5.6 THE CHANGING CLIMATE AND NATIONAL BUILDING CODES AND STANDARDS

Heather Auld*, J. Waller, S. Eng, J. Klaassen, R. Morris, S. Fernandez, V. Cheng, D. MacIver
Adaptation and Impacts Research Section, Environment Canada, Toronto, Canada

1. INTRODUCTION

The urban environment and its infrastructure will be impacted significantly by climate change (Wilby, 2007; Auld, 2008a; Stevens, 2008; Neumann, 2009). A UNEP study (UNEP, 2006) identified the built environment and its infrastructure as specific sectors needing "priority planning" for climate change adaptation. The UNEP (2006) study reviewed a number of sectors, as shown in Figure 1, and concluded that the most climate-sensitive sectors were those with capital assets lasting for decades, particularly infrastructure (e.g. cities, buildings, transportation) and energy and water utilities structures. Because infrastructure underpins so many of the economic activities of societies, any increased damage to infrastructure from changing extreme weather risks has the potential to impact safety and security, disrupt economic activities and result in increases in natural disasters (Freeman and Warner, 2001; Auld, 2008b).

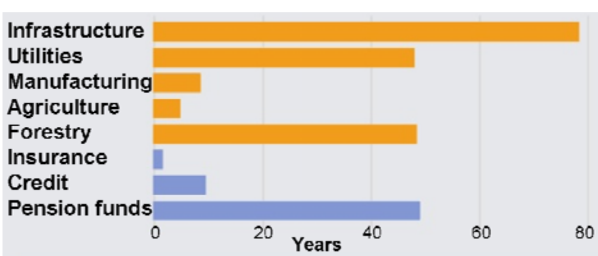

FIG. 1. Sector planning and investment decision period in terms of number of years forward on the sector's planning horizon (i.e. "forward commitment period by sector in years").
Source: Andlug Consulting and UNEP (2006)

* *Corresponding author address*: Heather Auld, Adaptation and Impacts Research Section, Environment Canada, 4905 Dufferin Street, Toronto, Ontario, Canada, M3H 5T4;
email: heather.auld@ec.gc.ca

Managing increased risks to infrastructure will require a variety of adaptation actions, including improved building codes and infrastructure standards, updated climatic design values for these codes and standards, enhanced climate monitoring, improved weather warning programs, better disaster management planning for changed risks, enhanced infrastructure maintenance and asset management standards, new structural materials and engineering practices, changed insurance and financial risk management, more rigorous land use planning and relocation of structures and replacement of unreliable or unsafe structures (Lowe, 2003; Auld, 2008a; Stevens, 2008).

This paper will concentrate on the climate science and services needed to support infrastructure engineering design, siting and development of improved national codes and standards for current and future climate conditions.

2. CLIMATE AND INFRASTRUCTURE DESIGN

The changing climate has the potential to regionally increase the frequency and/or intensity of extreme weather, increase weather-related disasters, impact the safety of existing structures, increase premature weathering regionally, change engineering and maintenance practices and to alter practices for building codes and standards (Auld, 2008a; Wilby and Dessai, 2010). Because infrastructure is built to survive for decades to come, it is critically important that adaptation options to climate change be developed today, incorporated into current designs and implemented as soon as possible. It is even more important that adaptation measures be developed to assess the resilience of existing infrastructure to changing climate conditions. When priority risks to infrastructure are identified, retrofitting measures will need to be developed to climate-proof the most vulnerable structures or the structures will need to be demolished or replaced (Auld, 2008a; Stevens, 2008).

2.1 Vulnerability of Infrastructure to Climate Extremes and Weathering

The robustness of the existing built environment and its infrastructure stock is variable. Over time, structures have been built to withstand a variety of extreme climate and weather conditions. The climatic design values or loads used that affect the “resilience” of these structures vary with the climate values used regionally, the age and type of structure, its maintenance record and the ‘margins of safety’ used for its design. The overall resilience can also be compromised in regions and countries with an “infrastructure deficit”, meaning that infrastructure has not been replaced or maintained at sustainable rates and that structures and their materials are aging and in use well beyond their intended lifespans. As a consequence, the proportion of infrastructure that is or will become vulnerable to changing extremes and to increased ‘weathering’ processes is likely increasing regionally. The changing physical and chemical atmosphere may be both increasing extremes regionally while also accelerating weathering processes and prematurely deteriorating existing infrastructure (Holm, 2003; Auld, 2008a).

Where extreme events are expected to increase regionally and/or structures are expected to weather prematurely, it is likely that small increases in climate extremes above regional thresholds will have the potential to bring large increases in damages to the urban and built environment (Coleman, 2002; Munich Re, 2005). 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 (Coleman, 2002; Munich Re, 2005). For example, an investigation of claims for buildings by the Insurance Australia Group indicates that above a critical threshold, a 25 percent increase in peak wind gust strength can generate a 650 percent increase in building claims, as shown in Figure 2 (Coleman, 2002). 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; Coleman, 2002; Freeman and Warner, 2001). Similar results have been obtained for flood and hailstone damages. In many cases, it is likely that these critical thresholds reflect storm intensities that exceed regionally averaged climatic design conditions (Coleman, 2002; Auld, 2008a). As a result, older infrastructure will come under growing risk of failure if climate extremes increase or weathering processes intensify, while other types of infrastructure will remain robust if regional extremes decrease sufficiently.

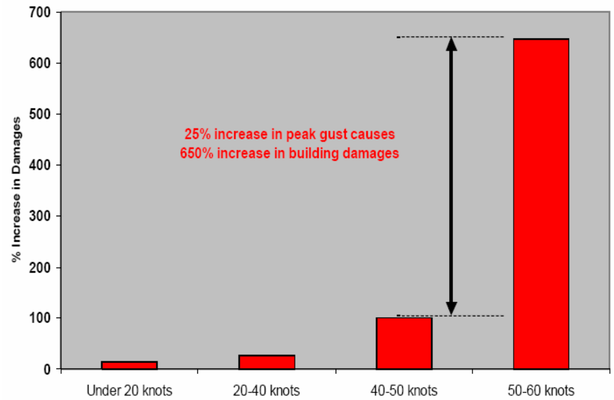

Fig. 2. Incremental building loss claims as a function of peak gust speed for Australia (Insurance Australia Group (IAG)).
Source: Coleman (2002)

The quality of construction, maintenance of structures and state of deterioration also strongly influence their damage potential and extent of claims. Lower quality construction and poor maintenance or premature deterioration over time can rapidly worsen the marginal damages for each threshold of wind or other climate parameter (Swiss Re, 1997; Munich Re, 2005).

3. Climatic Design Values for National Codes and Standards

The implementation of adequate building codes that incorporate regionally specific climate data and analyses can improve resilience for many types of risks (World Water Council, 2009; Wilby et al., 2009; Auld, 2008a). Typically, infrastructure codes and standards use historical climate data and analyses to calculate climatic design values, assuming 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 become less valid as the climate changes. The climatic design values used in national codes and standards include quantities like the 10, 50, or 100-year return period historical ‘worst storm’ wind speed, rainfall or weight of snowpack conditions.

Other climatic design quantities include percentile cold, hot temperatures and humidities (e.g. wet bulb temperatures), return period ice accretion loads and average degree day quantities (Canadian Commission on Building and Fire Codes, 2005).

In many parts of the world, current long-standing gaps and deficiencies in the determination of climatic design values are a source of existing uncertainty that impact current and future infrastructure reliability and safety (Auld, 2008a). Structures designed using site-specific climatic design values that are based either on lesser quality climatic data, sparse data, missing data records or short period datasets are the most vulnerable. Improved understanding of these uncertainties will result in better estimates of the existing climatic design values and help to determine whether and by how much structures designed from historical climate loads can tolerate further increases in loads under climate change. The uncertainties in existing climatic design values depend strongly on the complexity of the climate in a locality, the density of climate stations, quality and length of the climate data used for the estimation of climatic design values, the frequency of the extreme climate event, the statistical approaches used and spatial and temporal interpolation approaches applied for estimation at a location (Auld, 2008a). Efforts to monitor the changing climate for trends in infrastructure relevant variables and to regularly update design values for codes and standards will also ensure that infrastructure is optimally adaptable to existing climate conditions and better prepared for future changes. Improving the ability to deal with current climate vulnerabilities improves the capacity to deal with future climatic changes, particularly when these values can be adjusted over time to deal with additional changes in climate risks and vulnerabilities (Sperling and Szekely, 2005; Wilby and Dessai, 2010; Auld, 2008a).

4. ADAPTATION OPTIONS

Because new and replaced infrastructure will come to play an increasingly important role in adapting the urban environment to climate change, especially when compared to the costs of retrofitting existing infrastructure, it is important to design infrastructure today that will be adaptable to future climate conditions. To date, most climate change and infrastructure studies have focussed on the reduction of greenhouse gases. However, a limited number of climate change adaptation studies are available that provide guidance on the range of adaptation options needed (Wilby et al., 2009; Auld, 2008a,b; Stevens, 2008; Three Regions Climate Change Group, 2008; Neumann, 2009).

There are two main perspectives taken when developing climate change adaptation options, namely predictive Top-down and resilience Bottom-up approaches. The most widely represented approaches for developing adaptation options are known as ‘Top-down’ (often known as ‘scenario-led’) methods and involve a process of first downscaling climate projections from an ensemble of General Circulation Models or climate GCMs, using a range of future greenhouse gas emissions scenarios (Wilby and Dessai, 2010; IPCC, 2007). The resulting scenarios are then downscaled into an ensemble of finer or local scale information and fed into impacts models before finally invoking adaptation measures that should, in principle, maximize any benefits or counter anticipated risks. The term ‘top down’ is used to describe these measures because information is cascaded from one step to the next, with the number of permutations of emission scenarios, climate models, downscaling methods, impacts models and so on, proliferating at each stage. The range (or envelope) of uncertainty generally expands at each step of the top-down process from climate models to potential impacts to adaptation options and eventually, the total of the uncertainties associated with all of the potential impacts and their implied adaptation responses can expand to become almost implausible (Wilby and Dessai, 2010). Although more exhaustive characterization of uncertainty may be scientifically tractable (through international comparison studies involving large ensembles of climate models and downscaling methods), the prospect of reducing uncertainty depends on further progress being made in the underpinning climate science (Hawkins and Sutton, 2009; Wilby and Dessai, 2010).

‘Bottom-up’ approaches, on the other hand, tend to focus on reducing vulnerability to present climate variability and consider adaptation options to make structures less prone to uncertain and largely unpredictable variations and trends in the climate. Often, bottom-up approaches are based on forensic and other analyses of the factors that result in failures or enable successful coping to climate-related threats. Bottom-up approaches, for example, for flood risk could include efforts to upgrade flood forecasting systems, to flood-proof individual homesteads against floods on riverine islands or to lower the percentage of a population living in floodplains (Wilby and Dessai, 2010). The Bottom-up approaches are less suited to guide adaptation if coping thresholds change or if climate risks emerge that are outside the range of recent experience – which are both likely outcomes as climate change progresses. In reality, a blend of the bottom-up and top-down approaches that incorporate flexibility, monitoring and review are likely optimal. Adaptation needs to be informed by likely climate scenarios as well as the vulnerability that will result.

Wilby et al. (2009) assert that climate change scenarios can meet some, but not all, of the needs of adaptation planning and that greater effort must be given to the critique of climate change models used for these projections. In general, many studies conclude that the adaptation actions required for the future climate depend on the scale and significance of the potential climate risk and impact, the level of certainty on future changes, the capacity to act and the timeframes within which these future impacts will occur (Heltberg et al., 2009; Auld, 2008a, b; World Bank, 2008; Wilby et al., 2009). For instance, when the impacts of future changes remain highly uncertain, bottom-up "no regrets" or "low regrets" actions may initially offer the most realistic adaptation option. "No regrets" adaptation implies that the benefits of the option are justified irrespective of whether the impacts to future climate change occur. On the other hand, "low regrets" options have minimal cost or tend to "hedge" by dealing with the uncertainties of the future changes through investments in research, outreach and other limited measures (OECD, 2009; Prabhakar et al., 2009). Medium and high "regret" adaptation options include those measures that deal directly with climate change. Here, medium and high regrets terminology implies that the future climate poses significant or irreversible risks for the future and needs to be addressed, as would be the case for long-term investments in infrastructure with high failure consequences. Sometimes, decisions are taken to defer proactive adaptation actions until greater certainty is reached or to "bear the residual losses"; these options are best considered only when uncertainties over the direction of future climate changes are high, when capacity for adaptation is very limited, when adaptation options are currently not available or alternatively, when the impacts are low (Linnerooth-Bayer and Mechler, 2006; Heltberg et al., 2009; World Bank, 2008). No regrets and flexible options that perform well over a range of climate conditions are more justifiable than no actions (Wilby and Dessai, 2010; Auld, 2008a).

Studies for Australia (Stevens, 2008), Canada (Auld, 2008a; Girard and Mortimer, 2006; NRTEE, 2009; CSA, 2010), the U.K. (Wilby and Dessai, 2010; Three Regions Climate Change Group, 2008) and the United States (Neumann, 2009) conclude that a variety of retrofit measures will be needed to safeguard existing infrastructure while new adaptation approaches will be required for new infrastructure. All of these studies on infrastructure and adaptation recognize the need for:

- incorporation of increasing climate uncertainties into codes and standards,
- research to fill gaps on the future climate, including strengthened efforts to improve the modelling and downscaling of finer-scale climate events,
- development of statistical information on future climate change events, including improved tools, scenarios and climate downscaling to transfer coarse spatial and temporal resolution climate models into finer scales,
- monitoring of the climate and regular updating of climatic design values,
- comprehensive risk assessments and forensic studies for existing climate sensitive infrastructure, particularly focussing on critical climatic thresholds,
- formalized asset management and maintenance,
- investigation of the links between soft (e.g. ecosystems services) and hard engineering solutions (e.g. codes and standards)
- improved emergency planning, services and acceptable insurance and risk transfer mechanisms.

This paper will focus on the climate science and analyses components that are required for infrastructure adaptation.

5. INFRASTRUCTURE AND CHANGING CLIMATE EXTREMES

Where weather and climate extremes increase in future, the impact will be a reduction in the 'effective' return period event that existing structures were built to withstand (Auld, 2008a). Kharin et al., (2007), for example, indicate that under a changed climate over land areas of the globe, a current twenty-year extreme rainfall event could be expected every ten years (i.e. waiting period), on average, before the end of the 21st century. Alternatively, the “return period” or return level for extreme precipitation events may, on average, be reduced by roughly a factor of two over most land areas before the end of the century, with the greatest reductions in waiting times expected in tropical regions and high latitudes (Kharin et al, 2007).

However, uncertainties in the climate change models and their projections still mostly limit abilities to design for future extremes and their infrastructure related climatic loads. Ongoing improvements to climate change models and their spatial and temporal resolution, along with improved methodologies to treat model biases and localise results, will make it possible in the future to deal selectively with the growing uncertainty of future climate conditions. It is important to be aware, however, that an improved ability to downscale to finer time and space scales does not imply that the confidence in the projections from the scenarios is any greater (Wilby and Dessai, 2010).

In spite of the uncertainties of the climate models, some options are available currently or under development to selectively consider growing risks to infrastructure and to incorporate adaptation into design codes and standards. These options for national codes and standards include:

1. Increasing the safety or uncertainty factors used for design (i.e. where climatic loads are kept constant over the lifespan of the structure) (Sanders and Phillipson, 2003);
2. Incorporation of climate change adaptation factors or variations into codes and standards, where these factors allow for rapid updating of climatic design information and augmentation of climatic loads given evidence of likely increases in risks over the lifespan of the structure (Auld, 2008a; Association of British Insurers, 2003);
3. Modification of climatic designs or design load criteria based on climate change model projections over the structure’s lifespan (Fenton and Soleymani, 2010).

The safety or uncertainty factors used in codes and standards offer one means to reflect growing uncertainties in climatic conditions over the lifespan of the structure (Auld, 2008a; Sanders and Phillipson, 2003). Since uncertainty is well accepted as a part of engineering codes and standards and the regulatory process, it should be possible to deal with the growing uncertainty of future climate design values through increasing safety factors when evidence points towards the liklihood of increased climate risks over the lifespan of the structure. While regulators and the construction industry may be reluctant to include significant changes that increase 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 in codes and standards (e.g. variances obtained from different climate models that have been validated against the observed climate record). Historically, codes and standards have sometimes addressed changed uncertainties or increased risks by adjusting their safety factors.

Other adaptation approaches for inclusion of adaptation into national building codes and standards include the use of a regional “climate change adaptation factor” (Auld, 2008a; Association of British Insurers, 2003). This factor(s) could potentially accelerate the incorporation of regularly updated climatic design values into codes and standards and optionally allow for additional increases in regional climate loads over the structure’s lifespan. Typically, building codes and other infrastructure standards are slow to change and long and extensive peer-review processes are required before any changes are incorporated. The Climate Change Adaptation Factor could consist of two terms: (1) an adjustment term/factor that is applied to existing climatic design values to quickly update values for observed trends and (2) a term/factor that incorporates future projections of changed climatic design values. The first term could explicitly update climatic design values for the most recent climate observations and trends while the second term could account for projected climatic design values that increase regionally over the typical lifespan of a structure. One or both factors could be applied, depending on the climatic element as well as the regional interest in incorporating climate change adaptation. For example, regionally specific Climate Change Adaptation Factors could be used when comparison against climate trends indicates that updated and increased design values are needed or when it is likely that the risks from changing climate conditions will increase over time. A variation of this approach is already in application in the Northwest Territories, Canada to treat emerging trends in snow load roof collapses and is discussed further in Section 6.2.

A relatively new option for incorporating climate change adaptation into national building codes and standards involves the use of climate change model outputs to account for potentially changed risks over the lifespan of a structure. In one probabilistic approach to limit states design under development by Fenton and Soleymani (2010), a new methodology for climate change adaptation involves a re-work of climatic factored design loads from their static or stationary to new dynamic values, capturing both the projected mean and variance of a climatic load under current and future climate change conditions. Such an approach has the advantage of capturing the underlying uncertainty in the evolution of climatic loads over the lifetime of the structure. The approach also can be modified to include the potential of increasingly severe extreme events. Initial experiments using this probabilistic design approach show an increase in the overall factored design load of approximately 20% for a conservative climate change scenario over a 100 year lifespan of a building (Fenton and Soleymani, 2010). A reversal of the technique generates an increase in the probability of failure from 0.001 under current or static/stationary climate loading to 0.02 under dynamic/non-stationary climatic loading scenarios. The approach by Fenton and Soleymani (2010) has the potential to provide valuable insight into the impacts of changing climatic design loads on structural reliability using the limit-states design approach. The challenge will lie in providing an appropriate set of climate change projections of extremes (i.e. ensemble), given the limitations and uncertainties in the climate change models in dealing with extremes at finer scale resolutions.

6. CASE STUDIES: ADAPTATION IN CANADIAN BUILDING CODES AND STANDARDS

Northern and coastal regions in all countries represent some of the most immediately vulnerable regions needing adaptation solutions for infrastructure. In Canada's North, inland and coastal impacts have been reported for nearly every type of built structure, including buildings, roads, pipelines, water structures and mining ponds and it is clear that adaptation solutions are needed immediately (NRTEE, 2009).

6.1 *Arctic Climate Change and National Permafrost Standards*

Some of the most rapid climate changes on earth have been observed in the Canadian and U.S. Arctic regions, with rising temperatures resulting in permafrost melting at unprecedented rates (NRTEE, 2009; CSA, 2010). Climate is the principal factor controlling the formation and persistence of permafrost, with ground temperatures and permafrost active layer depths directly linked to time averaged mean air temperatures.

Measured temperature trends indicate that the western Canadian Arctic has warmed at a rate unprecedented in the last 400 years (ACIA, 2005), while over the past 15 years, mean annual air temperatures have risen more rapidly in the eastern Arctic than anywhere else in Canada (Vincent and Mekis, 2006: updated in 2008; CSA, 2010). These warming trends are projected to continue, with mean annual temperatures expected to rise over the next 100 years by a further 4-5°C over land and in winter by 4-7°C, even given moderate greenhouse gas emission scenarios (CSA, 2010; ACIA, 2005).

Permafrost and other ice regimes have always figured heavily into Arctic infrastructure design, construction, and maintenance in regions where construction and operating costs are already high due to distances, isolation and extremely cold environments (NRTEE, 2009; CSA, 2010). In particular, infrastructure systems in permafrost have depended critically in past on the stability of permafrost as a foundation material. But, with climate warming, a variety of infrastructure types in these latitudes are increasingly vulnerable to warming and thawing of the permafrost soil layer.

In response to melting permafrost conditions, the Canadian Standards Association (CSA) convened an Expert Team to develop a Guideline for foundation siting and design in permafrost regions. The Expert Team behind this CSA Guide included meteorologists, climate scientists, engineers, permafrost researchers, planners, municipal and territorial officials (CSA, 2010). The Guide, titled "Infrastructure in permafrost: A guideline for climate change adaptation" or CSA

Plus 4011-10, incorporated analyses from climate trends analyses and from an ensemble of climate change scenarios into its risk assessment and adaptation process. An ensemble of climate models was selected using criteria to determine the “best performing” climate change models for Arctic regions. Because the Arctic poses significant challenges for climate models (e.g. changes are occurring more rapidly than climate models have projected), it is critically important that the ensemble of models be chosen carefully, that the historical performance of the models be critiqued and that appropriate downscaling methodologies be used in projecting future climate changes (ACIA, 2005; Walsh et al, 2008).

Climate change projections were integrated into the decision-making component of the Guide through use of a risk assessment screening tool (CSA, 2010; Environment Canada, 1998). The climate change risk assessment tool weighted the vulnerability of the foundation to permafrost melting and highlighted a range of sensitivity based adaptation actions for foundation siting and design (CSA, 2010). The risk assessment consisted of a two-stage process: (1) the first stage involved use of the climate change screening tool to assess the level of climate change-related risk posed to a project, considering both the climate change sensitivity of the permafrost at a site and the consequences associated with an eventual failure of the project (CSA, 2010; Environment Canada, 1998). When the project was particularly vulnerable to climate warming and permafrost melting, the next step of the risk assessment was required; (2) the second stage required a rigorous climate change analyses over the lifespan of the structure and its foundation. This stage included detailed analyses of the ground thermal regime, evaluation of design limitations, development of a permafrost and structural monitoring and maintenance program and documentation on the structure’s design and construction (CSA, 2010).

6.2 *Arctic Climate Change and Snow Loads for Building Codes*

Changing precipitation patterns and types are also impacting infrastructure in Arctic regions. Total precipitation increases of 25 to 35% have been observed in the High Arctic since the 1950s (Zhang et al., 2000: updated in 2005; CSA, 2010). Other climate studies have indicated an increase in the annual number of days with snowfall, and increases in the frequency of heavy snowfall events in the High Arctic (Vincent and Mekis, 2006: updated in 2008). Meanwhile, storm activity in the Arctic, including the intensity of systems, has increased in the period from 1950 to 2006 (Cassano et al, 2006; Hakkinen et al, 2008).

Recent studies by the Government of the Northwest Territories (NWT) in Canada’s Arctic indicate that approximately 22% of the public access buildings in the NWT - schools, hospitals and medical centres, community centres - have been found to be at risk of collapse from changing (increasing) snow loads. Approximately 10% of these buildings have been retrofitted since 2004 while another 12% are currently under snow load "watch" status. Until studies on the changing snow loads and their expected trends can be completed, the Territorial Government has increased all existing ground snow loads in the National Building Code of Canada by a factor of 20% for their Territorial Building Code – a bottom-up adaptation measure that could be considered as equivalent to use of a 20% Climate Change Adaptation Factor.

6.3 *National Building Code Measures for Tornado-Prone Regions*

Severe convective storms pose a risk both to the safety of the Canadian public and to infrastructure. Tornadic events, while acting on a small scale, are the most significant and costly of climatic risks. The tornadic events of Barrie 1985 (Etkin et al., 2001), Edmonton 1987 (Charlton et al., 1997) and the Southern Ontario Tornado outbreak of August 2009 (Environment Canada, 2010) are among the most significant and costly tornado outbreaks in Canadian history. It is considered a matter of due diligence to pursue measures that safeguard the Canadian public from the potential for increasing catastrophic risk of tornadoes.

Based on multi-disciplinary forensic analyses of the Barrie 1985 tornado outbreak, various editions of the National Building Code of Canada (NBCC) from 1995 onwards (NBCC 2005) have been modified to include “tornado proofing” measures that protect lives in “tornado prone” regions. The NBCC commentary identifies tornadoes as a primary cause of death and serious injury from structural failure, but qualifies that it is generally not economical to design buildings to be “tornado-proof” to damages. The NBCC states that it is important to provide key construction details to protect building occupants. The NBCC also references forensic reports from the Barrie 1985 tornado and other outbreaks indicating that buildings in which 90% or more of occupants were killed or seriously injured by a tornado did not have anchorage of house floors into the foundation or ground, or anchorage of the roof to the walls. Anchorage of house floors to the foundation or ground is now addressed in the NBCC and for mobile homes by the Canadian Standards Association Document CSA Z240.10.1 (CSA, 2008), which has specific provisions for anchorage of both roofing and foundations.

Current research at Environment Canada is considering the climatic implications of a limit-states design approach that could be applied to tornadoes. Efforts are also underway to update, revise and consolidate tornado incident reports from across Canada to better define national "tornado-prone" regions for inclusion in the upcoming NBCC.

6.4 *Climate Change Provisions in the Existing National Building Code of Canada*

While the technical provisions of the current edition of the National Building Code of Canada (NBCC) assume that the past climate will be representative of the future climate, specific text was added to NBCC editions from 1995 to the present to advise users that the assumption of stationarity will become increasingly invalid under climate change as the regional frequencies and intensities of extreme events change. The commentary also highlighted the need for careful consideration of climate variability in estimated values of climatic design loads.

The historical climatic design values in the NBCC are being updated and improved through more rigorous quality control of the climate data, improved analysis procedures and incorporation of forensics studies and impacts databases (see Section 6.5). The continuous improvements to climatic design values are complemented by careful monitoring of climate trends and regular updates to design values. Ongoing studies will continue to focus on the development of methodologies that can acceptably and realistically incorporate climate change adaptation into the upcoming cycles of national codes and standards.

6.5 *Forensics Studies and Breaking Point Thresholds*

Forensic studies or post-event investigations yield critically important insights into vulnerabilities and performance of structures during extreme events. Forensic studies add to adaptation by supporting further fine-tuning of engineering design practices, improving climatic design values and informing future codes and standards to reduce vulnerabilities. Among the other benefits from forensic investigations is valuable information on infrastructure damage thresholds or "breaking points" for a given atmospheric hazard.

Recognizing the valued information in forensic analyses, Environment Canada is in the process of developing a climate and infrastructure impacts database to complement existing extremes analyses of high impact climate events in Canada. Climate and infrastructure impacts data have been collected on approximately 120 severe wind events in the province of Ontario for the period 1998-2009. These events span all seasons and represent a variety of extreme wind processes (e.g. intense extratropical cyclones, convective straight-line wind events, tornadoes). All of these high impact wind events have been collected and compiled from numerous sources (e.g. Environment Canada's Ontario Storm Prediction Center's Storm Data Capture Logs, post-event damage assessments, newspaper archives, Ontario Ministry of Natural Resources Forest Health Summaries, insurance loss claims, etc.), with the aim of determining the wind load values associated with various high impact thresholds, identifying regional differences in vulnerability, and understanding safety thresholds needing greater infrastructure adaptation and disaster management. The impacts information in general can prove to be invaluable and complementary to the statistical extreme value analyses that are traditionally used in developing climatic design criteria for building codes and standards. Processes for quality control and analyses of climate extremes are improved. Climate extremes data that have been quality control removed from Environment Canada's National Climate Data Archive are detected, and data gaps are filled in data sparse regions. Similar thresholds have been studied for other types of hazards (e.g. hail - Marshall et al. 2002; freezing rain - Klaassen et al. 2003).

Forensic threshold studies provide guidance on critical damage thresholds for different regions and types of infrastructure, but also provide guidance on the consequences of threshold exceedance. These threshold studies can be used to implement a number of disaster mitigation and management strategies; e.g. explicit impacts statements in weather warnings (i.e. tiered warning systems); guidance for long term mitigation measures (i.e. design requirements in codes and standards); criteria for disaster preparedness and response (i.e. specific impacts expected to guide preparation for response).

6.6 *Climate Guidance and Services for Climate Change and Vulnerability Studies*

In support of stakeholders, Environment Canada has developed an interface that distributes all of the IPCC contributed climate change scenarios and adaptation research results. The Canadian Climate Change Scenarios site (CCCSN, 2010; www.cccsn.ca) provides quality controlled climate change scenarios from numerous international research centres for all of the IPCC assessments (e.g. second or SAR, third or TAR and fourth or AR4 assessment) as well as for selected regional climate model outputs. The site allows stakeholders to critique or assess the modelled climate conditions against gridded observed climate data, to display scenario data spatially and temporally, to access additional “value added” climate fields (e.g. IPCC standardized extremes information) and to download downscaling and other helpful tools. This interface allows users to access much of the climate change scenario information for locations worldwide. Another Environment Canada interface, the Canadian Atmospheric Hazards Network (CAHN, 2010; www.hazards.ca), was developed to provide stakeholder access to peer-reviewed atmospheric hazards information and is intended for decision-makers, disaster managers, engineers and general public. The Hazards information includes extreme climate elements, including ice storm frequencies, ice accretion amounts, climatic design fields, return period extreme snowfalls, near extreme high temperatures, along with selected projections of future extreme climate elements.

7. CONCLUSIONS

The infrastructure adaptation approaches and methodologies presented in this paper aim to manage the risks posed by climate change without posing an undue financial burden today and into the future. This paper has provided an overview of the different approaches that can be considered for development of adaptation solutions: top-down scenario based approaches, vulnerability-based bottom-up approaches and combinations of the two. All of the approaches acknowledge that stationary climate conditions will not apply in the future and that better forward-looking adaptation actions are needed. However, the path forward in dealing with potential climate changes is not clear.

What is clear is that the cost of inaction and failure to adapt to climate change realities will lead to an increased strain on urban infrastructure. Projected increases in extreme events from climate change will increase the risks of catastrophic failure in the urban environment as structures are strained beyond their design limits. Changes to the physical and chemical atmosphere are also likely to increase the weathering or premature deterioration of existing infrastructure, further exacerbating risks. But, any additional burdens associated with early adaptation are likely orders of magnitude less in severity than the potential costs of inaction, which could result in widespread failure of the urban infrastructure under an extreme event. Studies indicate that the additional costs of making new infrastructure, and especially buildings, more resilient to climate change in Organization for Economic Corporation and Development (OECD) countries could range between 0.05-0.5% of GDP each year ($15 -$150 billion), with higher costs possible (Satterthwaite, 2008; Stern 2007). These estimates for infrastructure assets assume that additional costs, accounting for 1-10% of the total amount invested in construction each year, are required to make new buildings and infrastructure more resilient to climate change.

The methodologies needed to incorporate current and future climate change conditions into national codes and standards will reduce the risks to structures over their lifespans. It is very likely that the methodologies and approaches discussed in this paper will require further revisions, adjustments, reworking and corrections in upcoming years.

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