Environment Canada / Environnement Canada

ADAPTATION AND IMPACTS RESEARCH DIVISION (AIRD)
Environment Canada

ADAPTATION OPTIONS FOR INFRASTRUCTURE UNDER CHANGING CLIMATE CONDITIONS

By:
Heather Auld, Don MacIver, Joan Klaassen

OCCASIONAL PAPER 10

2007

ADAPTATION OPTIONS FOR INFRASTRUCTURE UNDER CHANGING CLIMATE CONDITIONS

Heather Auld[1], Don MacIver[1], Joan Klaassen[2]

1 Adaptation and Impacts Research Division, Environment Canada, 4905 Dufferin Street, Toronto, Ontario M3H 5T4

2 Atmospheric Science and Applications Division, Environment Canada – Ontario Region, 4905 Dufferin Street, Toronto, Ontario M3H 5T4

ABSTRACT

Climate change has the potential to impact the safety of existing structures, to increase the frequency of weather-related disasters, to regionally increase premature weathering and to significantly change design criteria and engineering of structures. Because infrastructure built in current times is intended to survive for decades to come, it is critically important that adaptation options to climate change be developed today, incorporated into design and implemented as soon as possible.

Prioritization of required adaptation actions will need to account for existing and future vulnerabilities, the variable lifecycles of structures and replacement and maintenance cycles. "No regrets" types of adaptation actions that are available today need to be applied as soon as possible. These include measures to reduce uncertainties in climatic design values, regularly updated climatic design values, enforcement of codes and standards, maintenance of climate data records and networks, consistent forensic analyses of infrastructure failures, regular maintenance scheduling and community disaster management planning. However, given the potential changes expected, it is also likely that many impacts on communities and infrastructure will lie outside of the coping ranges of existing infrastructure. When this occurs, engineering and planning practices will need to account for these growing uncertainties while new adaptation options are developed over time.

Keywords: infrastructure, codes and standards, climate change, adaptation

1. INTRODUCTION

Under changing climate conditions, it is likely that risks of infrastructure failure will increase worldwide as weather patterns shift and extreme weather conditions become more variable and regionally more

* Paper originally peer-reviewed for Proceedings of Engineering Institute of Canada: Climate Change Technology Conference, Ottawa, May 2006.

** Occasional Paper 10 follows from Occasional Paper 9. Occasional Papers 11 and 12 provide more detailed discussions of issues from Occasional Papers 9 and 10.

intense. According to the Intergovernmental Panel on Climate Change (IPCC, 2001), changing extreme weather events regionally 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 partially offset this effect. In all cases, changes in climate will require changes to the criteria for the design of infrastructure, as well as larger societal and sectoral changes. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) states that:

> *"The key features of climate change for vulnerability and adaptability are those related to variability and extremes, not simply changed average conditions. Most sectors and regions are reasonably adaptable to changes in average conditions, particularly if they are gradual. However, these communities are more vulnerable and less adaptable to changes in the frequency and/or magnitude of conditions other than average, especially extremes". (Chapter 18, page 879).*

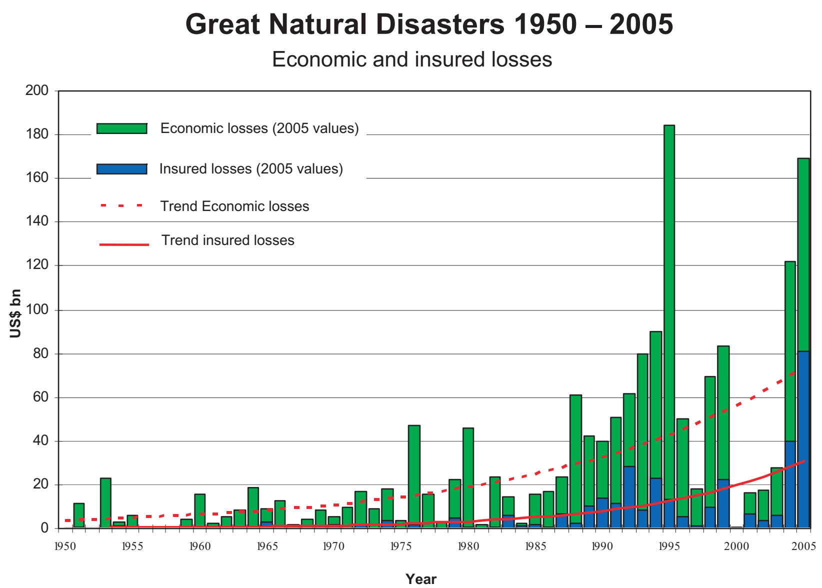

FIGURE 1. Losses from "great" natural disasters from 1950-2005 (US$), including trends in insured and other economic costs. (From IPCC 2001; Munich Re 2000; Munich Re 2005 and updated from Munich Re 2006). Natural disasters are defined as great if the ability of the region to help itself is overtaxed, as is usually the case when thousands of people are killed, hundreds of thousands made homeless or when a country suffers substantial economic losses.

Extreme weather is very damaging to infrastructure, as evidenced by weather-related damage and loss statistics worldwide. Figure 1 illustrates this trend for global disaster losses from 1950-2005 (Munich Re, 2000; Munich Re, 2005; Munich Re, 2006) Compared to the decade of the 1950s, the annual direct losses from large or globally significant natural catastrophes in the 1990s increased over 10 times, rising from US $3.9 billion to US $40 billion a year in 1999 dollars, while population grew only by 2.4-fold. In reality, these costs are larger by a factor of two when losses from relatively ordinary weather-related events are included. Most of the increases in losses were the result of weather-related high impact events. Other factors that influence losses and the vulnerability of communities and infrastructure to high impact weather events include increased wealth, more insured property, increased populations, development in higher risk locations such as coastal or flood zones, aging infrastructure and a growing reliance on uninterrupted services (e.g. electricity, communications). Of total losses averaging $40 billion a year, approximately $9.6 billion of direct damage occurred as a result of infrastructure losses (Freeman and Warner, 2001). In the case of flood losses, some estimates indicate that infrastructure failure and loss accounted for 65% of all flood losses (Swiss Re, 1997). According to studies undertaken by the Norwegian Building Research Institute (Liso et al, 2003), the costs of repairing damages to structures in Norway from storm events is estimated at about 5% of the annual investment costs for new construction, amounting to approximately $0.6US Billion (NOK $4 billion) annually in Norway alone. Although an increase in the number and intensity of storms regionally may play a role in these disasters, there is no question that a significant portion of the increasing costs are also the result of growing vulnerability of communities and infrastructure to high impact weather events for reasons cited earlier. (Pielke and Downton, 2000; Auld and MacIver, 2004).

"NO REGRETS" ADAPTATION ACTIONS

As Table 1 illustrates, new infrastructure projects are built on decadal scales. It is critical to their lifespan that adaptation options be developed and implemented as soon as possible so that the infrastructure can cope with the expected climate changes. Some options can be described as "no regrets" actions, defined as those actions where society would benefit from their implementation even if anthropogenic climate change did not take place (IPCC, 2001). These "no regrets" types of adaptation actions include measures to reduce and make redundant uncertainties in climatic design values and to update calculations, enforcement of engineering codes and standards, maintenance of the quality and length of climate change records and networks, consistent forensic analyses of infrastructure failures, regular maintenance of existing infrastructure and community disaster management planning. In other cases, the impacts of the future climate will lie outside of existing experience and the coping ranges of existing infrastructure. In these situations, adaptation options will need to be developed or learned over time through organized analyses of failures or forensic studies (adaptation learning). At the same time, all hazards approaches to disaster planning will need to become more widely adopted and rigorous.

Between the "no regrets" actions and the "adaptation learning" actions are the activities that build adaptation science and develop the adaptive capacity to respond in future. This hierarchy of adaptation actions describes the sequence of actions needed: (1) to address short term "no regrets" adaptation requirements (e.g. updating of climatic design values to include more recent climate conditions), (2) to develop adaptation science, solutions and decrease uncertainties needed to ensure sound actions within the next decade or two (e.g. incorporation of scenarios into climatic design values) and (3) progress to develop the solutions that will be needed in the longer term (e.g. relocation of communities, retrofits). Included in all of these sequences is the requirement for continual assessment of existing and changing risks, climate trends, climate change science and available technologies and flexibility to change directions and strategies as new information unfolds.

TABLE 1. Infrastructure Lifecycle Timeframes (Adapted from Planning Institute of Australia, 2004)

Structure	Phase	Typical Expected Lifecycle
Commercial Buildings	Retrofit Demolition	20 years 50-100 years
Housing	Additions and Alterations Demolition	15-20 years 60-100 years
Roads	Maintenance Resurface Reconstruction/Major Upgrade	Yearly 5-10 years 20-30 years
Bridges	Maintenance Resurface concrete Reconstruction/Major Upgrade	Yearly 20-25 years 60-100 years
Rail	Major refurbishment Reconstruction/Major Upgrade	10-20 years 50-100 years
Airports	Major refurbishment Reconstruction/Major Upgrade	10-20 years 50 years
Seaports	Major refurbishment Reconstruction/Major Upgrade	10-20 years 50-100 years
Dams/Water Supply	Major refurbishment Reconstruction/Major Upgrade	20-30 years 50 years
Waste Management	Upgrade Major Refurbishment	5-10 years 20-30 years
Sewers	Reconstruction/Major Upgrade	50 years

Some of the adaptation options for infrastructure and the built environment can be categorized according to the following timeframes::

1. **"No regrets"** actions, which include steps to:
   - Update and regularly revise structural codes and standards, climatic design values and engineering practices used for new infrastructure;
   - Reduce uncertainties and deficiencies in scientific and data analyses methodologies used to calculate climatic design values for new infrastructure;
   - Ensure sufficient density, data quality and record length of climate networks;
   - Enforce compliance to codes and standards for new infrastructure;
   - Regularly assess risks for existing infrastructure using climate change trend analyses with the aim of prioritizing regions, climate variables and infrastructure types for immediate actions (e.g. infrastructure sensitive to permafrost melting and ice loads);
   - Reduce premature deterioration rates for existing and new infrastructure (e.g. reduced moisture infiltration, improved maintenance of structures from weathering);
   - Provide accurate early Weather Warnings of hazards (in the appropriate format to the appropriate people);
   - Encourage energy efficiency and self-sufficiency;
   - Support multi-disciplinary forensic studies (adaptation learning) and risk reduction learning;
   - Encourage (or regulate) community pre-disaster and post-disaster management planning;
   - Create awareness of community risks and vulnerabilities;
   - Include disaster resistant construction and climate change adaptation topics in curriculum for engineering and planning professions.

2. **Short to medium** term adaptation actions to:
   - Adjust safety factors in codes and standards (or other measures) to reflect increasing uncertainties, increased variability or ranges of extremes in values and growing risks for new infrastructure under changing climate conditions;
   - Consider the development and incorporation of "Climate Change Adaptation Factors" for faster and more general updating of climatic design information;
   - Develop methodologies to incorporate climate change and socio-economic scenarios into climatic design values and engineering practices for new infrastructure;
   - Enhance safety and resilience of new and existing infrastructure for higher risk regions and infrastructure types;
   - Review existing engineering practices in light of the changing climate;
   - Prioritize and develop adaptation solutions such as retrofit technologies for the most critically at risk regions and most critical of existing infrastructure types;

- Consider standards for maintenance practices to increase the reliability of structures over time;
- Incorporate infrastructure adaptation into the planning, maintenance and replacement cycle of existing infrastructure.

3. **Longer term** adaptation actions to:
   - Where feasible, retrofit at risk structures for expected climatic design values;
   - Avoid or regulate development in vulnerable locations;
   - Relocate the most at risk structures and where needed, the most "at risk" communities;
   - Demolish and replace unsafe structures or abandon high risk locations.

"No Regrets" Actions: Addressing Deficiencies in Climatic Design Information

In Canada, and likely elsewhere in the world, current longstanding gaps and deficiencies in the determination of climatic design values prevent optimum decisions from being made on infrastructure reliability and safety. Structures designed using climatic design values that are based on poor climatic data, sparse data or previously short dataset records are particularly vulnerable. It is important that such uncertainties and deficiencies in climatic design values be addressed on a priority basis to ensure effective adaptation to current and expected climate variability. A better understanding of these uncertainties is needed to determine whether and by how much structures can tolerate slight increases in loads. For example, the climatic design values used in any given building code or infrastructure standard vary considerably by locality and region, by the date of its calculation and on whether design values have been regularly updated. The uncertainties in climatic design values will 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, statistical approaches used and spatial and temporal interpolation approaches applied for estimation at a location (Canadian Commission on Building and Fire Codes, 1995). In the near future, it will become even more important that climate station record lengths and quality be maintained or enhanced to allow adequate calculation and interpolation of climatic design values and that climate networks be enhanced or maintained in areas of sizable populations, near critical infrastructure and in the regions most vulnerable to climate change.

The impact of uncertainties in the estimation of historical climatic design values needs to be understood and reduced in order to optimize the safety and economy of structure and update future climatic design values. For example, conservative assumptions that were applied regionally in the past can result in additional margins of safety or overdesign in existing climatic design values. In other cases, due to climate data shortfalls not considered in data treatments or due to regional trends towards increasing climate loads, some existing climatic design values may already be at risk under current climate conditions and not be able to accommodate any further increases in loads. For example, increases in ice accretion loads or shifts in continuous permafrost zones in northern regions or in "tornado prone" zones will require adjustments to engineering codes and practices regionally.

As well as taking actions to minimize the uncertainties in existing climatic design values, it is important that climatic design values be regularly updated over time and incorporated into codes and standards. Under current processes, building codes and other infrastructure standards are typically slow to change, particularly since industry stakeholders sometimes can resist new changes that add to the costs of structures. Because new or replaced infrastructure will come to play an increasingly important role in building adaptive capacity, particularly when compared to the cost of retrofitting existing infrastructure, it is important to ensure that infrastructure is optimally adapted as soon as possible for existing and future climate conditions.

A first step option that would facilitate earlier adaptation and complement the eventual, larger actions that will need to be reflected in codes and standards is the introduction of a "Climate Change Adaptation Factor". The Climate Change Adaptation Factor refers to an adjustment factor that could be applied to existing climatic design values, reflecting recently observed changes, and future expectations of changes in climatic design values. The first term in the Factor, ($A_{current}$), has the capability of explicitly updating climatic design values by considering the most recent climate observations and calculating the adjustments needed to existing climatic design values. The second term, ($A_{climate\ change}$), is designed to account for projected increases and growing uncertainties in existing climatic design values as a result of projected climate changes. The second term plays a similar role to adjustments proposed by the Association of British Insurers (2003). The application of this Factor could include one or both components, as needed.

Climate Change Adaptation Factor = Factor ($A_{current}$) + Factor ($A_{climate\ change}$). Climatic design values for codes and standards need to reflect the changing climate conditions and to be assessed regularly against regional climate trends to determine whether existing margins of safety in structures have any remaining tolerances to accommodate increases in loadings. Localities and regions where climate trends are encroaching on tolerance limits require, on a priority basis, increases in climatic design values for new structures and potential structural reinforcement for existing structures that have been identified to be at risk to current climate variability and future change. For example, regionally specific Climate Change Adaptation Factors could be applied after comparison against climate trends to indicate that updated and increased design values are needed or when it is likely that the risks to specific structures from changing climate conditions will increase over time. While this approach has the advantage of providing a relatively easy means to update climatic design values regularly as new climate data and climate change scenario information become available, it could have the disadvantage of being difficult for users and inspection personnel to understand initially.

Methodologies must be developed to allow climate change scenario information to be incorporated into the design of infrastructure. Such studies and methodologies are rare. A study by the Meteorological Service of Canada, for example, on the potentially changing risks of severe ice storms has shown that several complementary analyses should always be considered when projecting the implications of extreme weather under changing climate conditions. The study (Klaassen et al, 2003), which identified potential regions in South-Central Canada that are at increased risks for severe ice storms under initial winter warming, indicated that considerable potential exists for the use of statistical synoptic map typing procedures in identifying trends in large scale or synoptic, regional and local scale weather patterns for severe ice storms. Statistical map typing methodologies and other climate change downscaling methodologies for extremes have considerable potential to provide projections from global and regional climate models using fields more reliably handled by the global scale models. Other complementary analyses used in the study (Klaassen et al, 2003) included storm tracking, assessment of threshold synoptic storm components for the most extreme ice storms affecting eastern North America, assessment of climate impact thresholds, and spatial or analogue approaches that correlate conditions and impacts in adjacent regions during the most severe storms.

Existing infrastructure failures are often shown to result from inadequate compliance to codes and standards. As a result, compliance and the development of institutional capacity to implement building standards and codes of practice will become increasingly important in future. Several studies have documented widespread damages as a result of the construction industry not complying with building codes and building inspections not detecting the violations. For example, the hurricane that hit Northwest Norway in 1992 caused damage to buildings in the order of US $0.2 Billion (NOK $1.3 Billion), with total damages to structures in general amounting to approximately US $3 Billion (Liso et al, 2003). The bulk of the damage to buildings was incurred on roofs and roofing and could have been avoided had the existing Building Regulations and Codes of Practice been followed (Liso et al, 2003). In the UK, analysis of claims and weather data have shown that a large percentage of wind related damage takes place at wind speeds lower than those to which buildings are nominally designed and are caused by failures to apply existing codes of practice (Buller, 1993).

Because of the varying safety factors used for each type of infrastructure, it is theoretically possible that some structures designed for longer return period extremes, such as hospitals, may be able to withstand more extreme atmospheric hazards with longer return periods while other structures with lower safety factors, such as electrical distribution lines, may readily encroach on the limits of their load tolerances. Where existing safety factors are relatively high or conservative, adaptation actions may not be required immediately to ensure structural safety. In other cases, a Climate Change Adaptation Factor may be needed to ensure timely adaptation actions. Further study is needed to determine whether and when structures will become “at risk” to the increasing uncertainty of climate design values and to assess the impact of changing engineering practices and codes and standards on the ability of structures to withstand surprises in extreme weather loads. In prioritizing adaptation requirements, studies are needed to identify which types of structures are most vulnerable to the changing climate (e.g. electrical distribution lines, wind turbines, tailing ponds). Such studies will also help to determine to what extent tendencies towards standardized cost-effective structures today may have compromised robustness or adaptability of structures. Alternatively, a review of generic building typologies that have survived over centuries may reveal characteristics that make these structures particularly adaptable to climate variations and changes (Steemers, 2003). The learning from such a review would serve to highlight adaptive attributes and sound building practices that historically may have been better adapted for local climatic conditions and also reveal current practices that are contrary to effective adaptation.

Finally, the relationship between atmospheric weathering processes, building materials, maintenance schedules and structures is complex and in need of further study (Auld et al, 2006a). The understanding of how degradation and damage can best be reduced economically is of growing importance for the design and construction of structures. In many areas, future building materials, structures and building enclosures, will need to withstand greater climatic impacts than they do today. When designing building enclosures to resist wind actions, materials and engineering practices will need to ensure the integrity of the envelope so that moisture does not enter the structure (Holm, 2003). A particular challenge will be the identification of weathering processes of greatest importance in order to develop appropriate adaptation responses. For instance, the duration of excessive precipitation may prove of greater importance for certain types of house facades, while the intensity of driving rain may be the most important element for other types of external walls. Freezing and thawing cycles may prove significant in winter climates for performance of masonry and concrete construction while polymer materials may be more affected by the sum of ultraviolet radiation (Holm, 2003). Adaptation actions could take the form of different formulations for materials (e.g. concrete, clay brick) or different engineering practices to ensure greater durability and requirements in standards for preventative maintenance.

Improved Community Disaster Management

Concerns over the impacts of weather-related hazards on vulnerable populations are growing, due to increasing risk factors such as population growth and urbanization, a rising proportion of poor living in vulnerable locations and the changing climate. Actions to reduce exposure to weather hazards or disaster management are necessary and will need to include adaptation actions such as planned responses to timely and accurate weather warnings, proper land use planning, good engineering design and practice, good maintenance of structures and efficiency and self-sufficiency in use of energy and services (Freeman et al, 2002; Planning Institute of Australia, 2004).

A very critical part of a disaster management strategy is the completion of a Vulnerability or Hazards Identification and Risk Assessment. The Ontario Emergency Management and Civil Protection Act (Government of Ontario, 2004), for example, legislates all municipal and regional governments in the province of Ontario to identify and assess various hazards and risks to public safety and infrastructure that may give rise to an emergency situation. The Act requires that a Hazard Identification and Risk Assessment or HIRA be completed and community risks prioritized. The result of this HIRA process is a list of priority hazards and identification of vulnerable groups, infrastructure, likely risks and potential interventions (Auld et al, 2006c). The Act requires that municipalities develop comprehensive emergency management plans that will include: an Emergency Operations Centre, planned responses for identified high risks, dangerous goods routes, community evacuation plans, emergency recovery plans, guidelines for risk-based land use planning, public education programs, an Incident Management System and an external assessment process (Government of Ontario, 2004). In support of the HIRA measures, Environment Canada and Emergency Management Ontario developed a web site (**www.hazards.ca**) and publication on atmospheric hazards that allows emergency managers to access climatological hazards information, customize atmospheric maps for their localities and to overlay regional combinations of hazards maps (Auld et al, 2004; Auld et al, 2006c).

The successful application of early warnings is another effective measure for disaster reduction. Effective warnings of impending events allow people to take actions that save lives, reduce damage, reduce human suffering, and speed recovery. In essence, accurate and timely weather warnings play a critical role in buying the time needed to evacuate populations, reinforce infrastructure and prepare for emergency response. While scientists and emergency managers are improving capabilities to warn for more weather and related environmental hazards and to increase warning accuracy, greater improvements are needed in measures to deliver warnings in a timely manner and to those people and regions mainly at risk. Improvements are also required for better coordination among warning providers, for better education of those at risk, and in building partnerships among the many public and private groups involved in response.

In many countries, weather warning systems consist of an escalating series of messages intended to alert the public and emergency responders to impending weather hazards of various magnitudes. Typically, these warning systems consist of advisories or watches for potential hazardous weather, with warnings issued as hazardous weather becomes more certain. As risks increase regionally under climate change, improved and expanded weather warning programs, such as specialized warnings for emergency responders, may be needed along with increased lead times. For example, the U.K. Meteorological Office currently provides Early Warnings of potentially disastrous weather events to emergency responders up to five days in advance so they can be prepared to respond to the effects of high impact weather. Because prediction of severe weather at this range, especially in any detail, is difficult, these Early Warnings are expressed in terms of probabilities, with warnings issued when the probability of disruption due to severe weather somewhere in the UK is 60% or more (U.K. Meteorological Office, 2004). Other expanded weather warning programs could include escalated warnings of potential community disasters that are based on infrastructure damage thresholds. These weather infrastructure warnings could include warnings of extreme ice loads or wind loads with the potential to disrupt transportation and to cause widespread failure of electrical power distribution networks (Klaassen et al, 2003) or alerts of extreme snow loads giving increased risks for building collapses (DeGaetano and Wilks, 1999). Similarly, expanded weather-health warnings and response systems for potentially “dangerous” environmental conditions could include community Heat Alert systems for vulnerable populations, waterborne disease outbreak and beach water quality alert systems for water managers (Cheng et al, 2004; Auld et al, 2004) as well as other health emergency alert systems. The Meteorological Services of several countries, including Canada, currently provide Heat Alert prediction systems for selected pilot cities when risks of elevated mortalities from heat wave events reach regional threshold levels. The U.K. Meteorological Office also supports health-related weather services aimed at assisting in more effective public healthcare planning and delivery. By building high-quality weather information into the decision-making process, public health officials, healthcare providers, researchers and others are able to plan emergency health care operations and activities with greater confidence, manage workload more effectively and make the best use of limited healthcare resources (UK Meteorological Office, 2004).

While emergency disaster response is important, climate change adaptation options for infrastructure and communities will ultimately require more intervention by land use planning authorities. Land use planning is a powerful tool to help reduce the loss of life and property. One study that indirectly illustrates this concept for flooding events (Brown et al, 1997) compared impacts from storm events in Michigan and neighbouring Ontario and found that nonagricultural flood damage from a set of storms moving through Michigan exceeded that of southwestern Ontario by a factor of about 900, even though the flood yields in Ontario were greater than those in Michigan. Their analysis ascribed the cause as greater development in flood-prone areas in Michigan. The storms generally exceeded land use design thresholds in Michigan, whereas in Ontario they did not.

Forensic disaster investigations likely will become increasingly important for adaptation learning. The performance of structures during extreme events needs to be monitored to confirm and to further fine-tune engineering design practices, as well as to assess climatic design values. As an example, many lessons were learned from the detailed investigations of how structures responded to the Barrie and Grand Valley tornadoes in southern Ontario, Canada in 1985. The studies of damages following the tornado outbreak indicated that occupants of houses that were destroyed by the tornadoes survived in buildings when the walls of their homes were properly secured to the foundations (Allen, 1986). As a result of these and other studies, the 1995 National Building Code of Canada increased requirements for anchoring of walls to foundations for “tornado prone” areas (Canadian Commission on Building and Fire Codes, 2005). Information on tornado risks and other extreme weather hazards can be found on the Environment Canada and Emergency Management Ontario web site **www.hazards.ca**.

Similar adaptation lessons have been learned worldwide from forensic investigations of damages following hurricane landfalls and flooding events. As illustration, the massive destruction of Hurricane Andrew (US $26 to 30 Billion) which struck the southeastern US in 1992, brought issues of construction, mitigation and the insurance industry into sharp focus (International Hurricane Centre, 1999). The recommendations from the Committee that investigated the damages had an impact on the South Florida Building Code and construction regulations. Changes were introduced for new product approval test criteria for building components that included impact and fatigue tests able to simulate flying debris. The Committee also determined that the most significant hurricane damages resulted from the loss of "integrity of the building envelope" and that the breaching of the exterior of a structure set off a chain of events that led to more severe damage (e.g. shutters can significantly reduce the net damage that a building sustains in a hurricane). Additional hurricane proofing measures have been introduced into the Florida Building Code in subsequent years, following increasing losses from hurricane damages.

Adaptation measures that decrease the energy requirements of buildings and ensure more disaster resistant energy service systems (e.g. renewable sources) can reduce losses from business interruptions and damages to property while helping to mitigate increases in the atmospheric greenhouse gases driving climate change. For example, energy efficient buildings are of value when backup power systems are needed during times of power outages. In the eastern North American Ice Storm of 1998, the costs of perished foods in residential freezers lost as a result of power outages was one of the larger costs faced by homeowner insurers. Likewise, more energy efficient windows, including those with retrofit films, can reduce energy losses by half while increasing their resistance to breakage from flying debris in windstorms. Studies, for example, have indicated that double-glazed windows with one low e-coating take three to four times longer to break than ordinary double-glazed windows (Anderberg, 1985; Mills, 2003). Similarly, durable energy efficient building envelopes (i.e. insulated concrete form construction) tend to be more resistant to flying debris than standard timber frame construction (Farnsworth, 2000). Insulating water pipes or insulating cold spaces where water pipes run can also save energy and reduce risks of frozen water pipes and water damage since insulated pipes cool and freeze less readily. The US insurance industry estimates that claims from frozen pipes have cost US $4.2 Billion over 10 years (IBHS and SBA, 1999).

Prioritization of Adaptation Actions for Critical Infrastructure and Regions

The many implications of the changing climate will require a structured approach for the reinforcement and retrofit of existing infrastructure, in planning for redundancy of critical infrastructure and in updating climatic design values and infrastructure codes and standards. Underlying these activities will be an ongoing need for careful monitoring of regional climate conditions to update priorities. This prioritization process will need to account for the variable lifecycles of structures and replacement cycles, including maintenance and upgrade cycles.

Critical infrastructure is defined in Canada as "those physical and information technology facilities, networks, and assets whose disruption or destruction would have serious impact on the health, safety, security, and economic well-being of Canadians or on the effective functioning of governments in Canada" (Grenier, 2001). Enhanced design of the most critical infrastructure (such as communications structures, power supply and distribution systems and emergency shelters) and built-in redundancies may improve the likelihood of continuous operation during extreme weather events, as well as improve response and recovery following disasters and generally reduce the vulnerabilities to regionally increasing extremes. The survival or failure of housing has also been claimed to be a key factor determining the severity of a natural disaster and the ability of a community to recover, indicating the importance of proper design and construction of housing (Davenport, 1999).

Although the eastern North American Ice Storm of January 1998 represented a weather disaster, it quickly turned into a technological disaster as well because of cascading impacts from power outages that, in some cases, lasted several weeks. Due to a whole chain of events, affected communities experienced a major malfunction of some of their other most critical infrastructure such as telecommunications, transportation, banking and financial systems, drinking-water supplies and, of course, energy infrastructures. The January 1998 Ice Storm emphasized that all components of critical infrastructure are inter-linked today, particularly given the nature of today's electronic and "just-in-time delivery" economies, industries and urbanized communities dependent on uninterrupted services.

While particular types of infrastructure will require priority adaptation action, particular regions may also require priority actions for enhanced design of new infrastructure and protection of existing infrastructure. Some of the greatest impacts of climate change on infrastructure will likely be noticed in exposed coastal zones, flood plain regions, heavily urbanized areas and permafrost regions. Adaptation options will require a suite of actions ranging from avoidance of the most vulnerable sites to expensive protection structures.

Many structures and communities in coastal zones and flood plains will face significant risks from the changing climate as a result of sea level rise, increases in storm surges, increases in water and air temperature, more extreme rainfall and storm intensity, and resulting land erosion and inundation from the sea. These impacts will likely lead to increased susceptibility of buildings and structures to damages in vulnerable locations and to more frequent disruptions to services (Planning Institute of Australia, 2004). All of these impacts could affect the future design and location of development. The more risky coastal locations that contain high cultural, environmental or financial value may require construction of expensive structures for protection against inundation, such as barriers and dykes and reinforcement of buildings and other infrastructure, along with measures to reduce premature weathering of materials, including enhanced maintenance.

Permafrost regions are already becoming vulnerable to climate changes. Over the next 100 years, under moderate emissions scenarios, average annual temperatures in the Arctic are projected to rise 3-5°C over land and by up to 7°C over the oceans, while winter temperatures increase by 4-7°C over land and 7-10°C over the oceans (ACIA, 2005). This warming will result in melting of permafrost and will require expensive monitoring of buildings, road-beds, pipelines, utility lines, dams and water diversion channels. The net result likely will be extensive repairs and modifications of existing structures, and changed techniques for new construction. While tested adaptation solutions are available, given warning of changes, reliable local information, and funding, the costs will be expensive. Proven methods of supporting roads, airports, and buildings can prevent settlement under permafrost thawing while expensive maintenance can protect facilities built on permafrost (University of Alaska Anchorage, 2000). New structures in permafrost regions can be built over gravelly “thaw-stable” permafrost to avoid the worst consequences, but more costly up-front actions will be required to select the most reliable and least vulnerable sites as the permafrost thaws. All of these actions imply increased road and runway construction and maintenance costs.

In Canada’s Western Arctic regions, the implications of not taking actions are becoming apparent. Environmental monitoring shows that the western Canadian Arctic is warming at a rate that is unprecedented over the past 400 years, with average winter temperatures warming as much as 3-4°C in the past 50 years (ACIA, 2005). As a result, roads and airstrips across the Western Arctic are sagging, cracking and deteriorating as the changing regional climate slowly melts the underlying permafrost. In many localities, asphalt surfaces have cracked, road shoulders washed away and roadbeds have sunk by as much as a metre (Airport Business, 2005). Adaptation solutions that have been applied with limited success (Airport Business, 2005) include the terracing of embankments to keep road sections from collapsing (Dempster Highway south of Inuvik), applying insulation under asphalt and installation of insulating liners as much as four metres deep under sagging airport runways (Yellowknife Airport). In the case of the Yellowknife Airport runway, the adaptation response required excavation of the runway to a total depth of four metres, including one metre into the permafrost and placement of 100 mm of rigid high-density foam insulation before backfilling the excavation with layers of sand, a geotechnical liner, crushed rock, and compacted granular sub-base and base materials. In a few cases, portions of the Canadian northern highway from Yellowknife to Fort Providence have been abandoned and rebuilt over more stable permafrost. In other cases, airport maintenance practices (e.g. Inuvik) have needed to change to cope with new freezing rain events (precipitation that previously fell as snow), leading to a tenfold increase in the volume of de-icer and gravel used at the airport.

It is expected that climate change will affect the costs and timelines for planning, upgrading and maintaining infrastructure. Prioritization of required adaptation and mitigation actions will need to account for the variable lifecycles of structures and replacement cycles, including infrastructure maintenance and upgrade cycles. Table 1 indicates the expected lifecycle activities for the various types of infrastructure. As the Table indicates, planning decisions are being made about buildings and other infrastructure today that have a very high probability of being affected by the direct impacts of climate change in the future.

When considering the implementation of adaptation solutions, structures with a design life of 30 to 50 years will need to consider different future climate conditions than others with a longer design life of 100 years. Short-lived assets and components, such as heating, ventilation and cooling systems, tend to be replaced at various times during the lifespan of a building, offering opportunities for adaptation or "phasing in" of systems to the changing climate. Other medium-life assets such as industrial plants, oil and gas pipelines, and conventional power stations that need to be modernized to take advantage of competitive technologies are also likely to be replaced or relocated over shorter time scales than other infrastructure and can become adaptable, particularly through upgrades and relocation. For structures not as likely to be relocated or replaced, such as housing, the challenges of adapting basic structural components will be more difficult. Due to the varied ages and replacement life of structures in the built environment, it will take time to change structures, institutions and other policies to cope with climate change realities.

Changing weather extremes and weathering processes associated with the changing climate are expected to effectively shorten the lifespan of existing structures in many regions. Where extremes increase, the impact will be a reduction in the "effective" return period event that existing structures were built to withstand. For example, 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 occur every 10 years by end of 21st century. Changes in the extreme daily precipitation rate are substantially larger than the changes in the annual mean precipitation rate. As the effective return periods of extreme events change with the climate, weather extremes will tend to exceed the design specifications for structures more frequently, decreasing the durability and resilience of the structure. Repeated extreme event loads (fatigue loads) cause deterioration of materials and can lead to eventual failure of the structure.

In the timeframe of climate change impacts, it is evident that new infrastructure will play an increasingly important role in building adaptive capacity as older structures are replaced over time (as shown by lifecycle timeframes in Table 1). For example, within the next 50 years and assuming a replacement rate of 1% to 1.5% for buildings, it is likely that roughly half of existing buildings will need to be demolished and replaced (Fernandez, 2002). Hence, within the timeframes for climate change impacts, new buildings will accumulatively account for an equal or greater fraction of the building stock and need to be designed to enable adaptation to climate change as soon as possible (e.g. through continuously updated building codes, increased safety factors or a Climate Change Adaptation Factor and incorporation of climate change scenarios).

The adoption of practices supporting the "diversified lifetime" of a building may also become a powerful adaptation option (Steemers, 2003). This will require that buildings and other structures become "designed for disassembly, separation technologies, materials reclamation and recycling, loose-fit detailing, lightly-treading foundations and other technologies that allow use to change over time" (Fernandez, 2002). The concept behind the "diversified lifetime" is that a structure be designed using a number of different parts with different design lives. As a result, uncertainty about a building's long-term use or environmental conditions can be reflected by reduced investment in some of its construction or components, with an inherent potential to adapt spatially and functionally to change. In the case of climate change, the objective would be to anticipate changing climate conditions (or even market conditions) and to consider whether it is worth investing for the longer term, depending on risks, benefits and uncertainties,. For the buildings sector, this could involve investing in a strategy for the key long-term parts of the building that will need to be able to cope with predicted climate change and allowing the short-term components of the buildings or structure to be designed for minimal climatic change and maximum flexibility.

Education and Outreach

The implementation of cost effective climate change adaptation measures to protect communities will require greater knowledge and understanding of climate change impacts in the public and private sectors. In particular, the planning and engineering communities will need to work closely with the climate community in order to become knowledgeable on regional climate change impacts for infrastructure and to identify and implement regional adaptation options. Consequently, an important step in promoting safe building construction in vulnerable regions will be the requirement to create awareness and appreciation of levels of risks within communities and within relevant professions. Since planning is a future oriented profession, adaptation to climate change is a challenge that this profession must accept and act upon as soon as possible. At the same time, professionals graduating from engineering and architectural programs as well as practicing professionals will need to have greater exposure in their curriculum to disaster resistant construction and awareness of climate change impacts and the need for adaptation.

Conclusions

Climate change will impact infrastructure through gradual changes in weather patterns, increasing variability and severity of extreme events. Because infrastructure built in current times is intended to survive for decades to come, it is critically important that climate change adaptation options be developed today and implemented as soon as possible. The many implications of the changing climate will require a structured approach for the updating of climate design values, codes and infrastructure standards, for reinforcement and retrofit of existing infrastructure and for planning redundancy of critical infrastructure. Underlying these activities will be an ongoing need for careful monitoring of regional climate conditions and prioritization of adaptation actions.

“No regrets” adaptation actions are available in the near term to reduce the vulnerability of infrastructure. These “no regrets” actions include measures to reduce uncertainties in climatic design values and to update calculations, to enforce engineering codes and standards, to safeguard the quality and length of climate data records and networks, to require regular maintenance of existing infrastructure and to ensure consistent forensic analyses of infrastructure failures and community disaster management planning. In other cases, it is likely that the impacts of future climate change will lie outside of existing experience and coping ranges of infrastructure, requiring that adaptation options be developed over time through “adaptation learning”.

In all cases, adaptation to climate change will require that planners, their agencies, the engineering community and community decision-makers consider timeframes beyond statutory requirements and even beyond the lifetime of most individuals. Improved understanding of climate change impacts and the need for adaptation must be combined with better risk assessment of community climate change impacts and vulnerability, the identification and avoidance of development in risky areas and ongoing incorporation of adaptation strategies into land use planning and community disaster management planning. Some adaptation options for infrastructure will require tough actions, including the location of new development in areas less vulnerable to the changing climate, the abandonment of land, structures and ecosystems in vulnerable areas, location of greenbelts in residential areas, altered building design and retrofits of existing structures and defence of vulnerable areas. Such actions are available but will entail significant costs, disruptions to communities and require political commitment and cooperation between all levels of government.

References

Airport Business, 2005. Studies Show Climate Change Melting Permafrost Under Runways in Western Arctic, Article by Bob Weber, June 2, 2005. Available at http://www.airportbusiness.com/article/article.jsp?id=2258&siteSection=4

ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press, 1042 pp.

Allen, D., 1985. Tornado Damage in the Barrie/Orangeville Area, Ontario, May 1985. Building Research Note BRN 240. National Research Council, Institute for Research in Construction, Ottawa, Canada, 23 pp.

Anderberg, Y., 1985. Brandfoersoek paa glaskonstruktioner [Fire Research on Glass Construction]. Lund University, Institute of Fire Technology, Lund.

Association of British Insurers, 2003. The Vulnerability of UK Property to Windstorm Damage. Association of British Insurers, London, UK.

Auld, H. and D. MacIver, 2006a. Changing Weather Patterns, Uncertainty and Infrastructure Risk: Emerging Adaptation Requirements. In Proceedings of Engineering Institute of Canada Climate Change Technology Conference, Ottawa, May 2006. Updated as Occasional Paper 9, Environment Canada, Adaptation and Impacts Research Division, Toronto, Canada.

Auld, H., J. Klaassen and N. Comer, 2006b. Weathering of Building Infrastructure and the Changing Climate: Adaptation Options. In Proceedings of Engineering Institute of Canada Climate Change Technology Conference, Ottawa, May 2006. Updated as Occasional Paper 11, Environment Canada, Adaptation and Impacts Research Division, Toronto, Canada, 2007.

Auld, H., D. MacIver, J. Klaassen, N. Comer and B. Tugwood, 2006c. Planning for Atmospheric Hazards and Disaster Management under Changing Climate Conditions. In Proceedings of Engineering Institute of Canada Climate Change Technology Conference, Ottawa, May 2006. Reprinted in The Americas: Building the Adaptive Capacity to Global Environmental Change. Environment Canada. Toronto, Canada; 2006. pp.237 - 254. Updated as Occasional Paper 12, Environment Canada, Adaptation and Impacts Research Division, Toronto, Canada, 2007.

Auld, H. and D. MacIver, 2004. The Changing Climate And Community Vulnerabilities to Disasters. In, Climate Change: An International Conference on Adaptation Science, Management and Policy Options (Eds. Fenech et al). Environment Canada, Toronto, Canada.

Brown, D., S. Moin and M. Nicholson, 1997. A comparison of flooding in Michigan and Ontario: soft data to support soft water management approaches. Canadian Water Resources Journal, 22(2): 125-139.

Buller, P., 1993. A thirty year survey of gale damage to buildings in the UK. iProceedings of the 1st IAWE European and African Regional Conference, Guernsey. Building Research Establishment, Watford, UK.

Canadian Commission on Building and Fire Codes, 2005. 2005 National Building Code of Canada. National Research Council, Government of Canada, Ottawa, Canada.

Cheng, S., H. Auld, G. Li, J. Klaassen, Q. Li., N. Comer, M. Campbell, N. Day, D. Pengelly and S. Gingrich, 2004. An Analysis of Possible Climate Change Impacts on Human Mortality in South Central Canada. In Proceedings of AMS 16th Biometeorology and Aerobiology Conference, Vancouver, August 25-26, 2004.

Davenport, A., 1999. The House That Won't Fall Down. In Proceedings of the Royal Society Conference on "Dealing with Natural Disasters", London, UK, October 27-29, 1999.

DeGaetano, A. and D. Wilks, 1999. Mitigating snow-induced roof collapses using climate data and weather forecasts. Meteorological Applications, 6: 301-312.

Farnsworth, C., 2000. Building for Disaster Mitigation. Home Energy, 2000, January-February: 28-33.

Fernandez, J., 2002. Diversified Lifetimes: Orchestrated Obsolescence for Intelligent Change. Thresholds, Journal Number 24, Reproduction and Production, Massachusetts Institute of Technology, Cambridge, Ma, USA.

Freeman, P. and K. Warner, 2001. Vulnerability of Infrastructure to Climate Variability: How Does This Affect Infrastructure Lending Policies? Report Commissioned by the Disaster Management Facility of The World Bank and the ProVention Consortium, Washington, DC, USA.

Government of Ontario, 2004. Emergency Management and Civil Protection Act. Emergency Management Ontario, Minister of Community Safety and Correctional Services, Government of Ontario, Toronto, Canada. Available at http://www.e-laws.gov.on.ca/navigation?file=home&lang=en

Grenier, J., 2001. The Challenge of CIP Interdependencies. Conference on the Future of European Crisis Management. Uppsala, Sweden, March, 19-21, 2001.

Holm, F., 2003. Towards a Sustainable Built Environment Prepared for Climate Change. Presentation to Global Policy Summit on the Role of Performance-Based Building Regulations in Addressing Societal Expectations, International Policy, and Local Needs. National Academy of Sciences, Washington, DC, November 3-5, 2003.

IBHS and SBA, 1999. Open for Business: A Disaster Planning Toolkit for the Small Business Owner. Institute for Business and Home Safety, Boston and US Small Business Administration. Available at http://www.ibhs.org/docs/openforbusiness.pdf

International Hurricane Centre, 1999. Weathering the Storm. In Florida International University Magazine, Spring 1999, Florida International University, Division of External Relations, Miami, Florida, USA. Available at http://news.fiu.edu/fiumag/spring_99/ihc.html

IPCC, 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Intergovernmental Panel on Climate Change Third Assessment Report, Report of Working Group II, Geneva, Switzerland.

Kharin, V. and F. Zwiers, 2005. Estimating Extremes in Transient Climate Change Simulations. Journal of Climate, 18: 1156- 1173.

Kharin, V. and F. Zwiers, 2000. Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere–ocean GCM. Journal of Climate, 13: 3760- 3788.

Klaassen J., S. Cheng, H. Auld, Q. Li, E. Ros, M. Geast, G. Li, and R. Lee, 2003. Estimation of Severe Ice Storm Risks for South-Central Canada. Report prepared for Office of Critical Infrastructure Protection and Emergency Preparedness. Meteorological Service of Canada, Environment Canada, Toronto, Canada.

Liso, K., G. Aandahl, S. Eriksen and K. Alfsen, 2003. Preparing for Climate Change Impacts in Norway's Built Environment. Building Research and Information, 31 (3-4): 200-209.

Mills, E., 2003. Climate change, insurance and the buildings sector: technological synergisms between adaptation and mitigation. Building Research and Information, 31 (3-4): 257-277.

Munich Re, 2006 . Topics Geo Annual review: Natural catastrophes 2005. Munich Available at http://www.munichre.com/publications/302-04772_en.pdf

Munich Re, 2005. Updated by Munich Re for UNFCCC COP11 events. Montreal, December 2005. Available at http://regserver.unfccc.int/seors/file_storage/uv83ms0u3xya5i2.pdf

Munich Re, 2000. 2000 Topics—Annual Review of Natural Disasters 1999 (supplementary data and analyses provided by Munich Reinsurance Group/Geoscience Research Group). Munich Reinsurance Group, Munich, Germany.

Pielke, R. and M. Downton, 2000. Precipitation and damaging floods: trends in the United States, 1932-1997. Journal of Climate, 13 (20): 3625-3637.

Planning Institute of Australia, 2004. Sustainable Regional and Urban Communities Adapting To Climate Change - Issues Paper. Planning Institute of Australia, Queensland Division, Australia.

Steemers, K., 2003. Towards a Research Agenda for Adapting to Climate Change. Building Research & Information, 31 (3-4): 291-301.

Swiss Re, 1997. Tropical Cyclones. 2201_9678, Swiss Reinsurance Company, Zurich, Switzerland.

UK Meteorological Office, 2004. Forecasting the Nation's Health. Available at http://www.metoffice.gov.uk/health/copd_forecasting.html

University of Alaska Ankorage, 2000. The Warming World: Effects on the Alaska Infrastructure. Synthesis of Workshop Proceedings, University of Alaska, Anchorage, January 5 - 6, 2000.

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*

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