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**CHANGING WEATHER
PATTERNS, UNCERTAINTY AND
INFRASTRUCTURE RISKS:
EMERGING ADAPTATION
REQUIREMENTS**

By:

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CHANGING WEATHER PATTERNS, UNCERTAINTY AND INFRASTRUCTURE RISKS: EMERGING ADAPTATION REQUIREMENTS

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ABSTRACT

As the climate changes, it is likely that risks for infrastructure failure will increase worldwide due to shifting weather patterns and extreme weather conditions becoming more variable and regionally more intense. Existing studies indicate that small increases in weather and climate extremes have the potential to bring large increases in damages to existing infrastructure.

Almost all of today's infrastructure has been designed using climatic design values calculated from historical climate data on the assumption that past extremes will represent future conditions. Changes in climate will require changes to these climatic design values, as well as larger societal changes.

Uncertainties in the climate change models and in the projections on the magnitudes and directions of future changes limit abilities to design infrastructure for future conditions. Until these uncertainties in the climate change projections are reduced, it will become critically important that climatic design values be calculated as accurately as possible and that values are regularly updated to reflect the changing climate. Since uncertainty is accepted as a part of construction codes and standards, it should be possible to deal with the growing uncertainty of future climate design values through measures such as increasing safety factors, forensic analyses of extreme events and use of climate trends and climate model projections based on surrogate climate variables.

Keywords: Weather extremes, infrastructure failure, uncertainty, climate change, engineering, adaptation

1. INTRODUCTION

Infrastructure is critically important to individuals and to communities. It serves to shelter and protect the life, health, psychological and social welfare of all of its inhabitants from the weather elements, sustains aesthetic and cultural values and underpins economic activities. Examples of critical structures include houses, hospitals, schools, factories, roads, bridges, communications structures, power

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** Occasional Paper 9 provides an overview of climate change infrastructure issues while Occasional Papers 10, 11 and 12 provide more detailed discussions.

distribution networks, water structures, etc. Because extreme weather is capable of damaging or demolishing infrastructure, any increases in severe weather risks have the potential to impact safety and security, disrupt economic activities and result in a natural disaster (Freeman and Warner, 2001).

There is growing concern worldwide that changes in climate will have significant impacts on infrastructure and communities. As the climate changes, it is likely that risks for infrastructure failure will increase in many regions. An inevitable result of the increased damages from the changing climate will be a dramatic increase in damage losses and increased requirements for resources needed to restore or retrofit structures. Because infrastructure underpins so many of the economic activities of societies, managing increased risks to infrastructure will require a variety of adaptation actions ranging from updated or increased climatic design values, improved building codes and infrastructure standards, better disaster management planning as a result of changed risks, enhanced climate monitoring and weather warning programs, more rigorous land use planning, structural maintenance standards, new structural materials, changed insurance and financial risk management through to relocation of structures and replacement of unreliable or unsafe structures. (Dalglish, 1998; Holm, 2003; Lowe, 2003).

This paper represents the first of two papers in this series dealing with changing weather patterns, climate extremes, climatic design value uncertainties, infrastructure risks and adaptation options for risks and potential opportunities. This paper outlines the need and provides general guidance for future adaptation actions. The second paper¹, “Adaptation Options for Infrastructure under Changing Climate Conditions”, attempts to prioritize categories of adaptation actions for infrastructure and engineering practice (Auld et al, 2006a). In general, the guidance and adaptation options highlight infrastructure that will be most impacted by changing climatic or environmental loads and includes buildings, electrical distribution systems, communications structures, highways and bridges, drainage infrastructure, etc. Additional papers are also provided in the Occasional Paper Series (11 and 12) that more specifically describe adaptation measures for weathering of building infrastructure under changing climate conditions (Auld et al, 2006b) and outline adaptation options needed to deal with changing atmospheric hazards and emergency management (Auld et al, 2006c).

Changing Weather Extremes and Infrastructure

According to the Intergovernmental Panel on Climate Change (IPCC, 2001a), extreme weather events may occur more frequently under climate change and have the potential to affect flooding, droughts and the frequency and severity of cyclonic systems (including hurricanes). Locally, factors such as changing winds or storm tracks might, in some cases, offset this effect. In all cases, changes in climate will require changes to the criteria for the design of infrastructure in addition to larger changes in communities and societies. While infrastructure components built in earlier times will remain robust should extremes decrease, those designed for earlier and lower extremes will come under growing risk of collapse if extremes increase. Overall, it is reasonable to expect that infrastructure damage could increase exponentially as a portion of total losses due to the changing climate.

¹ Refers to Occasional Paper 10 by Environment Canada.

Projected changes in extreme climate phenomena and their likelihood (examples)	Representative examples of projected infrastructure impacts
<p>Simple extremes:</p> <ul style="list-style-type: none"> • More intense precipitation events (very likely over many areas) 	<ul style="list-style-type: none"> • Increased flood, landslide, avalanche and mudslide damage • Increased pressure on government and private flood insurance systems and disaster relief
<p>Complex extremes:</p> <ul style="list-style-type: none"> • Increased summer drying and associated risk of drought 	<ul style="list-style-type: none"> • Increased damage to building foundations caused by ground shrinkage • Decreased water resource quantity and quality, impacts on hydro-power • Increased risks of forest fires
<ul style="list-style-type: none"> • Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (likely) over some areas 	<ul style="list-style-type: none"> • increased coastal erosion and damage to coastal buildings and infrastructure
<ul style="list-style-type: none"> • Intensified droughts and floods associated with El Niño events in many regions (likely) 	<ul style="list-style-type: none"> • Decreased hydro-power potential in drought-prone regions • Flood damage to infrastructure in hazard zones
<ul style="list-style-type: none"> • Increased intensity of mid-latitude storms (little agreement between current models) 	<ul style="list-style-type: none"> • Increased property and infrastructure losses
<ul style="list-style-type: none"> • Likelihood refers to judgmental estimates of confidence: very likely (90-99% chance), likely (66-90% chance). Unless otherwise stated, information on climate phenomena is taken from the Summary for Policymakers TAR WGI. • Impacts can be lessened by appropriate response measures. 	

TABLE 1. IPCC projected changes in climate extremes due to climate change and representative examples of infrastructure impacts.

In its deliberations, the IPCC considered representative examples of projected infrastructure impacts due to extreme climate phenomena (IPCC 2001a). Table 1 provides examples of potential infrastructure impacts likely to result from projected changes in extreme events.

CHANGING CLIMATE AND INFRASTRUCTURE VULNERABILITIES

The impacts of climate change on infrastructure and the built environment will require unique adaptation options due to the complexities associated with the construction sector and the uncertainties in the climate change information needed to inform adaptation decisions. For example, adaptation options will need to consider the following realities:

- Infrastructure typically has long lifetimes, with many structures expected to be still standing at the end of this century. Buildings, for example, are often designed with the intention that they remain stable for 50-60 years (Steeimers, 2003);
- The robustness of the existing stock of infrastructure is variable, with structures constructed to withstand varied extreme climate and weather conditions, depending on the age and type of structure, its maintenance record and the “margins of safety” used;
- Structures and their materials are aging and in many regions, infrastructure has not been replaced or maintained at sustainable rates. As a result, the proportion of the infrastructure that is vulnerable to extremes and to “weathering” processes is increasing. Regionally, infrastructure is also deteriorating prematurely or at accelerating rates due to the changing physical and chemical atmosphere (Holm, 2003);
- Many existing buildings and communities are located in vulnerable locations, including exposed coastal zones and river flood plains, and more rigorous disaster management planning will be required;
- The construction industry, building codes and standards and land use planning all have historically remained slow to change;
- Land use and building materials decisions are often dominated by short-term commercial interests rather than long-term risk requirements.

Current understanding of the potential impacts of climate change on infrastructure is still very limited and further research and development will be required to support decision-making. While a few studies are emerging from a handful of countries, most of these studies are based on generalities and on broad large-scale analyses. Among the challenges, there is a critical need for research to fill in the gaps between regional climate impacts and the requirements for designing infrastructure to withstand the climates of today and the future. More specific information is needed to determine which types of infrastructure and which regions are likely to experience the greatest losses in future and to develop climatic design information that minimizes additional risks for structures long into the future.

WEATHER EXTREMES AND INFRASTRUCTURE DAMAGES

As the climate changes, it is expected that small increases in weather and climate extremes will have the potential to bring large increases in damage to existing infrastructure. Studies indicate that damage from extreme weather events tends to increase dramatically above critical thresholds, even though the high impact storms associated with these damages may not be much more severe than the type of storm intensity that occurs regularly each year (Munich Re., 2005; Swiss Re., 1997; Coleman, 2002). In many cases, it is likely that the critical thresholds reflect storm intensities that exceed average design conditions for a variety of infrastructure of varying ages and condition. An investigation of claims by the Insurance Australia Group (IAG), as shown in Figure 1, indicates that a 25% increase in peak wind gust strength above a critical threshold can generate a 650% increase in building claims (Coleman, 2002).

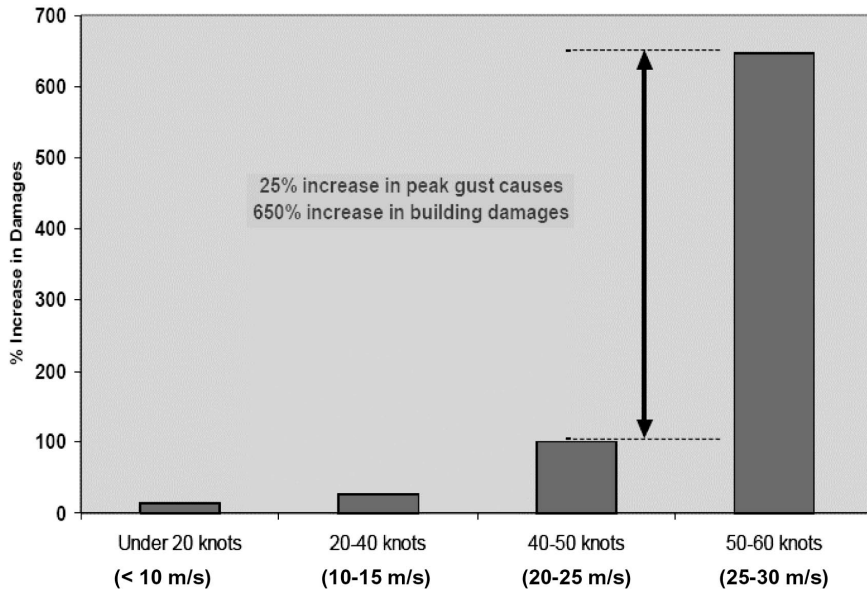
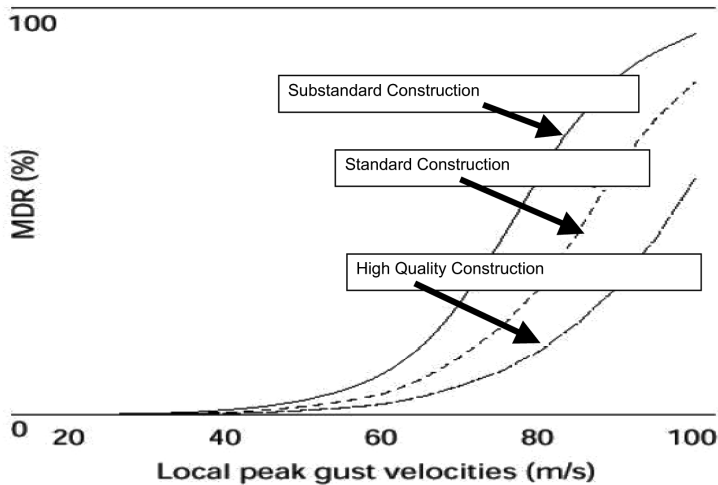


FIGURE 1. Source: (Coleman, 2002). Insurance Australia Group Building claims as a function of peak gust speed.

Similar studies indicate that once wind gusts reach or exceed a certain level, entire roof sections of buildings often are blown off, or additional damages are caused by falling trees. Typically, minimal damages are reported below this threshold (Munich Re., 2005; Swiss Re., 1997; Freeman and Warner, 2001; Coleman, 2002). Similar results have been obtained for flood and hailstone damages. For example, hailstones below a certain size have been found to not damage car panels whereas above this critical size, damage increases abruptly (Freeman and Warner, 2001). Likewise, similar damage curves exist for flood damage events (Munich Re., 2005; Swiss Re., 1997), indicating that a small increase in flood levels may vastly increase flood damage as incremental flood levels overwhelm existing infrastructure and flood protection systems. In general, flooding, ice storm and wind storm events tend to result in the most widespread, costly and direct impacts to infrastructure such as buildings, bridges, roads, communications, electricity generation and water systems.

The quality of construction and the maintenance of structures will strongly influence the damages and extent of claims. Figure 2 shows typical vulnerability curves for various quality of construction, where mean marginal damage from windstorms (MDR) increases exponentially with local peak wind gust velocities (Swiss Re., 1997). The curves reflect substandard quality, standard quality and high quality construction (bottom curve), respectively. Hence, as shown in Figure 2, moving from a wind speed of 40 meters per second to a speed of 60 meters per second increases marginal damage from about 2 to 10 percent. For buildings of substandard quality, an increase in wind speed from 60 meters per second to



Source: (SwissRe 1997)

FIGURE 2. Source: (Swiss Re, 1997). Relative mean marginal building damages (%) as a function of peak wind gust velocities for varying quality of construction. The results indicate, for example, that a 20 meter per second increase in wind speed can increase damages by 65%.

80 meters per second increases losses from 10 percent to 75 percent (Swiss Re., 1997). As wind speed increases, minor changes in velocity can drive up damage significantly. It is obvious that lower quality construction or poor maintenance over time rapidly worsens marginal damage.

Trends in Weather/Climate Extremes Globally

The climate is changing and will continue to do so, even with the most ambitious of mitigation successes. As a result, it is likely that initial changes observed in climate to date will accelerate for decades and centuries to come. The difficulty in both slowing emissions and in reducing the rate and amount of the eventual warming is attributed to the long lifetime of carbon dioxide as a greenhouse gas in the atmosphere, the slow response of the oceans and cryosphere to change and the long timescales involved in changing the global energy infrastructure and reliance on fossil fuel burning. (e.g., Karl and Trenberth, 2003).

Weather and climatic extremes are defined as significant departures from a normal state of the climate (Karin and Zwiers, 2005). Extremes or “anomalous weather” include events such as floods, droughts, severe thunderstorms, blizzards, ice storms, hurricanes, heat waves, cold spells and tornadoes.

Extremes can be quite regionally specific, with the result that the extreme for one location can be the normal for another. Because extreme weather is defined as anomalous and relatively rare, it can be difficult to detect trends in weather and climate records without having access to good quality, representative weather/climate data from well maintained observation stations with long periods of data records. The weather and climate monitoring programs and equipment from these long-term stations also need to have remained relatively consistent over time. In fact, lack of long-term climate data suitable for analysis of extremes is the single biggest obstacle to quantifying whether extreme events have changed over the twentieth century, either worldwide or on regional scales (Easterling et al. 1999).

What is known from trend analyses of the instrumented climate records globally is that there has been an increase in the global mean temperature of about 0.7°C since the start of the twentieth century (IPCC, 2007), and that this increase is often associated with a stronger warming in daily minimum temperatures than maximums (Easterling et al, 1997). Global precipitation has also increased in many regions over the same period (IPCC, 2007). The evidence for increases in extreme events is more variable to date. For example, analyses of trends in 1-day and multi-day heavy precipitation events in the United States and other countries show a tendency to more days with heavy 24-h precipitation totals (IPCC, 2001b; Karl and Knight, 1998). The number of days annually where daily precipitation exceeds 50 mm of precipitation has been increasing in the United States (Karl et al, 1996) while the frequency of 1 to 7-day precipitation totals exceeding station-specific thresholds for one in 5- year recurrences as well as the upper five percentiles have been increasing (Kunkel et al, 1999). The tendency in most countries that have experienced a significant increase or decrease in monthly or seasonal precipitation has been for this change to be directly related to a change of the same sign in the amount of precipitation falling during the heavy and extreme precipitation events (Easterling et al, 2000). This implies that there have been changes of the same sign (increasing or decreasing) in both the seasonal and annual totals and the frequency of 1-day heavy precipitation events, but in either case the heavy precipitation changes were always disproportionately larger.

Observations of storm event extremes, such as thunderstorms and tornadoes, often have biases due to such factors as increased population density and changes in observation programs and technologies. For example, the increase in tornado observations in Canada and the U.S. in recent decades could be due as much to the fact that more people live in or travel through tornado-prone areas and are able to report tornado occurrences that otherwise would have gone unreported. In addressing these types of data observation homogeneity and biasing issues for storm events, particularly for randomly or rarely occurring events like thunderstorms, one approach is to use a surrogate for extreme weather. This could entail the examination of long-term variability and trends in atmospheric conditions known to be conducive to severe weather (an example of this approach is shown in the Ontario severe ice storm case study described in a later section of this paper).

Projections of the statistical aspects of climate extremes into the future under changing climate conditions can be derived from global and regional climate models that represent possible future climate states given assumptions about greenhouse gas emission futures. Many of the model studies of

projected extremes under greenhouse gas enhanced climate change conditions agree with intuition, based on our understanding of how the climate system works. For example, model projections confirm that it is a reasonable hypothesis to assume that with greenhouse gas-enhanced climate change, the hydrologic cycle should intensify, leading to increased atmospheric water vapour content, increased precipitation rates and enhanced storm intensity. Though the climate models can simulate many aspects of climate variability and extremes, they still are characterized by systematic simulation errors and limitations in accurately simulating regional climate, such that appropriate caveats must accompany any discussion of future changes in weather and climate extremes (Easterling et al, 2000).

There are some consistencies among the studies on the potential impacts of a changing climate on extremes. These climate model consistencies on extremes include the following projections (Meehl et al, 2000; Easterling et al, 2000; Kharin and Zwiers, 2000, Kharin and Zwiers, 2005):

1. An increase in mean temperatures, resulting in more extreme high temperatures and less extreme low temperatures;
2. Night-time low temperatures that increase more in many regions than daytime highs, reducing diurnal temperature ranges;
3. Decreased daily variability of temperatures in winter and increased variability in summer in Northern Hemisphere mid-latitude areas;
4. Increased moisture content in many regions contributing to increased precipitation intensity;
5. A general drying of the mid-continental areas during summer with increased chance of drought due to the combination of increased temperature and decreased precipitation;
6. Changes in extreme precipitation are larger than the corresponding change in annual mean precipitation (often in both absolute and relative terms);
7. Future climate variability could more resemble an El Niño-like state in many regions, where seasonal precipitation extremes associated with a given El Niño would be more intense.

Where extremes increase, the impact will be a reduction in the “effective” return period event that existing structures were built to withstand. A recent study by Kharin and Zwiers (2005) analyzed changes in daily precipitation extremes under climate change using output from an ensemble of transient climate model simulations and concluded that the return period of extreme precipitation events may, on average, be reduced by a factor of two. This means that, under a changed climate, a current 20- year rainfall event could be expected every 10 years, on average, by end of 21st century. Similar to other studies, changes in the extreme daily precipitation rate are projected to become substantially larger than the changes in the annual mean precipitation rate. The implications for existing and new infrastructure are critical. As the effective return periods of extreme events change, the impact is that weather extremes will tend to exceed the design specifications for structures more frequently, decreasing the durability and resilience of the structure.

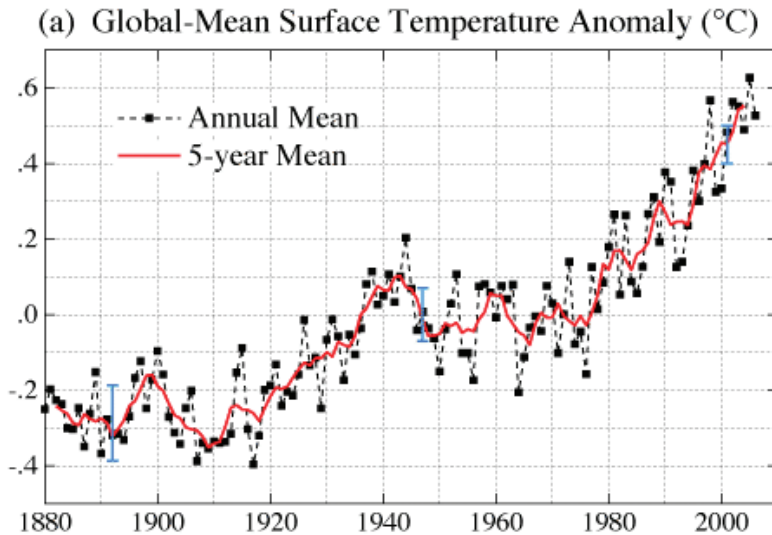


FIGURE 3. Global annual surface temperature relative to 1951-1980 mean, based on surface air measurements at meteorological stations and ship and satellite measurements for sea surface temperature. (From Goddard Institute for Space Studies, New York, N.Y. and <http://www.giss.nasa.gov/research/news/20070208/>.)

Trends in Canadian Weather/Climate Extremes and Infrastructure Impacts

Similar to global trends, as shown in Figure 3, the 1990s has been shown as the warmest decade and 2005 was the warmest year in the Northern Hemisphere (NH) recorded from the start of the previous millennium (Hansen et al, 2007). Surface observational records indicate a warming of about 0.6°C during the past 30 years. The rate and duration of warming of the Northern Hemisphere in the 20th century has been unprecedented during the last millennium.

In Southern Canada, surface temperatures have warmed by 0.5 and 1.5°C during the past century (Environment Canada, 2003). The greatest warming has occurred in the west and north, and also in summer and spring. Analyses of Canadian precipitation data indicates that conditions in many regions have, on average, been tending towards wetter conditions. Figure 4 (Vincent and Mekis, 2001) shows trends in the number of the number of days per year that rainfall in excess of a specified high rainfall threshold value is recorded at climate station (days per year with precipitation \geq 95th percentile). These and other trends in Canadian climate change indicators were analyzed by Vincent and Mekis (2001) for the period 1950-1999 and have recently been updated to 2003. The precipitation indices analyses used

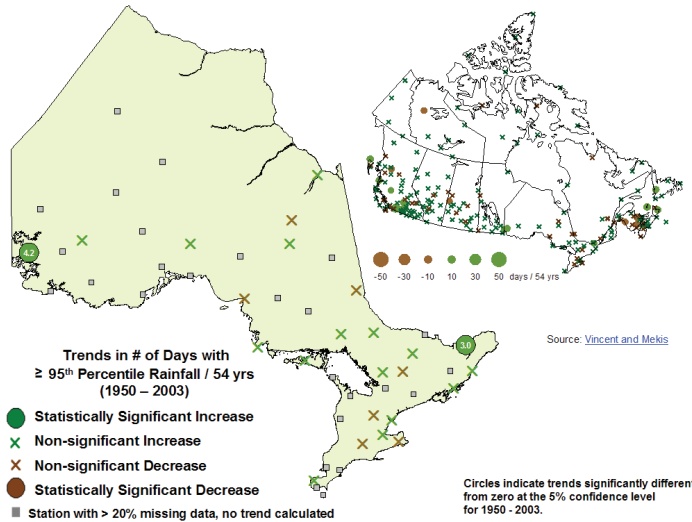


FIGURE 4. Trends in precipitation extremes for the number of days with precipitation $\geq 95^{\text{th}}$ percentile over the period 1950-2003. Circles indicate trends significantly different from zero at the 5% confidence level. Most stations show non-significant increases in precipitation at and above the 95th percentile. (Courtesy of Vincent and Mekis, 2006)

a special database of “adjusted” daily rain, snow and total precipitation amounts for 495 stations across Canada (Mekis and Hogg, 1999; Environment Canada, 2004), based upon the Environment Canada National Climate Archive station rainfall and snow ruler data.

Regionally, due to local climate influences, there are differences in warming and precipitation trends, with some regions even showing trends in precipitation in the opposite directions to national and global trends. In some parts of Ontario, including some locations to the lee of the Great Lakes, mean annual precipitation totals have increased at greater rates than other regions. On the other hand, trends in rainfall extremes, including the highest 1-day rainfall amounts, indicate both increasing and decreasing trends across the province, with non-significant increases appearing more frequently in northwestern Ontario.

CLIMATE AND ENGINEERING CODES AND STANDARDS

A changing climate poses many challenges for the built environment. In many countries, structures are designed using national building codes and infrastructure standards that depend on a set of climatic and seismic design values. Almost all of today’s infrastructure has been designed using climatic design values that have been calculated from historical climate data under the assumption that the average and extreme conditions of the past will represent conditions over the future lifespan of the structure. While this assumption has worked in the past, it will no longer hold as the climate changes.

Typically, decisions on how to build structures are primarily driven by the need to build both safely and economically. The appropriate balance must be struck between safety and required strength and serviceability over the life of the structure and over initial and maintenance costs. This balance can only be achieved using realistic estimates of future climatic design loads. While structures can always be "over-designed" to protect against natural hazards, the economic costs to societies can prove high.

Climatic design values include quantities like the 10, 50, or 100 year return period "worst storm" wind speed, rainfall or weight of snowpack conditions that are typically derived from historical climate data. Other climatic design quantities include percentile cold, hot or humid temperature or humidity conditions, return period ice accretion loads and average degree day quantities. A given return period storm does not mean that the design storm only occurs once in the named time frame but refers to the risk of an event being reached or exceeded in a period. A 50 year return period wind storm speed, for example, refers to a one chance in 50 wind speed that can be expected to be reached or exceeded in any year. On average, a 50 year return period storm has a 64 percent chance of being reported at least once in a given 50-year period, a 26 percent chance of occurring twice and an 8 percent chance of at least three occurrences in a 50-year time period (Cook, 1985).

Structural failures can result when climate extremes approach their design values and the engineering performance of the structure encroaches or exceeds uncertainty limits. For critical post-disaster buildings such as schools and hospitals, basic engineering loads are augmented by safety factors that account for uncertainties in strengths of materials and uncertainties in other engineering technologies (Canadian Commission on Building and Fire Codes, 2005). However, safety or uncertainty factors are not necessarily assigned to the climatic design values, with the implicit assumption being that these values are relatively stable.

Until the uncertainties associated with the directions and magnitudes of changes in climate extremes are known and can be incorporated into climatic design values, the safety factors used in codes and standards may need to be increased to reflect the growing uncertainties in climatic conditions over the lifespan of the structure. Since uncertainty is well accepted as a part of construction codes and standards and the regulatory process, it should be possible to deal with the growing uncertainty of future climate design values through measures such as increasing safety factors (Dalgliesh, 1998; Sanders and Phillipson, 2003). While regulators and the construction industry will undoubtedly be reluctant to include significant improvements and resultant increases in the costs of construction, the reality is that engineering and regulation are already based on statistical analyses of risk. Uncertainty over the future climate is one more source of variance or uncertainty that can be quantified by various methodologies (e.g. variances from different climate models). Improvements in downscaling methodologies and the development of climate change analyses techniques more appropriate for climate extremes (e.g. statistical map typing methodologies, decision modelling) will no doubt improve confidence in projections of climate change impacts and their implications for climatic design values. Other adaptation options, such as the use of a regional Climate Change Adaptation Factor, are available to accelerate the

incorporation of regularly updated climatic design values into codes and standards where needed and to handle expected regional increases in loads that could place local infrastructure at risk (Auld et al, 2006a).

PRIORITIZING IMPACTS AND VULNERABILITIES

Because infrastructure is built to last for many decades, it is important to understand and monitor emerging climate risks and to prioritize the impacts that require adaptation solutions. The many implications of the changing climate will require a structured approach in order to set priorities for the reinforcement and retrofit of existing infrastructure, for planning redundancy of critical infrastructure and for the updating of infrastructure codes and standards. Underlying all of these activities will be an ongoing need for careful monitoring of regional climate conditions in order to prioritize impacts and adaptation actions.

Regions where observed changes in climate are greatest, as well as infrastructure types with the lowest margins of safety and greatest risks to the observed changes will need adaptation solutions implemented first. In order to monitor risks, regional climate loads must be closely monitored and compared to the actual design loads and safety factors used in current structures. Meanwhile, new structures need to be designed and built with flexibility to accommodate future climate changes. At the same time, it is also critical that the climatic design values used in codes and standards for new infrastructure be updated regularly to reflect the most recent climate conditions.

The following case study illustrates analysis procedures that can be considered in projecting extreme events into the future. The study characterizes the emerging risks associated with severe ice storms and the changing climate for southern Ontario and explores a variety of approaches to estimate future risks.

Monitoring Severe Ice Storms and Infrastructure and Community Risks

Ice storm '98 reminded many Canadians and Americans of their vulnerability to long duration severe ice storms. In Canada, Ice Storm '98 was described in many words that reflected its unprecedented magnitude and impact. Lasting for almost a week and extending over parts of four provinces and seven states, the storm was responsible for accumulations of ice not previously recorded in central Canada. At the heart of the impacts from the storm was a massive power failure that affected 3.5 million people or more than 10 per cent of the entire population of Canada. Extensive community evacuations were organized in an effort to reduce the risks to lives, but despite these efforts, 28 human fatalities in Canada (with an additional 19 deaths in the U.S.) were directly attributed to the storm. Collapses of communication towers, phone lines and other communication infrastructure also hindered emergency response and recovery from the storm. Nearly 16,000 military were deployed in response to the disaster in the largest humanitarian assistance mobilization of Canadian Forces in the history of Canada. Economic losses from the storm totalled over \$5 billion in Canada alone (Klaassen et al, 2003).

The scientific question posed in the aftermath of the storm was “what was the return period?” Several studies were completed that outlined the meteorological aspects of the storm and its impacts, including comprehensive reports prepared by Auld et al (1998); Milton and Bourque (1999); DeGaetano (2000); Dupigny-Geroux (2000) and Environment Canada (1998). The Cold Regions Research and Engineering

Laboratory in New Hampshire also produced a scientific report evaluating the severity of the 1998 ice storm in northern New England and estimated its return period for this region of the United States (Jones and Mulherin, 1998). The Jones and Mulherin (1998) study indicated that return periods were not necessarily unprecedented for New England and that the December 1929 ice storm was of a comparable magnitude to Ice Storm '98. Their study estimated that the ice storm had a return period of 35-85 years for areas of upstate New York and for Vermont and New Hampshire, although other storms since 1929 have generated ice loadings comparable to the 1998 storm, but affected a smaller area. DeGaetano (2000) stated that for the limited number of stations that report hourly meteorological observations, the storm was unprecedented since the recording of U.S. digital records in 1948.

In response, Environment Canada, with financial support from Public Safety and Emergency Preparedness Canada (PSEPC), completed a comprehensive study to investigate whether ice storms of magnitudes approaching Ice Storm '98 were unprecedented for southern Ontario regions, whether risks may have differed historically between southeastern Ontario and the northeastern U.S. and whether the risks of such severe ice storms might be expected to increase in the near future as winters warm.

Forensic investigations of past severe ice storms that have impacted southern Ontario and adjacent states and provinces and their infrastructure failures provided invaluable guidance on likely vulnerabilities today and into the near future. The “forensic investigation” of these storms helped to identify trends and vulnerable areas within southern and eastern Ontario that might be at risk from an increasing risk of freezing rain and severe ice storms. This investigation included (Klaassen et al, 2003):

- A comparison of Ice Storm '98 with other significant freezing rain storms that have hit southern and eastern Ontario and the northern U.S. during the past century in order to assess relative frequencies,
- An update of the climatology of severe ice storms for southern and eastern Ontario and historical trend analyses for freezing rain storm indicators for Ontario and adjacent U.S. sites,
- Subjective meteorological and impact analyses of the most severe ice storms to have affected Ontario and adjacent U.S.. regions over the past century. These ice storms were identified from archived newspaper reports, from Canadian and U.S. weather service storm weather studies and from a database on communication tower collapses due to severe ice accretion amounts (communications towers are normally more robust to freezing rain storms than other infrastructure),
- Application of statistical weather map typing procedures to identify the weather patterns associated with severe freezing rain storms, including an assessment of trends in these contributing weather types,
- Projection of future risks using statistical downscaling from global climate models and the results of the statistical weather map typing (i.e. surrogates for extreme ice storms, which will not be explicitly handled by climate models) (Cheng et al, 2007).

The studies revealed that the major impacts from severe freezing rain storms affecting Ontario since the 1920s have occurred as a result of widespread and often long-lasting outages in the communications and power transmission and distribution systems. These damage and outages have often been caused by broken or weakened and sagged tree limbs, where accumulations of ice can increase the branch

weight of trees by 30 times or more. Studies have revealed that small branches and weak tree limbs break with ice accumulations between 1/4 and 1/2 inch (~6-12 mm), while 1/2 inch to 1 inch (~12-25 mm) accumulations cause larger branches to break (Klaassen et al, 2003). Without the presence of trees, power outages during ice storms have occurred only at relatively high ice loads. These studies indicated that tree management near distribution lines is an important adaptation action needed to reduce risks of power distribution system outages. The studies also indicated that the amount of ice accumulation in a storm is normally directly related to the amount and duration of freezing precipitation that falls during the storm. Normally, shorter duration events will have lower ice accumulation amounts than those of longer duration (i.e. 6-12 hours or longer).

The investigation also included an assessment of the CSA/CEA freezing rain ice design criteria for high voltage power and transmission lines. The results indicated that the existing design ice loading specifications for overhead structures (not freezing rain totals) adequately cover existing ice storm return periods for most regions, but would need to be upgraded if ice storm frequencies or amounts increase (Klaassen et al, 2003). In particular, the results indicated that eastern Ontario likely is the area most at risk for increasing ice risks and loads. However, transmission lines can fail and towers may be damaged in less severe ice storms under the effects of “galloping”, as the conductors and guy wires erratically oscillate and stretch under moderate but steady wind conditions.

The investigation of the most severe ice storm events over the past century suggested that the risks of major power outages lasting several days and hence, the potential for community disasters tends to increase when freezing rain amounts exceed approximately 30 mm. The historical evidence indicated that the potential for long power outages and for community disasters becomes likely when freezing rain totals exceeded approximately 40 mm (Klaassen et al, 2003). These criteria provide valuable guidance for emergency and disaster management planning – a “no regrets” adaptation action that provides clear benefits under current climate variability and additional benefits given climate change.

The forensic investigation noted that many of the most severe ice storms that have impacted southern Ontario in past brought even greater amounts of freezing rain further south into the adjacent U.S. regions. Indeed, some of the most severe ice storms to have affected the northern U.S. historically brought either lower freezing rain amounts or snow to southern and eastern Ontario. As illustration, of the 22 significant eastern U.S. ice storms assessed for this period, 8 storms brought more than 20 mm of freezing rain to southern Ontario but considerably greater amounts to U.S. locations. Of the remaining U.S. significant ice storms, 5 produced less than 20 mm of freezing rain over southern Ontario, another 8 brought snow or light rain and one did not impact Ontario at all (Klaassen et al, 2003).

Almost all of the ice storms that have impacted the northern U.S. had similar points of origin and followed similar tracks to the storms that impacted heavily on southern and eastern Ontario. The main difference was that the U.S. storm centres were located approximately 100-200 km further south at the time of freezing rain occurrence than the storms that impacted southern Ontario. This conclusion would support speculation that should storm tracks shift northwards with the initial degree or two of climate warming, the frequency of severe ice storms could possibly increase in southern and eastern Ontario.

The investigation also suggested that severe ice storm risks are moderated by the influence of the lower Great Lakes for weather stations along their shorelines.

Climate change science and models cannot yet predict how storm tracks will change in a warming climate or whether such changes could potentially lead to regional increases or decreases in ice storms. Using the results from synoptic map typing as surrogate indicators of severe ice storms, climate model projections were used to estimate future trends in risks. Similar conclusions to the storm tracking approach resulted, following application of downscaling methodologies appropriate for climate extremes to climate change model projections. The results (Cheng et al, 2007) indicated the potential by the 2050s under climate warming for ice storms lasting 4 hours and more to increase by 55% for Ottawa and 35% for Toronto. These results are based on the averaging of 4 GCM scenarios during the 3 coldest months, December to February.

CONCLUSIONS

Infrastructure is becoming increasingly vulnerable to the changing climate. The evidence can be seen in the exponential increases in worldwide losses from natural catastrophes, many related to infrastructure failures under extreme events. Globally, annual losses to weather-related events increased from \$3.9 billion in the 1950s to \$40 billion annually by the 1990s (Munich Re., 2005; IPCC, 2001a).

If infrastructure vulnerability to climate-related events is currently a cause for concern, it will become even more so in the future as the climate changes. Damage loss statistics indicates that small changes in climate variability can result in large increases in infrastructure damages. As the climate changes, it is expected that infrastructure will be impacted both through gradual changes in weather patterns (e.g. increasing freeze-thaw cycle frequencies) and through increasing variability of extreme events.

Because studies on the impacts of the changing climate on infrastructure remain scarce, research is greatly needed that improves knowledge of specific infrastructure exposures to different climate event risks. The research needs to link the potential for disasters to planned or new infrastructure and to already existing infrastructure types. As shown by the case study for severe ice storm risks in eastern Ontario, it is critically important that the climate be monitored to detect increasing hazard risks and that safety margins be monitored for infrastructure and region specific risks. Careful and regular monitoring of climatic conditions and loads at the local to regional scales and comparison of these recent loads to the historical design climatic loads for specific structures allows the safety margins inherent in existing infrastructure to be assessed for vulnerabilities. When constructing new infrastructure, it is important that the climatic design values used for design be regularly updated to reflect the most recent climate events. Where changes in engineering practices and climatic design values for new infrastructure are needed, approaches such as the use of a Climate Change Adaptation Factor should be considered on a regional basis. Meanwhile, research needs to continue for the development of scientific methodologies to incorporate climate change projections into engineering codes, standards and practices.

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