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Durability and Climate Change—Implications for Service Life Prediction and the Maintainability of Buildings

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Abstract: Sustainable building practices are rooted in the need for reliable information on the long-term performance of building materials; specifically, the expected service-life of building materials, components, and assemblies. This need is ever more evident given the anticipated effects of climate change on the built environment and the many governmental initiatives world-wide focused on ensuring that structures are not only resilient at their inception but also, can maintain their resilience over the long-term. The Government of Canada has funded an initiative now being completed at the National Research Council of Canada's (NRC) Construction Research Centre on "Climate Resilience of Buildings and Core Public infrastructure". The outcomes from this work will help permit integrating climate resilience of buildings into guides and codes for practitioners of building and infrastructure design. In this paper, the impacts of climate change on buildings are discussed and a review of studies on the durability of building envelope materials and elements is provided in consideration of the expected effects of climate change on the longevity and resilience of such products over time. Projected changes in key climate variables affecting the durability of building materials is presented such that specifications for the selection of products given climate change effects can be offered. Implications in regard to the maintainability of buildings when considering the potential effects of climate change on the durability of buildings and its components is also discussed.

Keywords: buildings; building components; building elements; climate change; degradation; durability; maintainability; service life prediction

1. Introduction

Sustainable building practices are rooted in the need for reliable information on the long-term performance of building materials; specifically, the expected service-life of building materials, components, and assemblies. This need is ever more evident given the anticipated effects of climate change on the built environment and the many governmental initiatives world-wide focused on ensuring that structures are not only resilient at their inception but also, can maintain their resilience over the long-term.

In this paper, climate resilience pertains to the ability of a building material, component or element to maintain its function if subjected to the effects of climate loads as may occur in the future under different climate change scenarios as compared to those effects arising from loads sustained under current historical climate conditions.

To provide context to the implications for the durability and maintainability of buildings as may be affect by changes in the climate in the future, it is useful to first gain an appreciation of the expected global climate change and thereafter some measure of the climate change of Canada, given that this study focuses on a Canadian perspective. Thereafter, a brief review of the impacts of climate change on buildings is provided as a framework in which the NRC research program on climate resilient buildings is described and thereafter, a review is given of literature pertinent to the degradation of building materials components and elements arising from the effects of climate change.

1.1. Global Climate Change and the Climate Change of Canada

There is evidence around the globe, perhaps also evident in every day weather, that the climate is changing much more drastically than recorded in the past, and the expectation is that climate change will continue into the foreseeable future. Historically observed and projected future global temperature changes based on different emission scenarios are given in Figure 1. The extent of global warming (°C) as provided in this figure is relative to the fifty year period spanning 1850–1900.

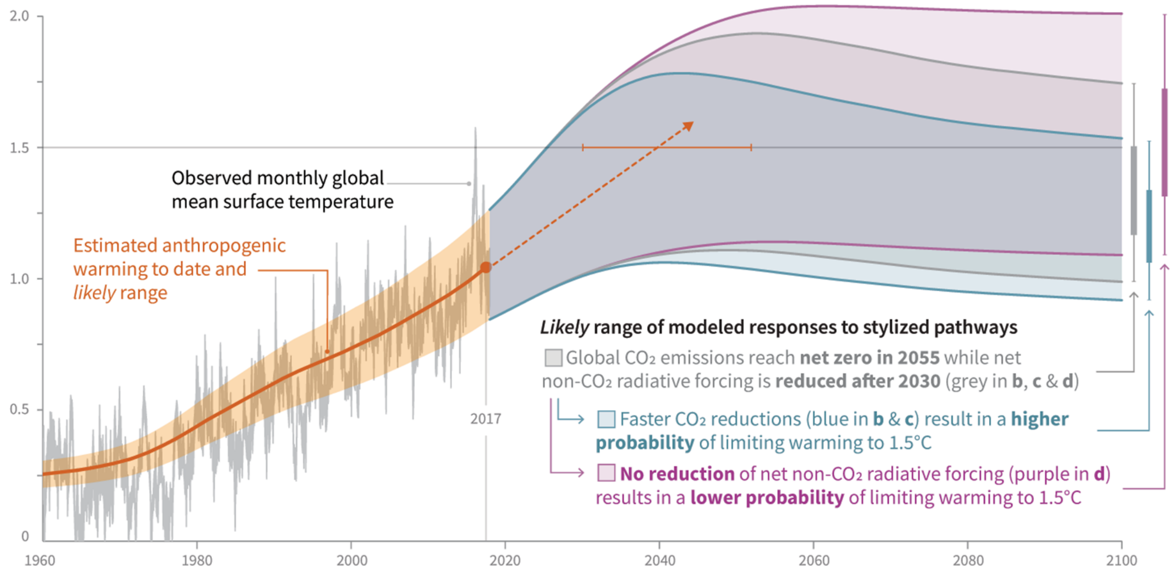

Figure 1. Observed and projected global temperature change based on different emission scenarios; global warming is relative to 1850–1900 (°C) [1].

The overall monthly global mean surface temperature is given, as is the estimated anthropogenic warming to date (in orange tint); the likely temperature range from anthropogenic warming is also provided. The orange dashed line that begins in 2017 projects increases in global warming in the future and indicates that the historically recorded rate of warming global temperatures are projected to increase by 1.5 °C or more in the future. Global warming could be kept at 1.5 °C level provided the CO_2 emissions are gradually reduced to net zero levels. Furthermore, the more rapidly emissions are reduced, the greater the likelihood that by 2100, global temperatures will be maintained at a 1.5 °C increase. The grey portion of the figure that stretches beyond 2017 shows the projected range of warming if CO_2 emissions are mitigated systematically following select "stylized anthropogenic emission and forcing pathways". Whereas, the blue curve shows the resulting effects on temperature change should reductions in CO_2 emissions reach net zero by 2040, the grey curve shows the scenario when the CO_2 emissions reach net zero by 2055. Finally, more rapid CO_2 emission reductions (grey and blue curves) suggest a higher chance of limiting warming to 1.5 °C than the purple curve that represents no decline in CO_2 emissions after 2030 and results in a lower likelihood of limiting warming to 1.5 °C.

Likewise, the climate of Canada is evidently warming, as shown in Figure 2 [2]. The figure shows time series of recorded average annual temperatures across the country that has fluctuated from year to year over the 1948–2018 period. The linear trend indicates that annual temperatures averaged across the nation have warmed continuously during this period adding up to a total warming of 7 °C over the past 71 years. The national average temperature for 2018 (January to December) was 0.5 °C above the mean temperatures over the 1961–1990 period, highlighting significant warming even in the recent decades.

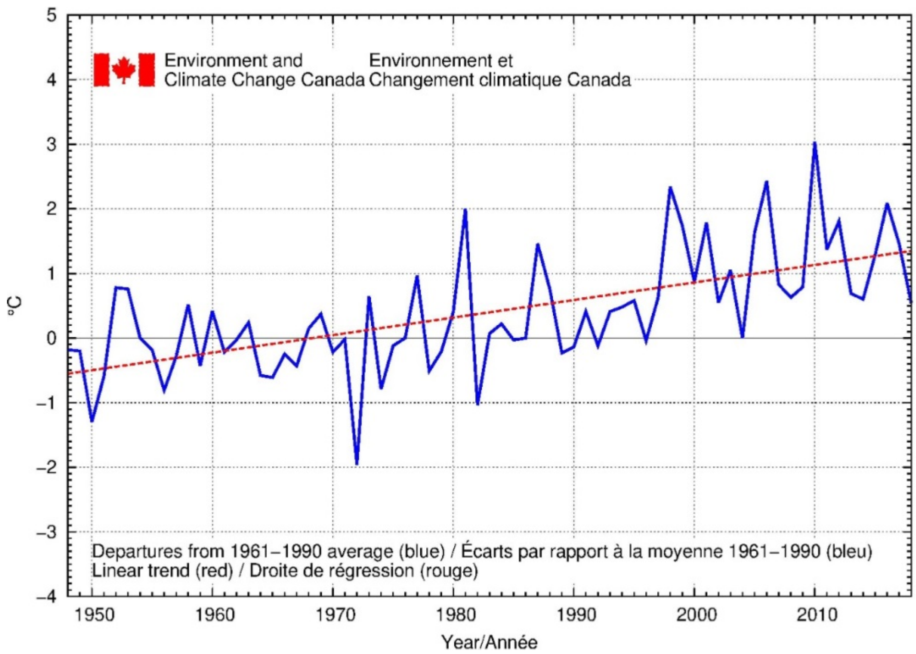

Figure 2. Nationally averaged annual temperature anomalies with reference to recorded temperatures over 1948–2018 [2].

The spatial temperature departures map, provided in Figure 3, shows that the Yukon, most of the Northwest Territories, as well as parts of Nunavut and British Columbia experienced temperatures above the baseline average in 2018, whereas, for some locations of Northern Quebec, temperatures were well below the baseline average. Annual temperatures were generally near the average recorded temperatures over 1961–1990 in the remainder of the country.

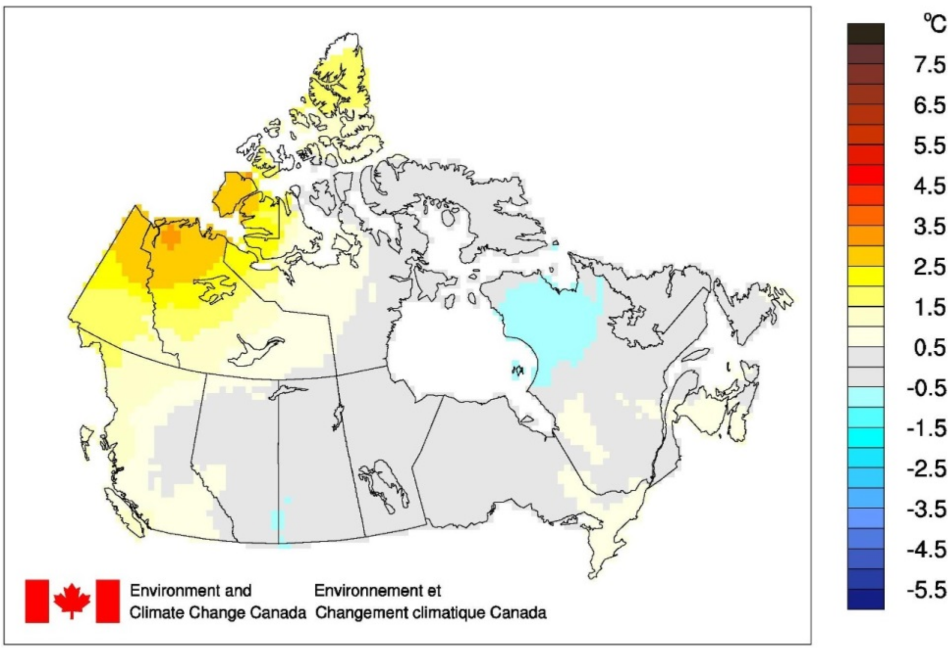

Figure 3. Spatial distribution of temperature departures for 2018 from the 1961–1990 average [2].

1.2. Climate Change and Impacts on Buildings

The primary driver for climate change produced directly by human activities is greenhouse gas (GHG) emissions. Of course, other natural climate determinants such as terrestrial, solar planetary, and orbital effects all affect the global climate. Nonetheless, given the presence of ever increasing amounts of GHG emissions to the atmosphere, climate change is upon us to the extent that there are to be expected changes, depending on the geographical location, in mean values for the primary climate variables that include: temperature, precipitation, humidity, solar radiation and wind speed. Additionally, the variability from mean values of these climate parameters is also expected to increase [3].

In Figure 4, a schematic is given that attempts to depict the complexity of the interrelation amongst climatic factors affecting buildings, land and coastal systems, and the degradation of the environment arising from the potential effects of climate change. This was adapted from that provided by de Wilde and Coley [3]. Buildings provide environmental separation between the outdoor environment, which is subject to the effects of climate change, and the indoor environment to ensure building occupants reside in healthy, comfortable, and functional dwellings. In Figure 4, from left to right, information is provided on: (i) climate change as a driving force; (ii) the environmental effects of climate change that pertain to buildings; and, (iii) the possible impact of those environmental effects on buildings.

As such, it is apparent that changes in mean values for the primary climate variables such as, temperature, precipitation, humidity, solar radiation and wind necessarily arise from natural climate determinants (i.e., solar planetary, terrestrial, orbital), but as well, from man-made greenhouse gas emissions that are driving changes to the future climate. Such changes will also affect the variability of the climate and this is revealed by the anticipated environmental effects in the future where the frequency and severity (duration and intensity) of extreme climate events will increase. Together with these effects, there will be a gradual change in the means of climate variables such as temperature, and an associated rise in sea levels given the warming temperatures.

What are the associated impacts on buildings, as may arise from these various environmental effects? There is anticipated, for certain locations in Canada, increases in the frequency, intensity and duration of precipitation events as well as increase peak wind loads and the frequency of occurrence of extreme winds. Hence, it is clearly expected that extreme wind-driven rain events will be more prevalent in the future. As such, the exterior of the building will be subjected to more intense climate loads of longer duration that will, in turn, increase the risk to premature degradation of building elements, such as roof, wall and fenestration systems, and as well, the risk of water entry of building elements, resulting in moisture-related problems.

Increases in global temperatures will bring about decreases in heating loads, as evident by reductions in heating degree days, and increases in cooling loads, in particular in urban agglomerations where heat island effects may prevail over the summer months. Lack of attention to extreme heat events may bring about overheating in buildings that, in turn, increases health risks to the vulnerable portion of the population such as the elderly, the sick and physically challenged, and the very young. In respect to the operation of buildings, there may be mismatch in the capacity to cool or heat buildings, depending on the season, that could bring about energy-use inefficiencies.

The general climate attributes associated with climate changes as may affect buildings have been known for decades. Hence, the need for climate resilience in buildings is apparent from the number of relevant tools, practices, and guides for increasing the climate resilience of new and retrofit buildings. A few notable examples include: the Public Infrastructure Engineering Vulnerability Committee (PIEVC) assessment protocol [4], the Institute for Catastrophic Loss Reduction (ICLR) Home Builder's Guide to promote the construction of disaster-resilient homes [5], the US Department of Housing and Urban Development (HUD) Climate Change Adaptation Plan [6], and the US Green Building Council's report, Green Building and Climate Resilience [7]. Common to all these resources is providing useful and practical information on how the climate will affect buildings in the future as may arise from a warming climate.

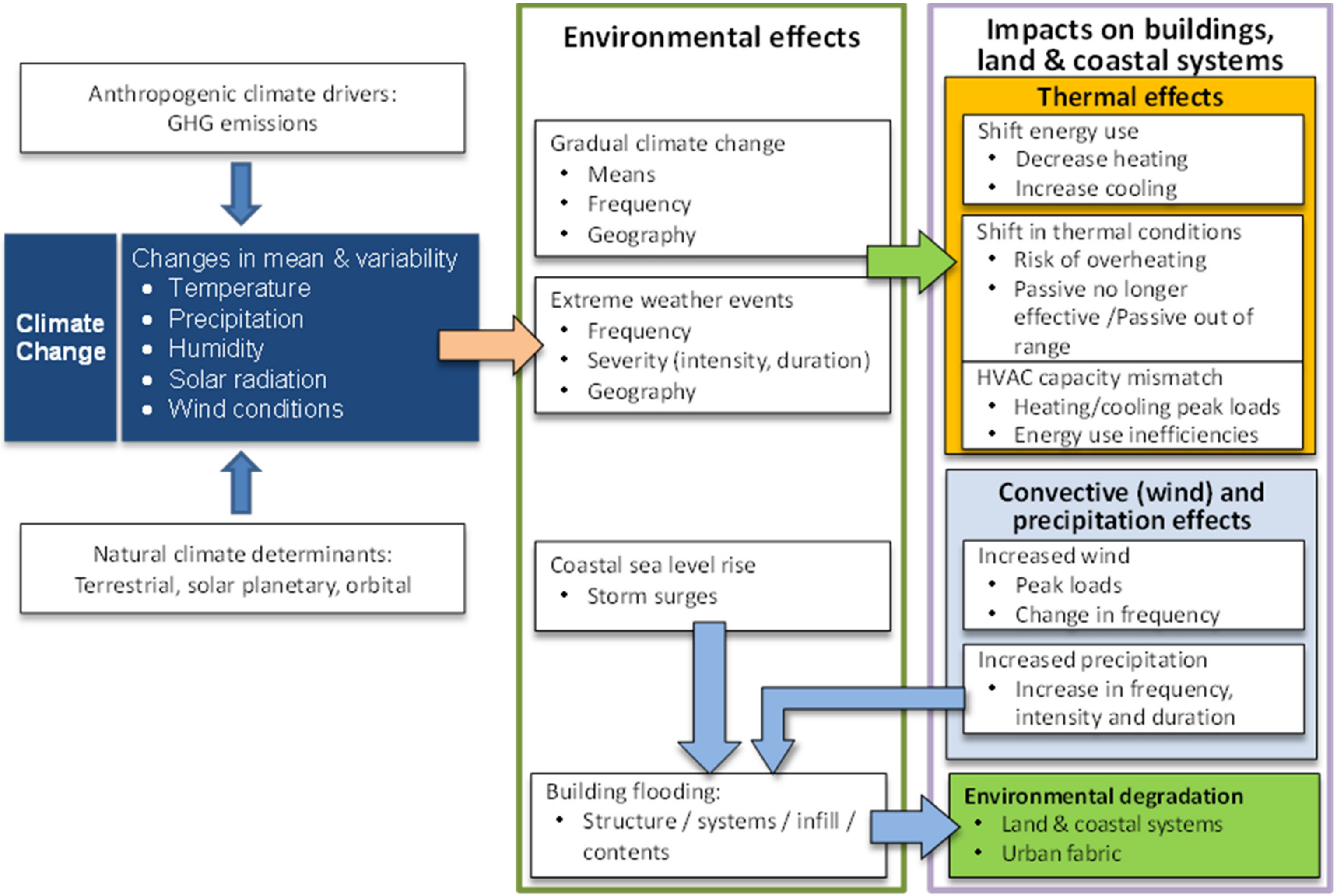

Figure 4. Climate change and impacts on buildings; adapted from [3].

There are also a number of well-developed approaches for the Wildland–Urban Interface (WUI) in North America, including the National Fire Protection Association wildland standards [8], the International Code Council WUI Code [9], as well as standards for buildings on floodplains [10].

Given the past activity globally in respect to mitigating the effects of climate change, what recent Canadian projects have been initiated to permit preparing the built environment for the expected increases in temperature, humidity, precipitation, wind as may arise from climate change? This is discussed in the next sub-section.

1.3. Research Program on Climate Resilient Buildings

The National Research Council of Canada (NRC) has also embarked on a research program related to buildings and climate change, more specifically, a project related to climate-resilient buildings and core public infrastructure [11]. Apart from the many different elements of this project, a key component is the development of climate design data based on different expected climate change scenarios [12]. Access to this climate data will permit determining the resilience of existing building structures, or new buildings, to expected climate change loads when comparing the response of building enclosures to historical loads. This will allow for mitigating any significant changes in response through adoption of suitable building design measures to reduce the risk to premature degradation and from which will evolve a guide to building enclosure design for existing building structures [13]. It will also permit developing hazard maps for different types of building products that will provide practitioners with information on the increased risk to degradation evaluated in relation to local climate conditions.

As part of the NRC research program, there was interest in knowing what previous work had been carried out on the durability of building envelope materials and building elements in respect to expected changes to the climate in the future. A concise summary is provided in Section 2 of previous work as has been completed on climate resilient building materials, components or elements, such as wall and roof assemblies. In regards to the durability of building envelope materials, brief accounts are given of works related to concrete and wood product degradation, the corrosion of metals; and the degradation of plastics due to the effects of solar radiation. Thereafter, studies on the durability of building envelope systems are reviewed for which the frost decay of masonry wall systems and the degradation of wood frame, roof and wall assemblies are briefly described.

In the subsequent section (Section 3), a discussion on the projected changes in key climate variables affecting durability of building materials and on climate issues as may affect durability and service life estimates of building materials and components is given, as this permits suggesting measures for the maintainability of buildings and selection of construction products for climate resilient design (Section 4).

2. Climate Resilient Buildings—Durability of Building Envelope Materials and Elements

The process of weathering of materials at the building exterior leads to their degradation that, in turn, leads to an increase in the rate and severity, of degradation over time [14]. In respect to the effects of climate change, it is unlikely that new mechanisms of degradation will develop. However, the changing climate will affect the built environment through steady changes in weather, increasing variability of and extremes in climate conditions [15]. The significant daily processes of weathering that contribute to premature degradation of the exterior of structures include wind-driven rain, temperature fluctuations, freeze–thaw cycling, frost effects, wetting and drying of porous materials, the action of solar and ultraviolet (UV) radiation, and chemical deposition on metals from the atmosphere.

A number of studies related to this topic specific to the Canadian context have been completed by Auld et al., [16–19]; to briefly summarize: given that buildings are in particular, vulnerable to the effects of weathering that degrade their durability and resilience to extremes conditions over time, it will become increasingly important in the future to ensure that building enclosures are able to resist wind-driven rain and to prevent moisture from penetrating the assembly.

In instances where it is projected that significant increases in degradation rate are to arise, adaptations to the building fabric may be required. In the context of climate change and existing buildings, adaptation is a means to further protect the existing building fabric, to enhance performance and control the rate of degradation. In regards to new buildings in a changing climate, design of buildings must be adapted to consider performance for both current and future climates. As such, building standards and building codes need to be revised to permit consideration of the effects of future climate on building design.

2.1. Selected Studies on Durability of Building Materials and Climate Change

Given that climate change is a global phenomenon, its effects on the durability of materials and building elements has, likewise, been studied broadly and in several countries. Some of the studies that have been carried out in the past decade relate to the effects of climate change on the durability of different materials and building elements, including: wood products, metals directly exposed to the environment (as opposed to imbedded metals), and plastic building products.

2.1.1. Concrete Degradation—Carbonation and Corrosion

(i) Concrete carbonation—increases in CO_2 concentration, and changes in temperature and relative humidity (RH), as my arise from a changing climate over the long-term, will accelerate the degradation processes and consequently, cause a decrease in, serviceability and durability and possibly the safety of reinforced concrete (RC) infrastructure. Peng and Stewart [20], report on an investigation of carbonation-induced degradation of RC under a changing climate for three cities located in China (Kunming, Xiamen and Jinan). A time-dependent analysis was conducted using Monte Carlo simulation, and included the uncertainty of climate projections, deterioration processes, material properties, dimensions and accuracy of the predictive models. Deterioration of RC structures in these cities was represented by the probabilities of initiation and occurrence of damage of reinforcement due to corrosion. It was found that by 2100, the mean depths for carbonation of the RC could increase by up to 45% for RC structures located in these cities due to a changing climate. It was also found that in temperate or cold climate locations in China, climate change can cause an additional 7–20% of carbonation-induced damage of RC buildings by 2100. Such findings permit development of climate adaptation strategies through consideration of improved RC design of structures to ensure their resilience over the long-term.

(ii) Concrete corrosion—Saha and Eckelman [21], report on investigating the effects on RC structures resulting from corrosion through increases in carbonation and chlorination rates. Different climate emission scenarios and (respectively, IPCC A1FI (high) and B1 (low)) were used together with downscaled temperature projections and code-compliant material specifications to model carbonation and chloride-induced corrosion of RC structures in the Northeast United States. Based on these results, it is expected that current RC construction as a result of climate change, will experience depths of penetration that exceed the current code-recommended cover thickness; in respect to the depth of chlorination, this would occur in 2055 and by 2077 for the depth of carbonation. The projected timeline is well within the expected service life of these buildings, indicating the potential for extensive repairs during the building service life.

2.1.2. Degradation of Wood Products

Although few studies have been completed regarding the durability and risk to degradation of wood products used in wood frame building construction, Lisø et al. [22] provided a highly useful overview of the decay potential in wood structures when subject to projected future changes in climatic conditions in Norway. The work consisted of developing a national climate index map that allows for geographically climate-differentiated guidelines for use of protective and preservation measures (e.g., impregnation, surface treatment or design precautions) for wood building elements. Based on this work, it is anticipated that in a changing climate, the vulnerability of wood frame structures in

Norway will increase given that climate change in this country is seen to increase the risk of decay of wood structures. The use of such mapping tools has permitted the development of technical guidelines for wood-based building enclosures, thus allowing a designer to consider both protective design and the preservative treatment of wood in relation to the expected projected climate conditions.

2.1.3. Corrosion of Metals

In Australia, as reported by Trivedi et al. [23], work undertaken by the Commonwealth Scientific Industrial Research Organisation (CSIRO), has shown that new metal structures are expected to last at least 50 years and well past 2064. As such, the effects of climate change must be considered in design and material selection, specifically in regard to changes in climate that increase the rate of corrosion of metal components. From this study, an estimate was provided of the greatest expected change in the rate of corrosion for the year 2070. Changes in corrosion were estimated for 11 coastal and inland locations in Australia. For each station, the climatic data in 2070 was estimated by modifying current data with probable changes based on two global climate models (i) the Meteorological Research Institute model [24]: (MRI-CGCM 3.2.2; most likely median model), and; (ii) the CSIRO model (CSIRO-Mk 3.5 dry climate model). For both models, a high global warming rate was assumed and with a GHG emissions scenario of intensive use of fossil fuel technology (i.e., A1FI scenario). The climatic data was then run through a corrosion "predictor" (a multi-scale process model) to predict corrosion at each location. The predictor revealed a moderate decrease in corrosion at inland locations but a substantial increase in coastal locations. The reduction in corrosion at inland locations was associated with a reduction in RH (i.e., surface wetness), whereas for coastal locations, the increase in corrosion was related to a greater build-up of salt due to fewer rain events.

Tidblad [25] reports on the prediction of atmospheric corrosion of metals in Europe based on climatic parameters derived from climate change scenarios for 2010–2039 and 2070–2099, using chloride deposition data from the project on 'Global Climate Change Impact on Built Heritage and Cultural Landscapes' [26]. For Europe, the future projected atmospheric corrosion of metals show that corrosion is governed by the effects of chloride deposition in coastal and near-coastal areas as is evident from maps portraying the corrosion of carbon steel and zinc. In extreme cases, the change can be as high as an increase in one corrosivity category and the corrosion can be higher than the highest values currently being experienced in Europe for coastal areas of Southern Europe. It is supposed that the reasons for increased coastal corrosion and reduced inland corrosion in Europe are similar to those as were found for Australia.

2.1.4. *Effect of Solar Radiation on Plastics*

Increased solar ultraviolet radiation (UV) reaches the surface of the Earth as a consequence of a depleted stratospheric ozone layer and changes in factors such as cloud cover, land-use patterns and aerosols. Increased levels of UV radiation, especially at high ambient temperatures, are well-known to accelerate the degradation of plastics, rubber and wood materials, thereby reducing their useful lifetimes in outdoor applications. As climate change is expected to result in a 0.9–5.4 °C increase in average temperature by the end of this century, depending on location, this indicates that the degradation of plastics due to exposure to solar radiation will only increase in the future. The useful lifetimes of plastics used routinely outdoors are ensured generally using light-stabilized chemical additives. Although the increased damage to materials due to an increased UV-B (280–315 nm) component in solar radiation reaching the Earth is not well known, such effects can be offset through the use of different approaches; e.g., light-stabilization technologies, surface coatings or, substitution of materials having an enhanced resistance to UV radiation. It is expected, then, that product manufacturers will take measures to ensure the stability of plastics in light of probable increases in UV-B and projected increases in ambient temperature, as may arise in the coming years due to climate change [27].

2.2. Hygrothermal Performance of Building Envelope Systems Affected by Changes in Wind-Driven Rain Loads Arising from Climate Change

The hygrothermal performance of building envelopes to future projected wind-driven rain loads has seldom been investigated in the past, although wind-driven rain and its consequence on buildings has been explored in many studies [28–32]. Only a few studies have been found to comprehensively assess the hygrothermal performance of building enclosures under future projected wind-driven rain loads. These included studies related to the frost decay of masonry cladding materials and the risk to degradation of wood frame, roof and wall assemblies in Sweden; each of these is briefly summarized in the subsequent sections.

2.2.1. Frost Decay of Masonry Materials

Different parts of Europe will necessarily experience different changes in the climate parameters that affect the masonry of heritage buildings. Grossi et al., from the UK [33], indicates that from the point of view of protection of the built heritage, a range of techniques have been developed to interpret climate data in terms of the risk of frost damage and provide meteorological parameters to guide plans for future management of heritage buildings. Emphasis has been placed on the way in which small changes in temperature can be amplified and have large effects on the phase change of moisture within materials where the freeze–thaw effect is a process in which a phase change occurs at an exact temperature. Thus, subtle increases in temperature, even of a few degrees, might positively affect porous building stones. Accordingly, Europe was mapped and divided into areas where the number of freeze–thaw cycles was mapped to which heritage buildings are subjected in a changing climate. From this effort, areas could be identified for likely increases or decreases in the frequency of freeze–thaw events. Thus, Europe is most likely to remain a temperate climate in the future and as such, the effects of temperature and temperature fluctuations on masonry materials are likely to diminish. Consequently, it may be expected that porous stone, as is typically used in monuments, located in future temperate climate zones may be less vulnerable to the degradative effects of freeze–thaw action and temperature change.

It has been shown [34] that the relative risk of degradation due to the effects of frost on porous masonry materials exposed to different climates can be expressed using a simple index incorporating information about the number of freezing events and the total 4-day rainfall occurring prior to freezing for the different months of the year. The index was based on multi-year records of daily air temperatures and rainfall data. The principal advantages of this method are that results are based on readily available series of long-term climate data.

Hygrothermal simulation models of external building envelopes incorporating calcium silicate brick (a frost-sensitive material) were shown to reproduce degradation due to frost action in winter months in the Netherlands [35] as compared to onsite degradation assessments. This model was used to predict frost behavior of such bricks in the future arising from a changing climate. Degradation of masonry and mortar materials caused by frost requires that the average temperature in the material be lower than the freezing point of water, whilst the moisture content of the masonry and mortar should be higher than the capillary saturation point. As such, frost damage may occur if a long-duration rain event is immediately followed by a severe frost given that the length of time over which rain will permeate the masonry will necessarily affect the moisture content. The results from simulations show a reduction in future risk of frost damage by 70%.

2.2.2. Degradation of Wood Frame, Roof and Wall Assemblies

Brischke and Rapp [36] have reviewed the potential impacts of climate change on wood deterioration. Their published work focuses on the effects of global warming and corresponding moistening on the durability of wooden building components. With the use of a mathematical wood decay model an attempt was made to quantify the influence of climatic changes on wood decay rates for various climate change scenarios. The decay model was based on both laboratory and experimental work for which climatic data, wood temperatures, wood moisture contents and decay rates recorded for several years across Europe were correlated. Examples of such predicted changes were provided for specific sites located in Sweden (Uppsala), Germany (Freiburg), the UK (Portsmouth), France (Bordeaux) and Croatia (Zagreb). The results showed that warming and humidification will lead to a significantly reduced service life in wooden building components under climate change. It was further determined that the quantity of climate-induced changes strongly depended on the geographic location and the present climate.

The effects of climate change on the moisture performance on building facades of common wood frame wall constructions in Sweden was assessed in Nik et al. [37]. To do so, the response of a building façade was assessed under historical (1961–1990) and future climates. Two different future time-frames—2021–2050 and 2071–2100—were analyzed. The climate simulated by the RCA3 regional climate model was considered to assess the impacts of climate change. The heat–air–moisture (HAM) simulation model, WUFI, was used to simulate hygrothermal response of building facades in historical and projected future climates. The moisture accumulation in the building façade was assessed for five cases: (a) when three different sets of atmospheric boundary conditions from GCMs were used to simulate regional climate in the RCA3 regional climate model; (b) when three different initial conditions were used to initialize the simulations in the regional climate model; (c) when the regional climate is simulated at two different spatial resolutions—25 and 50 km; (d) when two different methods of calculation of wind-driven rain loads were considered; and e) two different façade materials were considered. The results from the study pointed to an increased risk of moisture-related damage in building facades in Sweden as a consequence of climate change. In addition to this, uncertainties associated with differences in spatial resolutions of the regional climate model were found to be the highest among the five cases analyzed. Another important conclusion of this study was that detailed wind modelling around the buildings was not necessary to accurately model climate change impacts on moisture performance of the buildings in Sweden.

The hygrothermal performance and mould growth potential of a typical and three modified attic constructions in Sweden under potential climate change effects were evaluated in Nik et al. [38]. The historical and future projected climate were obtained from the climate simulations made using the RCA3 regional climate model. Three representative concentration pathways of future greenhouse gas concentrations were considered for analysis. The response of attics to climate was simulated using a whole building heat, air and moisture modelling software, HAM-Tools. The study found future increases in mould growth potential in Sweden as a consequence of future projected climate change. Among the three adaptive designs investigated, the attic with mechanical ventilation was found to be most resilient to the projected climate change effects.

Future projections of climate are associated with uncertainty that can stem from the existence of a wide range of climate models, different downscaling methods, and so on [39]. To account for this uncertainty, typically, a large ensemble of future projections is considered to assess the potential effects of climate change. However, given the computational and time constraints in assessing hygrothermal response under a large ensemble of climate scenarios, it is important to develop methods that can be used to encompass climate-related uncertainty in climate change assessments on buildings. In this regard, Nik [39] quantified the amount of uncertainty encompassed when typical and extreme climate data based on—(a) outdoor dry bulb temperature, (b) equivalent temperature, and (c) rainfall—are selected, and compared it with the uncertainty communicated by the entire ensemble of climate projections. The results of the study indicated that representative typical and extreme projections selected based on the simulated outdoor dry bulb temperature are able to capture the range of hygrothermal responses projected by the entire ensemble of climate projections.

Nik et al. [40] demonstrated that three representative years—typical downscaled year (TDY), extreme cold year (ECY), and extreme warm year (EWY)—selected based on outdoor temperature, are able to capture the range of simulated energy response of the buildings when exposed to long-term (30-year) climate. To demonstrate the approach, several synthesized weather data were created for two European cities: Geneva and Stockholm, considering two RCMs (RCA3 for Stockholm and RCA4 for Geneva), six GCMs (two for Stockholm and four for Geneva) and three emissions pathways (RCP 4.5 and RCP 8.5). Two different building models were exposed to the complete set of historical and future projected climate data, as well as to the climates of selected typical, and extreme warm and cold years. Based on the findings of the study, it was concluded that TDY, ECY, and EWY together are able to capture climatic variations present in the long-term climate, as well as reflect the climate uncertainties from the use of multiple scenarios.

2.3. Summary—Of Building Envelope Materials and Elements

As is evident from that reported in the previous sections, studies have been conducted at various locations around globe that serve their respective countries. In respect to climate change in Northern European countries (i.e., Sweden, Norway), wood degradation is of importance given the predominant use of wood as a construction material. Whereas, the effects of freeze–thaw action on stone and brick masonry materials is more relevant to other European countries where the use of such materials in construction are preferred. In countries such as Australia, where the use of metal roofing is common, corrosion of this roofing component is evidently of importance. To summarize:

- Carbonation of RC in three Chinese cities (Kunming, Xiamen and Jinan) is predicted to increase by 45% by 2100; based on model results of carbonation and chloride-induced corrosion of RC structures located in the Northeast United States, the depths of chloride penetration of these structures will exceed the current code-recommended cover thickness by 2055, and by 2077, the depth of carbonation.
- In Europe, the future projected atmospheric corrosion of metals (carbon steel and zinc) show that corrosion is governed by the effects of chloride deposition in coastal and near-coastal areas; hence, it is foreseen that in the future, corrosion of exposed metals in Europe will increase in coastal zones and decrease inland; similar results were obtained from an Australian metal corrosion predictor that revealed a moderate decrease in corrosion at inland locations but a substantial increase in coastal locations.
- Europe was mapped for the number of freeze–thaw cycles to which heritage buildings will be subjected in a changing climate; Europe is most likely to remain a temperate climate in the future and as such, freeze–thaw effects related to temperature fluctuations and rainfall on masonry materials are likely to diminish; in the Netherlands, results from simulations show a reduction in the future risk of frost damage by 70%
- Warming and humidification will lead to significantly reduced service life in wooden building components under climate change in Europe; examples of predicted changes were provided for specific sites located in Sweden, Germany, the UK, France and Croatia.
- Norway developed a national climate durability index map for risk to degradation of wood products; in a changing climate, the vulnerability of wood frame structures in Norway will increase, as will the risk of decay of wood structures; likewise
- In Sweden, under projected future WDR loads, the amount of water accumulated in the façade of common wood frame wall constructions was projected to increase in the future; the attics of wood frame homes in Sweden are projected for increases in mould growth potential in the future.

3. Discussion on the Durability of Building Materials as Influenced by Climate Change Effects

The discussion first focuses on the magnitude the anticipated effects of climate change for key climate variables such as projected changes to January and July temperatures, total precipitation and average wind speeds under globally averaged warming of 2 °C and 3.5. Thereafter, consideration is given to climate-related effects that will affect the outcome of service life prediction estimates, including an estimation of reliable future WDR loads and their spatial distribution, and, methods as may be used to encompass climate uncertainty. Each of these is discussed in turn.

3.1. Projected Changes in Key Climate Variables Affecting Durability of Building Materials

In Canada, a large fraction of today's infrastructure has been designed using climatic design values calculated from historical climate data without taking into consideration potential impacts of climate change. In other words, an inherent assumption has been made that past extremes will represent future conditions. To design climate-resilient infrastructure, projected future changes in climate will need to be estimated as accurately as possible and reflected in the climatic design values. These design values will also need to be regularly updated to reflect the advances in climate sciences, and climate model development. Additionally, it will be important to determine appropriate return periods for when the data should be recalculated.

Projected changes in temperature-related climate design values at 659 locations identified in Table C-2 of the National Building Code of Canada (NBCC) [41] and S6.1–14 Commentary on CSA S6-14, Canadian Highway Bridge Design Code [42], are presented in Figures 5 and 6. The figures contrast the consequences of two global warming (GW) scenarios, leading to 2° and 3.5° increases in globally averaged temperatures. The changes presented are averaged across a 31-year time-period and show differences between a historical time-period, i.e., 1986–2016, and future time-periods when select levels of globally averaged warming are projected to be reached. According to ECCC [43], a 31-year averaged globally averaged warming of 2° and 3.5° will be reached at future (center) years of 2049 and 2077, respectively.

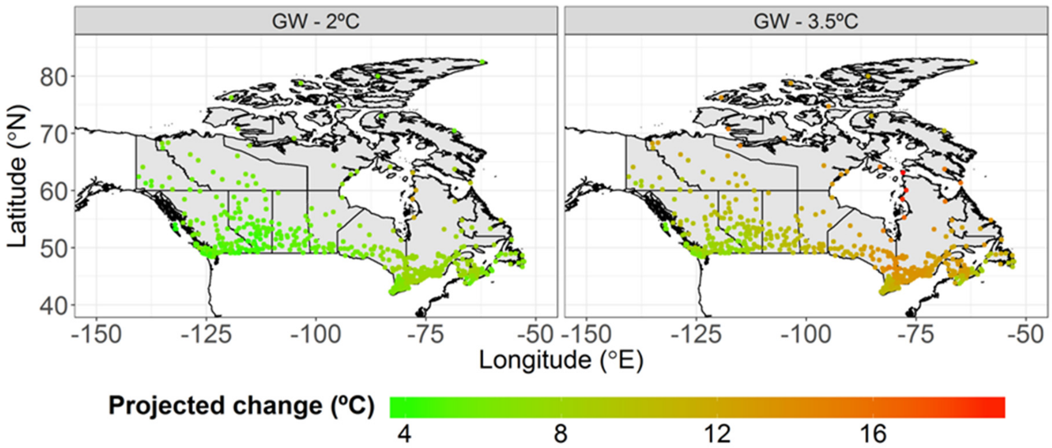

Figure 5. Projected changes in January 1% design temperatures in Canada under globally averaged warming of 2 °C and 3.5°.

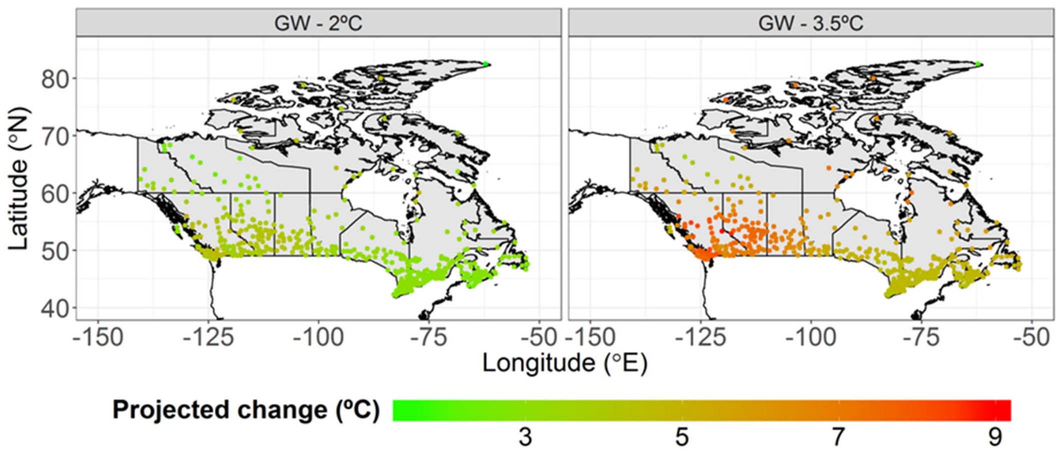

Figure 6. Projected changes in July 2.5% design temperatures (dry) in Canada under globally averaged warming of 2 °C and 3.5°.

The results clearly demonstrate significant increases in January 1% and July 2.5% (dry), temperatures across Canada as a consequence of climate change. The most significant increases are projected for the northernmost regions of Canada. More significant increases in the summertime design temperatures are projected for western regions of Canada than for eastern regions. On the other hand, more significant increases in wintertime design temperatures are projected for eastern regions of Canada than for western regions. As expected, more significant changes are projected under the 3.5 °C global warming scenario than the 2 °C global warming scenario.

In addition to temperatures, climate change is also expected to bring considerable shifts in other key climate variables that affect the durability of building materials. Projected changes in total precipitation and average wind speeds, as simulated by the Canadian Regional Climate Model, CanRCM4 under 2 °C and 3.5 °C global warming scenarios across Canada are presented in Figures 7 and 8, respectively. Higher precipitation totals have been projected for all parts of Canada with the highest increases projected for the northernmost regions. As projected in the case of temperatures, higher precipitation increases have been projected for higher levels of global warming i.e., under 3.5 °C global warming scenario than, for instance, under a 2 °C global warming scenario. However, the sign of change is more uncertain in the case of wind speeds as a larger fraction of the Canadian landmass is projected to have increases in the future as opposed to decreases in wind speeds.

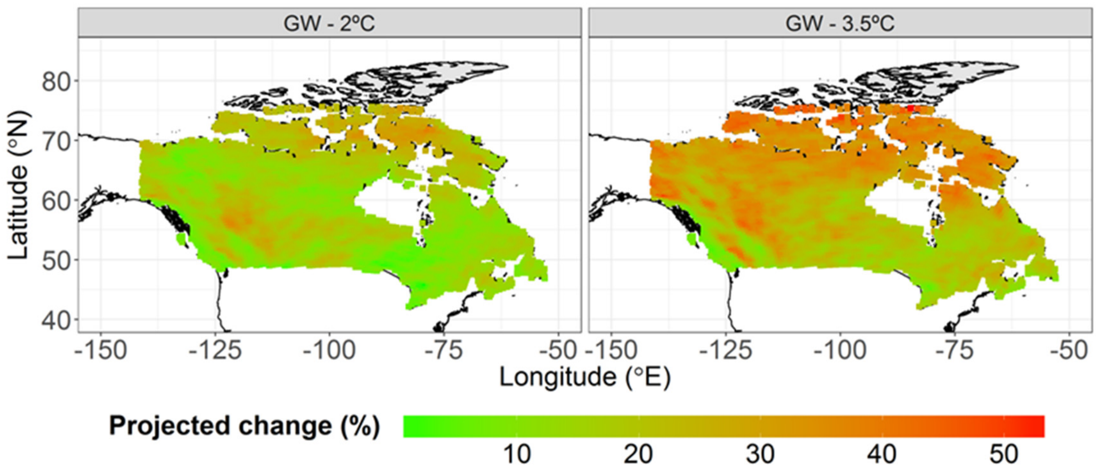

Figure 7. Projected percent changes in total precipitation across Canada under globally averaged warming of 2 °C and 3.5°.

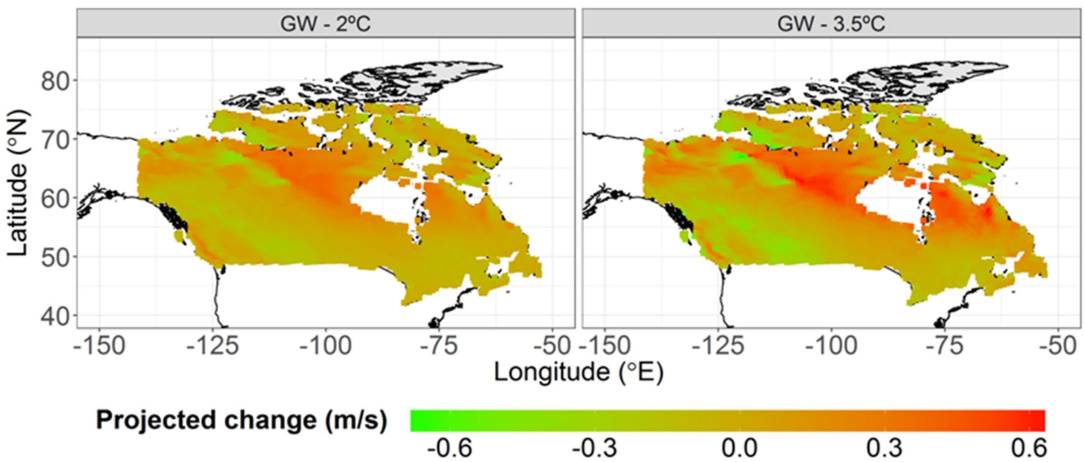

Figure 8. Projected changes in average wind speeds across Canada under globally averaged warming of 2 °C and 3.5.

The above results highlight that buildings across Canada will be exposed to a climate that is expected to be remarkably different from that observed historically during their design life. Therefore, when considering the durability of buildings and their materials and elements, durability evaluations should account for the non-stationarity in climate loads.

There are, indeed, uncertainties associated with the future projections of climate as contributed by the many global climate models developed by climate groups across the globe, different approaches to downscale the climate projections, and range of future emission scenarios in accordance with which the projections are made. Since, however, uncertainty in design data is accepted as a part of construction codes and standards, it should be possible to account for multiple sources of uncertainties associated with future impacts of climate change by reflecting them, for example, in the choice of novel safety factors in building design which take into account the inherent uncertainty in design data. These issues are discussed in the subsequent sub-section.

Although the information presented in these figures for projected values of wind speed, precipitation, winter and summer design temperatures, and heating degree days under different global warming scenarios provides an estimate of the order of magnitude of the expected effects of climate change, it has still to be determined exactly how such information is to be presented in the NBC and how practitioners are to use the additional information to affect design decisions.

3.2. Consideration of Climate Issues as May Affect Durablity and Service Life Estimates

Consideration should be given to two issues as related to climate that will affect the outcome of service life prediction estimates. These include the estimation of reliable future WDR loads and their spatial distribution, and methods as may be used to encompass climate uncertainty

(i) Reliable estimation of future WDR loads and their spatial distribution: The climate simulations in the GCMs and RCMs are performed at 100–300 km and 25–50 km spatial resolutions, respectively. Climate variables such as wind and rainfall, and their extremes, are not accurately simulated at this spatial resolution as their propagation mechanisms are influenced by local geophysical factors that are not resolved in the GCMs or RCMs. Several studies have used very-high-resolution (sub-4 km) limited-area climate models to simulate these climate variables more accurately [44–47]; however, such simulations are computationally expensive. There is a need to devise a strategy to obtain reliable long-term estimates of wind and rainfall variables which can facilitate more accurate assessment of building response to the effects of climate change.

(ii) Methods to encompass climate uncertainty: Future climate projections are associated with uncertainty contributed by a wide range of sources such as the choice of GCMs, greenhouse gas emission scenarios, downscaling methods, bias-correction methods [48]. Additionally, climate change impact assessments are performed at time-periods spanning at least 20 years or more. Hygrothermal simulations are computationally expensive and it is impractical to evaluate hygrothermal performance of wall assemblies over time-periods in excess of 20 years, and under a wide array of climate simulations. To reduce the computational costs, it is important to develop methods that can be used to encompass climate-related uncertainty and identify representative climate years/scenarios without compromising on the range of projected changes. Nik [39], for example, obtained an acceptable range of hygrothermal response when only typical and extreme climate projections were used for performing hygrothermal simulations as opposed to the entire set of future projections available. The concept can also be extended to choose the reference years that represent typical and extreme WDR conditions and only consider those years for hygrothermal simulations.

4. Maintainability of Buildings and Selection of Construction Products for Climate Resilient Design

The expectation is that in the coming decades, the general climate of Canada is to become warmer, with some locations experiencing more intense and frequent rain events of longer duration, thus producing heightened wind-driven rain loads. Hence, the atmosphere is not only likely to be warmer but also more humid; however, structural wind loads may increase but only in the far northern latitudes and not likely in current urban areas. What guidance can be offered building practitioners in respect to building maintainability and the selection of construction products to achieve climate resilient performance over the service life of the building?

The maintainability of buildings and related performance indicators have been thoroughly reviewed and conceptually defined by Asmone et al. [49] in a "Green" building context, that is, buildings conforming to the precepts of sustainability whilst accommodating environmental, economic and societal requirements. Maintainability, as opposed to the action of the maintenance of buildings relates to the ability to forecast maintenance costs over the expected life cycle (service life) of the building. Hence, the need for the use of life cycle costing tools, together with service life planning to develop a viable maintenance plan. The "Green" building trend has gained momentum in recent years and it has increasingly been considered as a means of addressing concerns over climate change and the effects of global warming on buildings and their occupants [50]. Such approaches now also include life cycle environmental assessment tools whereby the environmental impact of specific construction design and product choices can be known and considered in the overall service life plan. Nonetheless, in regards to mitigating the effects of climate change, there is little specific information that has been made available relating to the maintainability of buildings over the long-term, irrespective of the availability of rating tools for "Green" building or the development of performance indicators to help achieve highly sustainable and maintainable building projects.

Given that revised climate data that accounts for projections of climate change are not yet available what information can be provided to expert practitioners in respect to the selection of products for new buildings or for the retrofit of existing buildings? Considering that the construction of new buildings and renovation of existing buildings cannot be halted and given the available research on this topic, some recommended specifications for the selection of products arising from climate change effects are provided in Table 1. Two aspects related to the expected climate change effects are considered; those that relate to an increase in: (i) global warming, and (ii) wind-driven rain loads. The notional specifications for selection of products and methods of installation are provided for each of the two aspects in terms of the specific environmental agent acting to cause degradation. For example, should global warming be the anticipated effect arising from climate change for a specific location of interest, then it is expected that higher temperatures and a broader overall range of both annual and diurnal temperature change will occur for that location. Accordingly, one ought to specify dimensionally stable products having a lower coefficient of thermal expansion, thus providing a reduced overall daily and annual dilation; e.g., amongst several possible choices of window frame products, the selection of plastic fenestration components has the lowest coefficient of thermal expansion when directly exposed to solar radiation. Additionally, components should be specified with compatible thermal expansion coefficients to ensure that interaction between components does not also increase the risk to degradation of the assembly.

Global warming will also accelerate the aging process of products directly exposed to solar radiation and the exterior environment due to more prolonged periods of higher temperature and from exposure to higher levels of UV-B radiation. Products such as roofing and cladding components, insulted glass units, plastic fenestration components, polymer-based waterproofing and sheathing membranes, jointing and sealing products, paints and coatings for cladding and comparably exposed components would also be subject to accelerated aging. As such, only products of proven and heightened resistance to heat aging and UV radiation ought to be specified.

Likewise, guidance is provided in Table 1 for specifying products where there is an expected increase in wind-driven rain loads. In this instance, one would expect higher average humidity conditions within windows and door frames, and openings in which the components are installed with an increased incidence of liquid moisture being in prolonged contact with fenestration products. Hence, specification for these types of products would require dimensionally stable products that resist prolonged exposure to both heat and moisture, and more robust design for the installation of such products in wall assemblies. Furthermore, metal products must be resistant to corrosion given that they may be in contract with moisture.

Table 1. Notional specifications for the selection of products given climate change effects.

Climate Change Effects	Environmental Agents	Notional Specifications for Selection of Products, Methods of Installation
Increase in global warming	Higher temperatures and broader overall range of both annual and diurnal temperature change	Dimensionally stable and compatible products having lower coefficient of thermal expansion thus providing a reduced overall dilation (e.g., for: plastic fenestration components directly exposed to solar radiation)
		Products having enhanced elasticity and are resistant to repeated movement cycles (e.g., when considering jointing and sealing products)
	Accelerated aging process due to more prolonged periods of higher temperature and from exposure to higher levels of UV-B radiation	Products of proven and heightened resistance to heat aging and UV radiation (i.e., for products directly exposed to solar radiating and exterior environment, e.g.,: roofing, and cladding products, IG units; plastic fenestration components; polymer-based waterproofing and sheathing membranes; jointing and sealing products, paints and coatings for cladding and similar exposed components)
Increase in wind-driven rain loads	Environmental conditions within window and door frame and in installation openings having higher average humidity conditions together with increased incidence of liquid moisture in more prolonged contact with fenestration products	Select the more robust design approaches that enhance drainage of water from surfaces and minimise the likelihood of retention of water in interstitial spaces (e.g., for: wall assemblies and for window design and installation)
		Dimensionally stable products when wetted and having enhanced resistance to hydrolysis (i.e., degradation from contact with warm liquid water) (e.g., for: insulation products used to ensure continuity of thermal resistance at wall-window and door interfaces; polymer-based waterproofing and sheathing membranes; jointing and sealing products)
		Metal product components having enhanced resistance to corrosion after being wetted (e.g., roof, cladding, window frame, window ties, brick ties products)

5. Summary

A brief overview has been provided related to climate change effects on the durability of building materials and building elements. This overview attempts to provide some perspective on the magnitude of the effects and how such changes in climate variables will affect the durability of building materials and building elements in the coming years. The weathering and degradation of various building materials have been discussed and examples of recent studies are provided that relate to frost decay of masonry materials, the degradation of wood products and concrete elements, the corrosion of metals, and the effect of solar radiation on plastics.

In the final section, the development of climate change design data is reviewed whereby examples are given of expected changes in climate design data (e.g., wind speed; precipitation; design temperatures) for two climate change scenarios. The information presented in these figures for different global warming scenarios provides an order of magnitude of the expected effects of climate change. It has yet to be determined exactly how such information is to be presented in the NBC and how practitioners are to use the additional information to affect design decisions. Irrespective of how such information is to be implemented in the NBC, when considering the durability of buildings and their materials and elements, durability evaluations should account for the non-stationarity of the future climate.

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