fenech and Heather Auld*

Occasional Paper 9: *Changing Weather Patterns, Uncertainty and Infrastructure Risks: Emerging Adaptation Requirements, Heather Auld and Don C. MacIver*

Occasional Paper 10: *Adaptation Options for Infrastructure under Changing Climate Conditions, Heather Auld, Don C. MacIver and Joan Klaassen*

Occasional Paper 11: *Weathering of Building Infrastructure and the Changing Climate: Adaptation Options, Heather Auld, Joan Klaassen and Neil Comer*

Occasional Paper 12: *Planning for Atmospheric Hazards and Disaster Management Under Changing Climate Conditions, Heather Auld, Don C. MacIver, Joan Klaassen, Neil Comer and Bryan Tugwood*

Occasional Paper 13: *The Americas: Building the Adaptive Capacity to Global Environmental Change, Adam Fenech, Heather Auld, Don MacIver, and James P. Bruce*

Occasional Paper 14: *Climate Change Adaptation Literature, James I. MacLellan*

Occasional Paper 15: *Impacts of Climate Extremes on Biodiversity in the Americas, Marianne B. Karsh and Don C. MacIver*

FOR ADDITIONAL COPIES, CONTACT:

ADAPTATION AND IMPACTS RESEARCH DIVISION
Environment Canada
4905 Dufferin Street, Toronto, Ontario
CANADA M3H 5T4

Attention: Don MacIver
don.maciver@ec.gc.ca