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# WEATHERING OF BUILDING INFRASTRUCTURE AND THE CHANGING CLIMATE: ADAPTATION OPTIONS


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## ABSTRACT

The changing climate will impact infrastructure through gradual changes in weather patterns, increasing variability and potential increases in extremes. Although most concerns have focused on changing extremes, the changes in day-to-day weathering processes may be equally important. These significant day-to-day weathering processes that contribute to premature deterioration of structures include wind-driven rain, freeze-thaw cycles, frost penetration, wetting and drying, wind-driven abrasive materials, the action of broad spectrum solar radiation and ultraviolet (UV) radiation, and atmospheric chemical deposition on materials.

Adaptation options need to be developed to consider changing weathering processes, including more frequent freeze-thaw cycles in colder regions, potentially increased atmospheric chemical deposition, initially increasing UV levels and changes to precipitation regimes. Since buildings are particularly vulnerable to weathering impacts that compromise their durability and resilience to extremes over time, it will become increasingly important in future to ensure that building envelopes and enclosures are able to resist wind actions and to prevent moisture from entering the structure. Many of the required adaptation actions may take the form of different formulations for materials or different engineering practices to ensure greater durability standards for preventative maintenance.

***Keywords:*** Weathering, deterioration, climate change, infrastructure

## 1. INTRODUCTION

In contrast to extreme events, where the damage to infrastructure is done within minutes or days of the event, premature infrastructure failure caused by weathering or deterioration from the weather elements

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** Additional information on climate change impacts on infrastructure, adaptation options and disaster management can be found in Occasional Papers 9, 10 and 12.

usually takes months or years to become evident. Similar to the natural environment, man-made structures are also subject to erosion caused by the slower day-to-day processes of wind-driven rain, by freeze-thaw cycles, frost depth penetration, wetting and drying, erosion by abrasive materials, by the action of broad spectrum solar radiation and ultraviolet (UV) radiation, and by chemical reactions and breakdown in the presence of water, oxygen and assorted pollutants.

Some of the agents for premature deterioration of structures and their components include biological, thermal, mechanical and chemical processes. Biological agents carried by the atmosphere can result in fungi or moulds on surfaces while chemical agents in atmospheric moisture (e.g. rain or water vapour) or by direct deposition can lead to corrosion in metals or deterioration in concrete. Thermal agents (and UV radiation) change the dimensions of materials, leading to cracking and fissuring in polymer-based materials such as vinyl cladding, window frames, sealants and gaskets. Similarly, thermal stresses in the form of freeze-thaw cycles can lead to premature aging of porous materials such as stone, brick masonry and mortar. Finally, mechanical agents such as wind-driven dust or rain or rain loads themselves act as structural loads and can contribute to other weathering agents (Lacasse, 2003).

The amount of deterioration that actually results for any given material depends on the agent of deterioration (mechanical, thermal), the resilience or responses of materials or components as a result of in-service loads and the duration of the load effect. As example, thermal aging in polymers would depend on the amount of time that a material is above a threshold temperature while the deterioration of wood materials might depend on the wetting cycles.

## WEATHERING OF MATERIALS IN NORTH AMERICA

Premature weathering or deterioration of structural materials is becoming a concern in many regions, with changes in the physical and chemical environment being attributed, in part, as causal agents. Exacerbating concerns over the premature deterioration of infrastructure are issues related to aging, over-used infrastructure and accelerated deterioration as a result of changing climatic and chemical atmospheric conditions. Opportunities to address these concerns have been further limited by trends towards a steady decline in spending on public infrastructure, when rated as a share of economic activity (IPCC, 2001). In North America, for example, public spending on a broad range of new infrastructure projects represented almost 4.5% of GDP in the early 1960s, but had declined to less than 2% in the 1990s (Statistics Canada, 1999; USBEA, 1999). This reduced rate of spending on replacement and expansion of infrastructure to meet growing population and urbanization demands has resulted in a significant proportion of aging, “over-used” infrastructure that is increasingly vulnerable to selected climatic hazards (IPCC, 2001). The American Society of Civil Engineers, for example, has warned that many dams in the United States have exceeded their intended lifespans (Plate and Duckstein, 1998). More than 9,000 regulated dams have been identified as being at high risk of failing, with the result that there may be significant loss of life and property from future failures.

In many parts of North America, concerns are growing over the premature deterioration of materials such as clay brick, reinforced concrete and pavement as a result of the changing atmosphere and

**Table 1.** Potential impacts of a changing climate on the weathering of infrastructure materials.

| Examples of weathering processes likely impacted by the changing climate | Potential infrastructure impacts |
|---|---|
| • Increased freeze-thaw cycles (followed by decreases in warmest winter regions) | • Premature deterioration of concrete, pavement<br>• Roof ice damming<br>• Moisture damages |
| • Higher temperatures, increased chemical reactions<br>• More freeze-thaw cycles in cold winter climates | • Increased corrosion; above some thresholds, decreases in corrosion rates<br>• Accelerated deterioration of building facades<br>• Premature weathering<br>• Fractures and spalling |
| • More intense precipitation events<br>• Changes in timing of seasonal precipitation, rainfall, length of season for wetting of surfaces | • Increased decay processes (e.g. wood)<br>• Increased rain penetration (e.g. wind driven rain) and moisture absorption<br>• Decreased durability of materials<br>• Efflorescence and surface leaching concerns<br>• Damaged or flooded structures |

construction practices (Auld, 1999; Haas et al, 1999). Some of these accelerated weathering processes and their potential impacts from a changing climate are summarized in Table 1.

In northern latitudes, there is evidence that recent warmer winters in traditionally colder winter climates are resulting in more frequent freeze-thaw cycles and leading to potentially greater weathering of susceptible infrastructure materials such as concrete and pavement (Auld, 1999; Stutzman, 1999; Green et al, 2003). These increasing freeze-thaw cycles in cold regions (CCME, 2003) are also being implicated for enhancing susceptibility to building roof ice damming and moisture damages (Magnuson et al, 2000; Baker, 1967). Under further winter warming, it is projected that higher temperatures will influence chemical reactions, as well as influence the frequency of freeze-thaw cycles. In the coldest winter climates, initial climate warming will likely lead to increased freeze-thaw cycles, while regions with the mildest winter climates could eventually expect declines in frequencies of freeze-thaw cycles with further warming.

If this rate of deterioration of infrastructure is not addressed through adaptation actions, existing structures may become more vulnerable to the changing climate of the future. In general, the deterioration rates of materials increase with warming temperatures due to increased times of wetness and faster chemical reactions. In some materials and climates, deterioration reaches a maximum, and then is followed by a decrease in the corrosion rate as a result of a faster evaporation of moisture layers after rain and a decrease in wetness time (Lstiburek, 2002; Lacasse, 2003). Changes in the timing and spatial distributions of seasonal and annual rainfall will also change the length of time during which surfaces are wet, affecting surface leaching and the moisture balance that influences material decay processes. Accelerated deterioration of structures could also result where rainfall events become more frequent or intense, especially if accompanied by higher winds.

The impacts of the changing atmosphere on the durability of structures and their materials will vary with materials, construction practices, and regional climates. Concrete, for example, is subject to deterioration caused by absorption of moisture and thermal expansion and contraction. In cold climates, changes in daily temperatures through the freezing point or freeze-thaw cycles trigger the expansion and contraction of moisture absorbed by the concrete. The resulting mechanical action causes fractures and spalling. Airborne components, such as carbon dioxide, can cause adverse chemical reactions of concrete which can cause surface deterioration.

Saturated masonry, such as clay brick, can undergo several freeze-thaw cycles during the winter in northern climates. This action can contribute to premature deterioration of the masonry, especially if the cores of the brick units are filled with water when the wall freezes. In fact, snow and ice can prove more damaging to masonry construction than rainwater since a portion of the snow or ice melts during the day and refreezes at night, allowing the walls to undergo daily freeze-thaw cycles. Repeated wetting of the walls also increases efflorescence concerns.

### Rust and Corrosion

In the U.S. alone, industry losses due to rust and corrosion are estimated at more than $200 Billion per year (American Galvanizers Association, 1998). Rust is caused by the action of corrosive elements in the atmosphere, such as acidic fumes, sulphur particles, caustic dust, chlorine and salt collected on painted surfaces. These atmospheric corrosive elements become activated by dew and condensation, leading to rust (oxidation) processes that weaken underlying metals considerably. Temperature changes also exacerbate the problem when contraction and expansion of the structure cause surface paint to crack and split, exposing the underlying metals to the corrosive elements. While rust and corrosion effects can be minimized through sandblasting, priming and sealing, the effects of oxygen and moisture continue to weaken the integrity of structures to the point of failure.

According to a 1997 report published through the Canadian Institute for Research in Construction of the National Research Council Canada, corrosion of the reinforcing steel or rebar in concrete structures is one of the primary causes of premature deterioration of North American bridges, parking garages and other concrete structures (Gu and Beaudoin, 1997). This deterioration is particularly prevalent in areas where road salt is applied to bridge decks, highways and other road surfaces during winter weather conditions. Corrosion within reinforced concrete leads to costly repair and replacement bills. Estimates indicate that the corrosion of reinforcing steel within concrete structures such as bridges and parking garages costs North American infrastructure managers billions of dollars every year. The annual repair bill for the approximately 600 problem parking garages in Canada alone subjected to premature deterioration of concrete amount to more than $200 million per year (Gu and Beaudoin, 1997). Repairing corrosion-damaged concrete includes options such as removing unsound concrete, patching, and applying waterproofing membranes. When salt has caused the initial rebar and concrete damage, however, that salt contamination remains in the concrete, continuing to corrode the rebar.

## PREMATURE WEATHERING

Buildings are particularly vulnerable to weathering impacts over time that compromise their durability and resilience to extremes. Uncontrolled moisture accumulation in structural materials can reduce the structural integrity of building components through mechanical, chemical and biological degradation. It is the function of the building envelope, which includes the exterior walls, foundations, roof, windows, insulation, connectors, and doors that enclose the indoor environment, to separate the indoor from the outdoor environments (Bomberg and Brown, 1993). To maintain its durability over time, the building envelope needs to prevent weather elements from entering the structure and becoming trapped inside the walls, which can cause wall components to continue to decay. Durability of the building envelope and provision of the desired service life more or less assure protection of building occupants from all weather elements and systems contained within it, along with the contents.

If the building envelope fails during a storm, damage to contents typically raises the total loss by a factor of 2 to 9 over the cost of repairing the building itself (Sparks et al, 1994). Following Hurricane Andrew in August 1992 and subsequent hurricanes in recant years, for example, recommendations from the various committees that investigated the damages resulted in subsequent changes to the Florida Building code. These changes added measures that require the building envelope to remain in place and capable of protecting contents during the design extreme wind event (Minor, 1994). Other publicized cases of moisture damages from envelope failures in North America include the Vancouver condos in Canada, and the North Carolina housing units and Seattle leaky homes in the U.S.

### Leaky Buildings

It has been stated that three things destroy materials in general and wood in particular: water, heat, and ultraviolet radiation. Of these three, water is the most important by an order of magnitude (U.S. Department of Energy, 2003). Premature deterioration of the building envelope or enclosure is mostly the result of water leakage around walls and windows and represents a source of significant economic losses. The widespread failures of building envelopes in Vancouver, British Columbia and in Seattle, Washington, for example, led to greater attention and research on the building envelope. The Vancouver experience, where building enclosure failures were claimed to have reached epidemic proportions in the late 1980s and 1990s, resulted in a loss of public confidence in multi-unit residential construction. The costs of repairs for multi-family wood frame buildings or “leaky condos” in the Lower Mainland region of British Columbia alone were estimated at $1 Billion, while indirect costs were estimated at another $2 Billion (Kayall, 2001; CMHC, 1996). The Canadian Mortgage and Housing Corporation studied the damages (CMHC, 1996) and acknowledged that mild and moist climatic conditions ‘increase the likelihood of water ingress, intensifying the process of wood rot’.

In Canada, documentation on the premature failures of building envelopes in various regions of the country – notably on the West Coast, British Columbia, as well as Ontario and the Atlantic Provinces – has led to increased efforts to develop climate indices in relation to the performance of walls (Cornick and Chown, 2003). British Columbia’s envelope failures occurred in a climatic region affected by significant rainfall and mild weather. Rainfalls here vary significantly with location and distance from major mountain ranges in the British Columbia Lower Mainland area, with total annual precipitation amounts ranging between roughly 1,400 and 2,100 mm per year, mostly in the form of rain and falling between November and June. The British Columbia envelope failures were attributed primarily to "water retention within the load- bearing, external stud walls" as a result of the adoption of face sealed cladding systems which were fixed directly to the timber frame, a practice which became prevalent in the 1980's (CMHC, 1996; Kayall, 2002). In climates characterized by high rainfall and driving winds, these directly clad systems are very sensitive to failure. The investigation concluded that rain screen wall assemblies (i.e. a ventilated and drained cavity between the stud walls and external cladding) offered the most robust resistance to fungal decay and that directly clad 'stucco' finishes or exterior insulation and finish systems (EIFS) were unsuitable for use in the British Columbian coastal climate (CMHC, 1996; Lawton, 1999).

### Moisture and Temperature Impacts

A combination of high moisture content or liquid water, and high temperatures contribute to mould growth, wood decay, and metal corrosion. Other causes of deterioration include freeze-thaw cycles. Likely contributing to the growing concern over moisture issues and premature failures of the building envelope is the hypothesis that today's buildings tend to be built of materials less resistant to the presence of moisture over extended time, increasing their vulnerability. For example, thin sheets of gypsum or plywood serving as substrates behind thin veneers of cement plaster, stone, or masonry simply do not perform well when assaulted by the continuous presence of moisture. So called "barrier" systems composed of coated foam sheets or wood composites that are intended to completely stop water or moisture from infiltrating the exterior envelope rarely survive real weathering conditions (Simpson and Atkins, 2002).

Water and moisture can cause structural damage, reduce the thermal resistance of building materials, change the physical properties of materials and deform materials. Damage by moisture includes rotting of wood studs and other components, efflorescence and spalling of masonry systems and rusting of wall fasteners (Simpson and Atkins, 2002). Excessive moisture in the building envelope may affect the health of occupants directly as well as through the potential for growing bacteria and mould. In summary, moisture problems can lead to questionable structural integrity of the envelope or to an unhealthy indoor environment, each capable of rendering a building "unfit-for-use". In addition, moisture can also adversely impact other non-health and safety performance factors such as the effectiveness of thermal insulation and aesthetic appearance.

Historically, successful approaches to moisture control have followed strategies to prevent building assemblies and surfaces from getting wet from the exterior and to prevent building assemblies and surfaces from getting wet from the interior. If building assemblies or surfaces get wet, or start out wet, the strategy is to allow them to dry (Lstiburek, 2002).

Rainwater, especially wind driven, is described as the moisture source that can impact the performance of the envelope the most. A number of recent studies have concluded that the primary failure mechanism leading to moisture problems is rainwater penetration through exterior walls, windows and doors. Often, poor design and construction quality due to tighter project budgets and schedules and unskilled labour, a lack of good maintenance practices over the building's lifecycle, the use of new materials and technologies that are inconsistent with the functioning of the total structure and design practices not suitable to the climate of a region are blamed for increasing risks of rainwater penetration. In response to perceived declines in quality, several code and standards organizations in North America have established guidelines for construction and maintenance of durable buildings.

### Hygrothermal Approaches

A new discipline of engineering, hygrothermal analysis, has emerged as moisture damages have become one of the main causes of building envelope deterioration (Lstiburek, 2002). In many countries more or less sophisticated procedures for hygrothermal analysis are included in national standards or building codes, specifying the indoor and outdoor environmental conditions. Moisture engineering approaches often use the concept of limit states (limiting conditions) in specifying building durability. In structural engineering, loads and load resistance are considered and limiting states, such as deflection, are specified. A similar approach is applied to moisture or hygrothermal engineering in specifying measures to ensure better building durability. For hygrothermal analysis, rain, temperature, humidity and the interior climate are considered environmental loads with principal limiting conditions such as rot, decay, mold and corrosion. A damage function (damage process) analysis is then used to determine whether a limiting condition, such as mold growth, is achieved (Lstiburek, 2002).

Thermal regions, rain exposure zones and interior climate classes are all climatic or environmental loads that can be used to determine the moisture engineering practices needed for building envelopes and mechanical systems. Lstiburek (2002) proposes that building envelopes and mechanical systems should be designed relative to a set of hazard classes that, taken together, define the "climatic load".

Moisture accumulates in the building envelope when the rate of moisture entering the building system exceeds the rate of moisture removed from the building. When moisture accumulation exceeds the ability of the building's materials to store that moisture, problems can result. This moisture-storage capacity is a key determinant of system performance. The proper use of climate zones is key to understanding and managing moisture flow inside buildings. In all climates, building systems can get wet from the exterior via liquid flow and methods to control the flow of liquid are similar. However, the methods for controlling moisture that enters systems via air flow and diffusion differ for each climate.

Climate, location and season determine the location of air barriers and vapor barriers, pressurization vs. depressurization, and ventilation vs. dehumidification. Moisture usually moves from warm to cold (driven by the thermal gradient) and from more to less (driven by the concentration gradient). In severe cold and cold climates that dominate in Canada during heating seasons, moisture from the interior tends to flow towards the exterior by passing through the building envelope, requiring that building systems should be protected from getting wet from the interior and must be allowed to dry toward the outdoors (Lstiburek, 2002). Consequently, air and vapor retarders are typically installed toward the interior warm surfaces, and permeable materials should be used as exterior sheathings to allow moisture to escape.

In addition, relatively low moisture levels should be maintained in conditioned spaces.

Several climatic classification schemes and climate index approaches are available to guide building moisture management practices. One scheme that is used widely but remains simple to calculate is the hygrothermal climate regions for North America (Lstiburek 2002). This scheme is also simple enough to provide guidance for potential climate change implications for moisture deterioration, while giving general guidance for adaptation options.

The climatic load zones for North America used in hygrothermic practice, as shown in Figure 1 and Table 2, are broadly defined by Lstiburek (2002). These load zones are summarized in Table 2.

- **Severe Cold:** A severe-cold climate is defined as a region with approximately 8000 Fahrenheit heating degree days or greater or approximately 4450 Celsius heating degree days or more. In North America, severe cold climate regions vary in annual precipitation. Building deterioration issues include rotting roofs, drafty rooms, poor radiant comfort, ice dams, mold, wet basements, window condensation, back drafting water heaters, peeling paint, and high heating-fuel bills.
- **Cold:** A cold climate is defined as a region with approximately 4500 Fahrenheit heating degree days (2500 Celsius degree days) or greater and less than approximately 8000 Fahrenheit heating degree days (4450 Celsius degree days). Temperatures drop below 0º C in winter and snow accumulates. Building deterioration problems are similar to those for severe cold conditions, although at slightly reduced risks.
- **Mixed-Humid:** A mixed-humid climate is defined as a region that receives more than 508 mm (20 inches) of annual precipitation, has less than or approximately 4500 Fahrenheit heating degree days (2500 Celsius degree days) and where the monthly average outdoor temperature drops below 7ºC (45ºF) during the winter months.
- **Hot-Humid:** A hot-humid climate is defined as a region that receives more than 508 mm (20 inches) of annual precipitation and where the monthly average outdoor temperature remains above 7°C (45°F) throughout the year. Average monthly temperatures stay above 7°C throughout the year.
- **Mixed-Dry:** Average monthly temperatures drop below 7°C during winter months and less than 508 mm (20 inches) of rain falls annually. Building performance and deterioration issues include back-drafting, water heaters and cooling energy bills. Building issues include the need for everything in moderation.
- **Hot-Dry:** Average monthly temperatures stay above 7°C throughout the year and less than 508 mm (20 inches) of rain falls annually.

Similarly, rain exposure conditions can be further classified in its simplest form by annual rainfall totals as:

- **Extreme:** 1525 or more mm (60 inches) annual precipitation
- **High:** 1015-1525 mm (40-60 inches) annual precipitation
- **Moderate:** 508-1015 mm (20-40 inches) annual precipitation
- **Low:** under 508 mm (20 inches) annual precipitation

**Table 2.** Climatic load zones for North America used in hygrothermic practice (derived from Lstiburek, 2002).

| Climatic Zone | Thresholds |
|---|---|
| Severe Cold | • 4450 Celsius HDDs or more<br>• Temperatures drop below 0°C and snow accumulates<br>• Vary in annual precipitation |
| Cold | • 2000-4450 Celsius HDDs<br>• Temperatures drop below 0°C and snow accumulates<br>• Building deterioration similar to Severe Cold conditions, but slightly altered rates |
| Mixed-Humid | • 2500 Celsius HDDs or less<br>• More than 508 mm precipitation<br>• Monthly average outdoor temperatures drops below 7°C during winter months |
| Hot-Humid | • More than 508 mm annual precipitation<br>• Monthy average outdoor temperature remains above 7°C during winter months |
| Mixed-Dry | • Less than 508 mm annual precipitation<br>• Monthy average outdoor temperature drop below 7°C during winter months |
| Hot-Dry | • Average monthly temperatures stay above 7°C throughout year<br>• Less than 508 mm precipitation |

Under both of the classification maps shown in Figure 1, many locations in Canada would be described as Severe Cold (Prairies and North) or Cold (southern Ontario, East Coast). The Mixed-Humid zone applies to Coastal B.C. The Moisture Exposure zones range from Extreme (coastal B.C.) to Low (North) in Canada.

The rainfall exposure map is useful in practice for managing rainwater infiltration through wall strategies (Steffen, 2000). Current best practice guidelines from the Canadian Wood Council, for example, suggest that a building face seal strategy would be acceptable in low risk zones, a concealed barrier would be needed in moderate zones, a rainscreen in high zones, and pressure-equalized rainscreen in extreme rainfall zones such as found in coastal British Columbia and parts of Atlantic Canada.

## CLIMATE CHANGE AND PREMATURE DETERIORATION

As the climate warms, it is expected that heating degree day values will decrease and that the boundary between the severe-cold and cold zones will shift northwards, decreasing some risks for interior moisture risks. In a few Canadian coastal regions, the boundary of the mixed humid and the cold zones will also shift northwards, increasing interior and exterior moisture risks as some locations move into the mixed humid zone.

As illustration, consider a typical house in Ottawa, Ontario, located on the border between Ontario and Quebec. Ottawa is currently situated just inside the severe-cold hydro-thermal region with a moderate rain exposure zone, as shown in Figure 1. Best moisture control practices for this climatic zone and building use involve temperature control within several degrees and an interior relative humidity range of between 20 percent and 60 percent (preferably less). Air pressures are typically moderated within a 5 Pascal range to allow safe operation of combustion appliances and to control contaminant transport. Attic assemblies are vented.

Under the various Global Climate Model scenarios for climate change found on the Canadian Climate Scenarios Network web site (CCCSN, 2007), Ottawa is projected to make the transition from a severe cold climate zone to a cold zone. During the baseline period from 1961-90, Ottawa's Heating Degree Days or HDDs (in Celsius) averaged in excess of 4600, with moisture exposure conditions in the moderate zone. Climate change projections from the CGCM2 scenario A21 and the more GHG conserving B21 scenario indicate warming winters, with a decrease in HDDs to values between roughly 3700 and 3900 by the 2050s (**www.cccsn.ca**). Rain exposures remain in the moderate zone, although

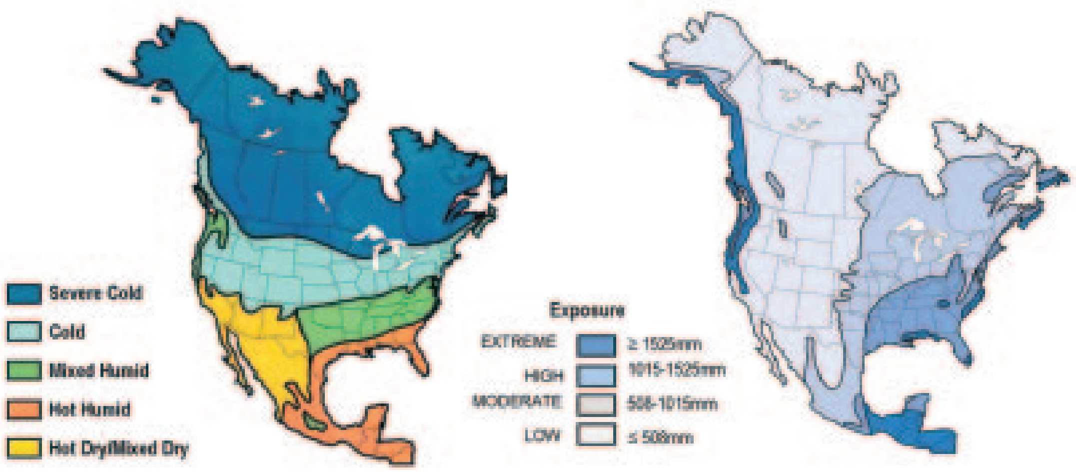


**FIGURE 1.** Hygro-Thermal Regions (Left) and Rain Exposure Zones (Right) of North America. *(Adapted from Lstiburek, 2002)*

the number of rain days is projected to increase by about 15 per cent while winter snowfall days decrease. Using mid-range GHG emission assumptions, Canadian climate model projections suggest that average temperatures will increase by 2 to 3°C by the 2050s, while winter temperatures warm by an average of 3 to 4°C. The various climate change models vary in the warming and moisture regimes projected for the future, with the potential changes strongly dependent on future global GHG emission assumptions. The results indicate that strict interior moisture management practices for cold climates will continue to be required for Ottawa, although more stringent interior moisture control is likely needed under the current climate conditions.

Figure 2 shows trends in historically observed freeze-thaw cycle frequencies for Ottawa CDA for the period 1890- 2004, based on observed temperatures that include the influence of urban heating as well as the changing climate. Analysis of the historical data indicates an increase in winter freeze-thaw cycles for Ottawa – a trend that is likely to continue with expected initial winter warming. The number of December – March freeze-thaw cycles has averaged 34.4 days for the historical period, increasing to 40.8 days when averaged over the last 20 year period from 1984-2004 and 41.6 days over the last 10 years. Adding 2°C to the recorded winter temperature variability (and record) of the past 20 years increases the frequency of freeze-thaw cycles from 41 to 45 days. Eventually, winter temperatures will warm to the point where trends in freeze-thaw cycle frequencies level off or become steady and then begin to decrease with further warming. Anecdotal observations for the Ottawa area indicate that impacts from

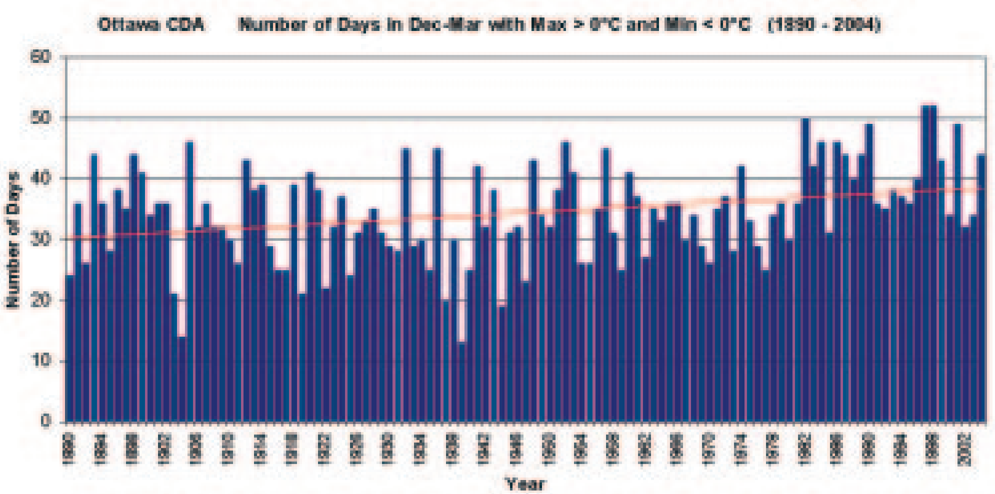


**FIGURE 2. Historical changes in mean winter (Dec-Mar) freeze-thaw cycles through 0°C for Ottawa CDA, based on historically observed temperatures. The red line indicates trends over the period of record in the number of freeze-thaw days (Dec-Mar).**

the increasing frequency of freeze-thaw cycles are increasing winter weathering of pavement surfaces and winter road maintenance challenges due to a greater incidence of ice buildups on road surfaces.

## ADAPTATION OPTIONS: CONTROLLING PREMATURE DETERIORATION OF STRUCTURES

As the climate warms, much of the southern-most populated regions of Canada that currently lie within the severe-cold zone are projected to make the transition to the cold zone. While this transition should slightly reduce some of the risks associated with interior moisture management issues, other changes in the climate could increase moisture infiltration from exterior surfaces and counter the warming benefits. For example, under climate change, the number of annual rain days is projected to increase for many southern Canada locations, with winter snowfall days for interior locations also projected to decrease. At the same time, freeze-thaw cycles may increase in cold climate zones with initial warming, likely increasing ice damming and weathering pressures on structures and materials, such as clay brick and concrete.

Preliminary studies indicate that in much of Canada, freeze-thaw cycles are happening more frequently during the year (CCME, 2003). Most of the stronger trends have been found in Ontario (Klaassen, 2001). The weakest have been in British Columbia. At Trenton, Ontario, freeze-thaw events (defined for changes from -2°C to +2°C) have been increasing at the rate of 3.2 days per decade. At Swift Current, Saskatchewan, the rate is 3.9 days per decade. An interesting exception is the city of Toronto, where freeze-thaw cycles have been decreasing or levelling and are likely influenced by urban heat effects associated with the city's growth (Klaassen, 2001).

Ice dams on buildings are caused by non-uniform roof surface temperatures and occur due to heat escaping from the house. According to Larson (1997), "there is a complex interaction between the amount of heat loss from a house, snow cover and outside temperatures that leads to ice dams." Ice dams cause millions of dollars of structural damage to houses every year, including water damage from roof leaks. There are many ways to treat the symptoms, but proper air sealing, insulation, and attic venting are the best ways to eliminate the problem.

While the frequency of freeze-thaw cycles has increased in many regions of Canada since at least 1980, freeze-thaw cycles alone do not contribute to the deterioration of bricks, concrete, roofing and other building materials. The combination of moisture with the freeze-thaw cycle is a critical factor in the weathering process. Even wind during a precipitation event becomes an important factor, as it can determine the amount of "wetting" of a vertical building surface. Other weather factors to be considered include radiation, air-borne pollutants and acid rain (although rain acidity has been on the decline since the 1970s). The weathering process is further complicated when, for example, we have a combination of the weathering factors acting at the same time. For example, materials can be irradiated after having been wet by precipitation or even when they have high moisture content as a result of high atmospheric relative humidity.

## Effective Moisture Control

Effective moisture control within the building envelope is essential if the service life of the structure is to be realized. A study by the Norwegian Building Research Institute estimates that three-quarters of all building damages registered in Norway resulted from water and moisture infiltration and the health costs associated with problems from moulds, etc. (Liso, 2001). These results, in effect, impose a requirement for durability over the service life of the building, where any loss of function over the service life of a structure may result in health costs (e.g. moulds) as well as infrastructure no longer able to resist extreme events.

One key to avoiding moisture problems is to keep the drying time of buildings as short as possible. Another key to avoiding moisture problems is to control moisture entry. In cold climates that dominate many regions of Canada, adaptation requires that building systems should be protected from getting wet from the interior and must be allowed to dry toward the outdoors. In addition, relatively low moisture levels should be maintained in conditioned spaces (Lstiburek, 2002). As southern regions of Canada warm, many locations will make the transition from severe-cold hygrothermal climate zones to cold hygrothermal zones, which should slightly reduce interior moisture damage risks.

General water management strategies have been articulated into a set of design principles called the 4Ds (Table 3): deflection, drainage, drying and durable materials. These strategies are briefly summarized in Table 3. With respect to rain penetration control, deflection refers to design elements and details that deflect rain from the building minimizing rainwater loads on the building envelope. Drainage, drying and durable materials are principles that deal with the management of water once it has reached or penetrated the envelope. Building design patterns that incorporate the drainage principle include pitched roofs and sloped surfaces at horizontal elements. Drainage also needs to collect incidental moisture accumulation in the wall assembly and return it to or beyond the exterior face of the cladding by means of gravity flow, usually in a plane between the cladding and the sheathing. Drying allows wall assemblies to remove moisture accumulations by venting and vapour diffusion. The drying potential of both the cladding and the wall sheathing/framing must be considered and cavities introduced for drainage purposes must also offer a means to dry the cladding material by back venting (Steffen, 2000).

## The Changing Atmosphere and Weathering

Many of the changing climate weathering processes will also be acting in concert with changing solar UV radiation. Of the solar wavelengths, the UV-B component is particularly effective in damaging synthetic building materials such as plastics and natural materials such as wood and rubber (Andrady et al, 2003). Any further depletion of the stratospheric ozone layer and resulting increase in UV radiation levels will tend to decrease the service life of such susceptible materials. At the same time, the changing climate is likely to increase weathering processes through increased temperatures and increased absolute humidity. Both of these increases, particularly the higher temperatures, will tend to accelerate the rate of photo-degeneration of materials and shorten service life. Adaptation approaches that are

**Table 3.** Summary of building water management and adaptation strategies (4Ds).

| Building water management strategy | Design and adaptation options |
|---|---|
| Deflection | • Design elements and details that deflect rainwater |
| Drainage | • Management of water once it has penetrated the envelope<br>• Pitched roofs, sloped surfaces at horizontal elements<br>• Collect water and moisture accumulation in wall assembly (gravity flow) |
| Drying | • Management of water once it has penetrated the envelope<br>• Venting and water diffusion<br>• Cavities introduced in cladding for drainage and drying<br>• Back venting |
| Durable materials | • Management of water once it has penetrated the envelope<br>• Consider drying potential of materials (e,g, cladding) |
| Combined with solar UV radiation | • Radiation damages materials (UV-B most effective)<br>• Works in combination with other weathering processes, especially moisture<br>• Different formulations for plastics, surface protection technologies |

available to reduce the damaging impacts of UV radiation consist of different formulations for plastics (light-stabilizer technologies), more light resistant grades of plastics and the use of surface protection technologies for wood.

The relationship between atmospheric weathering processes, solar radiation, building materials, maintenance schedules and structures is complex and in need of further study. 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, as the climate warms, future building materials, structures and building enclosures will need to withstand changed climatic loads. 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.

## DISCUSSION AND CONCLUSIONS

Weather and climate affect many aspects of building durability and performance, with the result that future changes in climate are expected to affect much of the existing and future building stock. A number of climate change factors are likely to have an impact on building deterioration on different time and length-scales. Many of these change factors will increase or accelerate weathering of structures while other factors will decrease weathering risks. Many of these changing weathering processes will be also acting together with changing solar UV radiation and more intense and frequent rainfall events and wetting times.

The environmental and economic benefits of increasing the durability of structures and their components are significant. A durable building, for example, provides a long period of time to amortize the environmental and economic costs that were incurred in building it. Durable products and materials do not need to be replaced or repaired as frequently as less durable ones, requiring less investment in raw materials, energy, and environmental impacts and spreading their costs and environmental impacts out over more time. Inevitably, long-term durability is a function of the quality of design, construction, operation and maintenance of a building. To achieve durability, quality assurance is essential at every stage in the life of the building or structure and its operation. In future, regions where weathering processes are increasing along with costs for repairs may need to consider implementation of maintenance standards.

More work is needed to determine the impacts of the changing atmosphere on materials and infrastructure. While the evidence is not clear, there are indications that many aspects of a warmer climate will increase weathering processes. Unfortunately, there are, as yet, few completed studies focussing on the possible impacts of climate change on the built environment, including the durability of its structures and materials. More studies are needed to better understand the extent to which existing buildings and structure will be able to meet future climate change challenges and to guide decisions on the implementation of adaptation measures to increase their level of reliability.

An immediate benefit of studies on the impacts of climate change is that the building industry itself may become more aware of the need for local climate adaptation to both the variability of the existing climate and to future changes. At the same time, studies on climate influences on structural and materials durability are likely to lead to reviews and improvements to current construction practices. In many cases, the implementation of adaptation measures for durability are also likely to provide co-benefits in the form of reduction of GHGs. Measures that better control moisture problems in structures, for example, often improve energy efficiency while also extending the durability of the structure and reducing the embodied energy inherent in the structure over its lifecycle.

## References

American Galvanizers Association, 1998. Available at http://www.galvanizeit.org/

Andrady, A.L., H.S. Hamid and A. Torikai, 2003. Effects Of Climate Change And UV-B On Materials. Photochemical and Photobiological Sciences, 2: 68–72.

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., D. MacIver and J. Klaassen, 2006b. Adaptation Options for Infrastructure under Changing Climate Conditions. In Proceedings of Engineering Institute of Canada Climate Change Technology Conference, Ottawa, May 2006. Updated as Occasional Paper 10, 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.,1999. Adaptation to the impacts of atmospheric change on the economy and infrastructure of the Toronto-Niagara Region. In B. Mills and L. Craig (eds.) Atmospheric Change in the Toronto-Niagara Region: Towards an Integrated Understanding of Science, Impacts and Responses. Proceedings of a workshop, May 27-28, 1998, University of Toronto. Environmental Adaptation Research Division, Waterloo, Ontario, pp. 103-121. Baker, M., 1967. Ice on Roofs. Canadian Building Digest, CBD-89, Institute for Research in Construction, National Research Council, Ottawa, Canada.

Bomberg, M. and W. Brown, 1993. Building envelope and environmental control: issues of system integration, Journal of Thermal Insulation and Building Envelopes, 17: 5-12.

CCCSN, 2007. Canadian Climate Scenarios Network. Environment Canada web site. Available at www.cccsn.ca

CCME, 2003. Climate, Nature, People: Indicators of Canada's Changing Climate. Climate Change Indicators Task Group, Canadian Council of Ministers of the Environment, Winnipeg, Manitoba.

CMHC, 1996. Survey of building envelope failures in the coastal climate of British Columbia. Vancouver. Canada Mortgage and Housing Corporation. Ottawa, Canada.

Cornick, S. and G. Chown, 2003. Defining Climate Regions as a Basis for Specifying Requirements for Precipitation Protection for Walls NRCC-45001. Canadian Commission on Building and Fire Codes, National Research Council of Canada.

Green, M., A. Dent and A. Bisby, 2003. Effect of freeze-thaw cycling on the behaviour of reinforced concrete beams strengthened in flexure with fibre reinforced polymer sheets. Canadian Journal of Civil Engineering, 30: 1081-1088.

Gu, G. and J. Beaudoin, 1997. Research on Cost-Effective Solutions for Corrosion Prevention and Repair in Concrete Structures. Construction Canada, 39(6): 36-39.

Haas, R., N. Li and S. Tighe, 1999. Roughness Trends at C-SHRP LTPP Sites. Roads and Transportation Association of Canada, Ottawa, Canada.

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.

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

Kayall, D., 2001. The Role of the Building Envelope Professional in the Aftermath of Vancouver's Leaky Condominium Crisis. Proceedings for Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes. Clearwater Beach, Florida, December 2-7, 2001.

Klaassen, J., 2001. Analysis of thaw-freeze cycles at Canadian locations in the 20th century. Environment Canada-Ontario, Internal report. Toronto, Canada.

Lacasse, M., 2003. Durability and performance of building envelopes. NRCC-46888. Institute for Research in Construction, National Research Council Canada.

Larson, T., L. Hendricks and P. Huelman, 1997. Ice Dams. University of Minnesota Extension Service. Minnesota, U.S.

Lawton, M.D., 1999. Reacting to durability problems with Vancouver buildings, In 8th International Conference on Durability of Building Materials and Components, Vancouver, Canada, May 28 - June 3, pp. 989-999.

Liso K., 2001. Effects of Climate Change on Built Environments. Cicerone 5/2001, Centre for International Climate and Environmental Research, Oslo, Norway.

Lstiburek, J., 2002. Moisture Control For Buildings, NREL Report No. 33288. ASHRAE Journal, February 2002, 44(2), 36-41.

Magnuson, J., D. Robertson, B. Benson, R. Wynne, D. Livingstone, T. Arai, R. Assel, R. Barry, V. Card, E. Kuusisto, N. Granin, T. Prowse, K. Stewart, and V. Vuglinski, 2000. Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science, 289: 1743-1746.

Minor, J., 1994. Windborne Debris and the Building Envelope. Journal of Wind Engineering and Industrial Aerodynamics, 53: 207-227.

Plate, E. and L. Duckstein, 1998. Reliability-based design concepts in hydraulic engineering. Water Resources Bulletin, 24(2): 235-245.

Simpson, G. and J.B. Atkins, 2006. AIArchitect. American Institute of Architects, 13, February 3, 2006. Available at http://www.aia.org/aiarchitect/thisweek06/0203/0203bp_envelope.cfm

Sparks P., Schiff S. and Reinhold T. 1994. Wind damage to envelopes of houses and resulting insurance losses. Journal of Wind Engineering and Industrial Aerodynamics, 53:145-155.

Statistics Canada, 1999. Canadian Economic Observer: Historical Statistical Supplement. Statistics Canada, Ottawa, Ontario, Canada.

Steffen, M., 2000. Moisture and Wood-Frame Buildings. Building Performance Series No. 1. Canadian Wood Council Ottawa, Ontario, Canada.

Stutzman, P., 1999. Deterioration of Iowa Highway Concrete Pavements: A Petrographic Study. NISTIR Report 6399, December 1, 1999, National Technical Information Service, U.S. Department of Commerce, Virginia, USA.

USBEA, 1999. National Income and Product Accounts, Survey of Current Business. United States Bureau of Economic Analysis, Washington, DC, USA.

U.S. Department of Energy, 2003. Introduction to Building Systems Performance: Houses That Work II. Office of Energy Efficiency and Renewable Energy, National Technical Information Service, Springfield, Virginia, USA.

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