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Climate Change Projection and Its Impacts on Building Façades in Singapore

Lup Wai Chew [1], Xian-Xiang Li [2,3] and Michael Y. L. Chew [1,*]

[1] College of Design and Engineering, National University of Singapore, Singapore 117559, Singapore
[2] School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou 510060, China
[3] Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai 519000, China
* Correspondence: bdgchewm@nus.edu.sg

Abstract: Singapore is one of the most populous countries, and the majority of the population stays in high-rise public flats. In 2021, there were about 1.1 million public residential units, of which 79% were above 20 years old. The number of incidents of falling objects from a height has been increasing due to the aging and deterioration of buildings. The Periodic Façade Inspection (PFI) regime was enacted in 2020 to mandate façade inspections for all buildings above 13 m and exceeding 20 years old. However, the relatively new PFI regime has not considered the potential impacts of climate change on building façades. In this paper, the common root causes of façade defects that can be impacted by climate change are first identified. Based on the climate projection in Singapore to 2100, Singapore is expected to experience a higher mean temperature, a higher rainfall intensity, more extreme rainfall events, and a higher wind gust speed. Overall, these changes in the climate pattern will accelerate corrosion or degradation, material fatigue, adhesion failure, biological attack, and humidity or dampness. The impacts of climate change on vertical greeneries are also discussed. This paper provides a first insight into the key concerns to focus on for the future revision and improvement of the PFI regime to incorporate climate change impacts on façades.

Keywords: climate change; façade inspection; falling objects; building maintenance; facility management; public safety

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1. Introduction

Buildings are inseparable from modern human lives, as people spend about 90% of their time indoors [1,2]. Urbanization has not only sprawled horizontally, where lands are cleared and buildings are erected, but also vertically, where we continue to build taller and taller buildings, especially in land-scarce cities [3,4]. With the unprecedented rate of urbanization, the field of building maintenance and management has been growing in both research and applications [5–7]. One of the major areas in building maintenance and management is building inspection for defects and fault detection. Comprehensive reviews on building inspection are available in the literature [8–11]. Visual inspection remains the most common approach for building inspection [8]. However, visual inspection has limitations, as it is subjective and prone to human errors, time-consuming, and cannot detect hidden defects [12]. Advanced technology such as 3D laser scanning, infrared thermography, photogrammetry and remote sensing, digital image processing, and machine learning can aid visual inspection and decision making [8,13].

Singapore is a small island nation with a land area of about 700 km^2, located near the equator, as shown in Figure 1. Being one of the most densely populated countries in the world, Singapore has a building stock consisting mostly of high-rise buildings, with a population of 5.45 million in 2021 [14]. Eighty percent of Singapore's population lives in public residential units, which are mostly high-rise flats [15]. Figure 2 shows the number of public residential units in Singapore since 2000. The total number of units exceeded

1.0 million in 2016 and reached about 1.1 million in 2021. The percentage of units above 20 years old (indicated by the numbers above the bars) has been steadily increasing, from 44% in 2000 to 79% in 2021. With the aging and deterioration of buildings, there has been an increase in the number of incidents of falling objects from a height in Singapore [16]. Figure 3 shows two example cases of falling objects from a height from public residential buildings in Singapore [16].

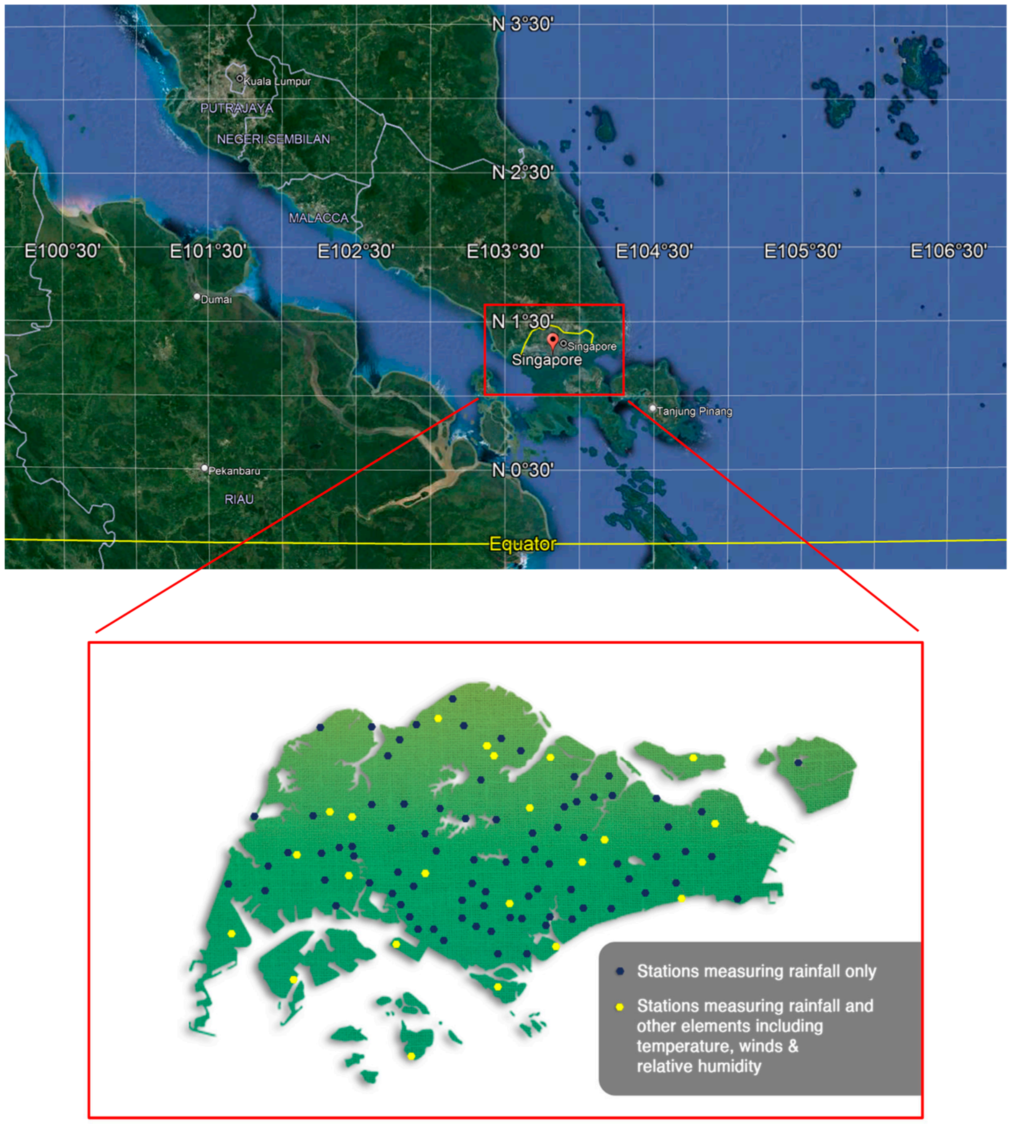

Figure 1. The location of Singapore as seen from Google Earth. The inset shows the distribution of weather stations in Singapore (image reproduced with permission from the website of Meteorological Service Singapore [17]).

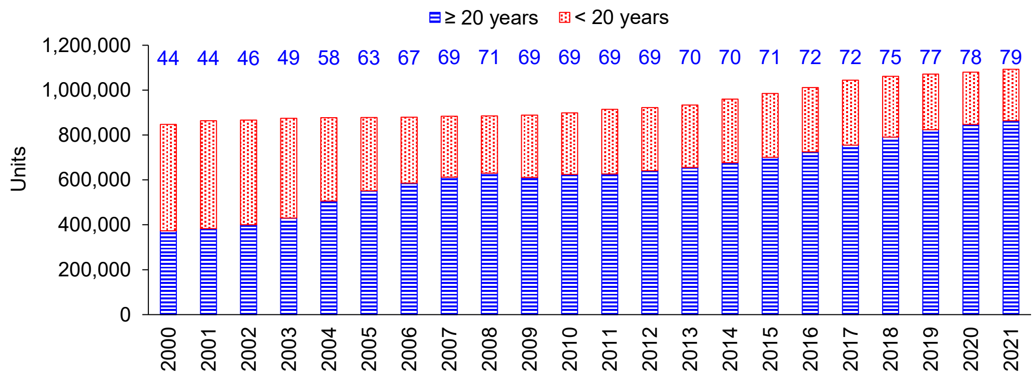

Figure 2. Number of public residential units under the management of Housing and Development Board Singapore above (blue) and below (red) 20 years old. The numbers in blue indicate the percentage of units above 20 years old.

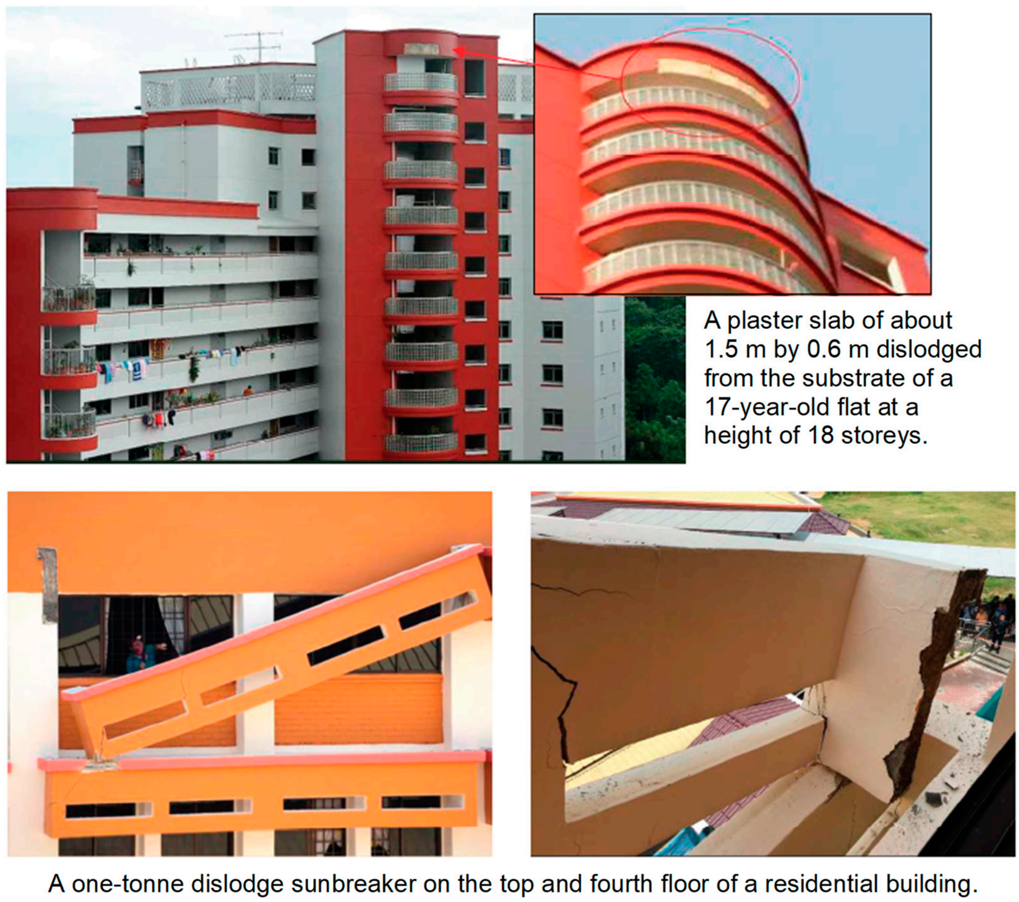

Figure 3. Two cases of falling objects from a height from residential buildings in Singapore; image from Chew [16].

Professional guidelines such as ASTM Standards and Guidelines [18,19] and Hong Kong's Mandatory Building Inspection Scheme [20] can help with early defect detection and reduce the risk of falling objects. With inputs from two rounds of public consultation and over 20 rounds of engagement sessions with stakeholders, the Singapore Building and Construction Authority (BCA) introduced the Periodic Façade Inspection (PFI) regime [21] in 2020. Under the newly enacted PFI regime, all buildings above 13 m and exceeding 20 years old are required to undergo façade inspections by competent persons every 7 years. A competent person may be either a registered professional engineer in the civil or structural engineering discipline with the Professional Engineers Board, or a registered architect with the Board of Architects, and must complete training for façade inspection. Singapore BCA estimated that more than 4000 buildings will be inspected every year under the PFI regime [22]. The inspection process includes full visual inspections of the entire façade that can be performed on the ground level and close-range inspections to probe for defects, followed by a full façade investigation if required. Technology such as infra-red thermography and unmanned aerial vehicles can be used with approval to facilitate the inspection.

While the PFI regime lays the cornerstone for the early detection of façade deterioration in Singapore, it has not considered the potential impacts of climate change on building façades. The Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6), prepared by 234 authors after assessing more than 14,000 scientific publications, provides clear evidence that climate change is induced by human activities [23]. The impacts of climate change are geographically disparate. For example, sea-level rise is expected to be more severe in the equatorial regions and around Australia, southern Africa, and North America [24,25]. Research on climate change and its effects is also geographically disparate; most research has been focusing on the temperate climate zone, especially in North America and Europe. Ironically, the tropics, which are expected to be more severely affected by climate change, have gained less attention in research [26–28]. Singapore is a tropical island country located just about 1° north of the equator. As more than 30% of Singapore's land area is less than 5 m above sea level [29], Singapore is highly prone to sea-level rise, with a projected sea-level rise of up to 1.0 m by 2100 [30]. While the more well-known consequences of climate change, such as sea-level rise and heat waves, have received due attention, the "hidden" problems of the effects of climate change on building façades are less studied and understood [31]. Cities with many high-rise buildings are particularly at risk of falling objects, which can cause economic loss and injuries. For example, Grøntoft [32] estimated that a temperature increase of 2 °C and a 20% increase in rainfall would elevate the annual maintenance cost by 0.1 Euro/m^2 in Norway, while Yanagawa et al. [33] reported that there were 2650 trauma patients injured by falling or flying objects in Japan between 2004 and 2019. Therefore, the objective of this paper is to evaluate the potential impacts of climate change on building façades in Singapore and identify the key concerns. Section 2 describes the projected climate change scenario in Singapore. Section 3 discusses the impacts of climate change on building façades, followed by a discussion on the limitations of this paper in Section 4 and concluding remarks in Section 5.

2. Projected Climate Change Scenario in Singapore

Singapore's climate change projection has been studied by the Centre for Climate Research Singapore (CCRS). The first study was completed in 2013, while the second study was completed in 2015 [34,35]. The major findings from the second study are consistent with the findings in IPCC's Fifth Assessment Report (AR5) [36], released in 2014. Recently, CCRS announced that the third study contextualizing the IPCC's Sixth Assessment Report (AR6), released in 2022, will be completed by September 2023 [37]. This paper uses the climate projection from CCRS's second study, published as a scientific report [34] and a report to stakeholders [35]; both are available for download on the CCRS website [38].

The CCRS Second National Climate Change Study [34,35] used nine general circulation models (GCMs), participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) [39], which were the same models used in the global climate projection in IPCC's AR5. The outputs from these GCMs were downscaled to regional scale with a resolution of 12 km by the regional climate model (RCM) HadGEM3-RA. Three experiments were run: a historical simulation from 1950 to 2010 for model assessment, and projections to 2100 under Representative Concentration Pathways 4.5 and 8.5 (RCP4.5 and RCP8.5, respectively). The key findings on the projected dry-bulb temperature, humidity, rainfall and wind speeds are briefly outlined in Section 2.1 through Section 2.4.

2.1. Projected Dry-Bulb Temperature

The most important parameter quantifying climate change is the dry-bulb temperature (hereafter "temperature"). Since the 1980s, Singapore has undergone rapid development and has a warming trend of 0.23 °C per decade, higher than the global warming trend of 0.18 °C per decade [40]. The higher warming trend in Singapore can be explained by warming due to urbanization on top of warming due to global climate change [41]. Table 1 summarizes the projected ranges of increment for daily minimum, mean, and maximum temperatures. The baseline minimum, mean, and maximum temperatures from observation (1980–2009) were 24.1 °C, 27.4 °C, and 31.8 °C, respectively. This means that under RCP8.5, the daily mean temperature could reach 32.0 °C, while the daily maximum temperature could reach 36.7 °C by the end of the century. Correspondingly, there will be an increase in the frequencies of warm days (where the maximum temperature exceeds 34.1 °C) and warm nights (where the minimum temperature exceeds 26.2 °C) [35].

Table 1. The ranges of projected increment (°C) in daily minimum, mean, and maximum temperatures under RCP4.5 and RCP8.5 for the mid-century period (2040 to 2069) and the end-century period (2070 to 2099) [35].

Projected Period	Scenario	Minimum	Mean	Maximum
2040–2069	RCP4.5	1.3–2.3	1.3–2.2	1.3–2.7
	RCP8.5	1.8–3.0	1.8–2.9	2.0–3.1
2070–2099	RCP4.5	1.4–2.9	1.4–2.7	1.5–2.8
	RCP8.5	2.9–4.8	2.9–4.6	3.1–4.9

2.2. Projected Humidity

Singapore's climate is classified as an equatorial rainforest, fully humid (*Af*) under the Köppen–Geiger climate classification [42]. Humidity is consistently high throughout the year and can reach 100% relative humidity during rainy days. Observation revealed that relative humidity in Singapore has not been changing, staying around 83% (annual mean) from 1980 to 2009. Relative humidity was projected to drop slightly to 80.7% and 79.2% under the RCP4.5 and RCP8.5 scenarios, respectively [35].

2.3. Projected Rainfall

It is extremely challenging to predict rainfall, due to the complex multi-physics involved [43,44]. The projected total annual rainfall was inconclusive, as different models showed both increase and decrease. However, based on the observations from rainfall stations, the total annual rainfall in Singapore has been increasing by 67 mm per decade since 1980 [45], suggesting that it is more likely for the total annual rainfall to increase in the future. Unlike the total annual rainfall, which was inconclusive, the extreme rainfall projection was more consistent, where seven out of nine regional climate models predicted a statistically significant increase in extreme rainfall in the CCRS Second National Climate Change Study [34,35]. These models predicted the number of extreme rainfall events (>56 mm per day, based on the 95th percentile from past observation between 1980 and 2009) will increase under both the RCP4.5 and RCP8.5 scenarios. The observed percentage contribution of extreme rainfall events (>56 mm per day) was 22.8 %. Under the RCP4.5 scenario, this percentage is projected to increase to 36.3% and 35.3% from 2040 to 2069 and from 2070 to 2099, respectively. Under the RCP8.5 scenario, the projections are 32.7% and 44.1% from 2040 to 2069 and from 2070 to 2099, respectively. A high-resolution (1.5 km) model also projected that rainfall intensity will increase under the RCP8.5 scenario. It is also worth pointing out that the models projected that "wet periods get wetter and dry periods get drier", as the climatologically wetter months (November to January) are projected to receive more rainfall, while the climatologically drier months (February and June to September) are projected to receive less rainfall.

2.4. Projected Wind Speed

The projection of the mean 10-m wind speed was inconclusive. Under RCP8.5, some models predicted increasing wind speed, while some models predicted the opposite trend. These models with 12 km spatial resolution cannot capture extreme winds, but a high-resolution model with 1.5 km resolution simulating for a shorter period (10 years) suggested that wind gust speed will increase by 5 to 10% under RCP8.5. However, these numbers should be treated as a rough estimate, as the simulation period was short.

3. Impacts of Climate Change on Building Façades

Based on the common defects on different types of façades summarized in the Guidelines on Periodic Façade Inspection [21], the common root causes of defects were identified. Table 2 lists the common root causes of defects on façades and the meteorological parameters associated with the root causes. Among these root causes, poor workmanship can affect the quality of façade maintenance [46] but was excluded from this study, as workmanship is not expected to have a direct impact from climate change. In addition, the effect of poor workmanship on façade degradation may not be easily measurable. Biological attack is often induced by humidity or dampness, and therefore, the discussion on humidity or dampness and biological attack is combined in Section 3.4.

Table 2. Common root causes of defects on façades and the meteorological parameters associated with the root causes.

Common Root Causes of Defects on Façades	Associated Meteorological Parameters
Corrosion or degradation	Temperature, humidity, rainfall, wind
Material fatigue	Temperature
Adhesive failure	Temperature, humidity, rainfall
Humidity or dampness	Humidity, rainfall, wind
Biological attack	Humidity, rainfall, wind
Poor workmanship	-

3.1. Corrosion or Degradation

Many defects are due to corrosion, including the corrosion of the façade itself, corrosion of connections between a façade and the supporting structure (e.g., screws and clamps), and corrosion to external structures, such as sunshades and air conditioner brackets. Corrosion is the gradual deterioration of a material due to chemical or electrochemical reactions with the surrounding environment. The most common corrosion is the rusting of metal, a process accelerated by the presence of moisture. Rainfall is the major cause of metal corrosion in façades. Therefore, alteration in rainfall frequency and intensity due to climate change is expected to have a huge impact on corrosion-related failures. Section 2.3 suggests that the number of extreme rainfall events are projected to increase in the future under both RCP4.5 and RCP8.5. Corrosion is already a common cause of falling objects in humid Singapore, so an increase in the frequency of extreme rainfall will increase the risk of falling objects associated with corrosion. Furthermore, heavy rainfall often occurs with gusts, which causes the problem of wind-driven rain [47,48]. Corrosion-prone materials that are normally shielded from rain may still be wetted due to wind-driven rain. Note that this paper does not include the degradation of timber or modified wood due to rainfall, as they are not commonly used in Singapore as construction material. Interested readers may refer to the relevant literature, for example, the research by Ormondroyd et al. [49], Nik [50], and Prieto and Silva [51].

The impacts on corrosion by an elevated temperature is not trivial. On one hand, a higher temperature can speed up the rate of corrosion; on the other hand, a higher temperature can accelerate the evaporation of water on façade surfaces and joints, and thereby reduce the rate of corrosion [52]. The discussion in Section 2.1 ascertains that the temperature in Singapore will continue to rise. However, Section 2.3 discusses that both the number of extreme rainfall events and rain intensity are expected to increase due to climate change. Due to the competing effects of temperature on the rate of corrosion, the overall impacts of climate change on corrosion or degradation remain uncertain.

3.2. Material Fatigue

Material fatigue can be caused by thermal cycles or mechanical cycles. In the context of climate change, this paper focuses only on the thermal cycle. High temperatures can induce stress due to thermal expansion. While different building materials are expected to have different thermal expansion coefficients, the same building material can have different thermal expansion coefficients, depending on the orientation of the crystallite texture and treatment during production [53]. Spagnoli et al. [54] developed a theoretical model to predict the thermal fatigue of marble slabs due to cyclic temperatures. That model predicted that a clamped slab under thermal cycles can fail in just three years. Chau and Shao [55] showed that under a cyclic temperature fluctuation of 15 °C, a crack can grow to cause failure in a 3-cm thick rock panel in less than a year.

Section 2.1 outlines that the maximum daily average temperature in Singapore could increase by up to 4.9 °C in the future. As high temperatures exceeding 36 °C have become more frequent in Singapore [56], with the projected temperature increase due to climate change, the daytime temperature in Singapore could exceed 40 °C in the future. Exterior surfaces exposed to solar radiation can be up to 20 °C warmer than the surrounding air [57,58], so a façade's temperature can exceed 60 °C during the day and drop to below 30 °C at night. In short, climate change is expected to increase the temperature variation, thus accelerating crack growth in façades due to cyclic thermal loading.

3.3. Adhesive Failure

The common causes for adhesion failure on building façades have long been investigated [59,60]. Environmental effects, particularly the thermally induced and moisture-induced movements, can accelerate the deterioration of adhesives [60–62]. The actual mechanism of adhesion failure of materials, systems, components, or features on an externally exposed façade in a city dominated by tall buildings is much more complex. The impact of climate change when translated to a microlocal condition, consisting of the combined effects of (a) cyclical moisture and temperature exposure, (b) thermal shock, (c) hot water immersion, (d) wind-driven rain, (e) air/water pollutants, (f) relative humidity, (g) aggressive agents, etc., plays a very significant effect on the integrity of the adhesion. As thermal stress and moisture can accelerate the deterioration of adhesives, more incidents of falling objects due to adhesive failure can be expected with higher projected temperatures and rainfall intensity due to climate change. Section 2.4 suggests that wind gust speed is projected to increase by up to 10%. Note that the projected wind speed is the meteorological wind speed. Local wind speeds around a building or façade can deviate significantly from the meteorological wind speed. Building layout, building height, building shape, roughness elements, and many other parameters can affect the local wind speeds [63,64]. Although the increase in the meteorological wind gust speed is small (up to 10%), the local wind speed can be amplified, which induces a larger pressure difference across a façade or other elements such as a window. This larger pressure difference can then induce a larger stress on the adhesives and can dislodge the façade or the elements should the adhesives fail.

3.4. Humidity or Dampness and Biological Attack

While the relative humidity in Singapore is not expected to increase due to climate change (Section 2.2), extreme rainfall events are expected to increase (Section 2.3). Rain intensity is also projected to increase due to climate change. More frequent rainfall and higher rain intensity will increase the period of water contact on façades, which elevates the risks of corrosion or degradation (Section 3.1) and biological attack. Biological attack on façades, such as molding and microbial growth, is common in tropical climates [65,66]. Biological attack on façades mostly causes aesthetic problems, such as staining, but can induce cracking if ignored in the long term. Another imminent issue due to rainfall events is rain penetration into sheltered areas. The concept of building porosity in the form of openings or voids [67,68] has been widely adopted in Singapore to improve ventilation and thermal comfort. Despite its benefit, building porosity allows rain droplets to penetrate into sheltered areas due to advection by wind, causing the issue of wind-driven rain [47,48], as shown in Figure 4. In addition, vertical greenery, which will be discussed in detail in Section 3.5, has become a common feature in façade design. Similar to other living plants, vertical greenery needs irrigation, and irrigation increases the chance and period of water contact on façades. The selection of plant species is also important to minimize biological attack on the vertical greenery itself and the façade supporting it. In summary, with both the frequency of extreme rainfall events and rain intensity projected to increase due to climate change, inspection should cover not only façades exposed to direct rainfall, but also "sheltered" façades exposed to wind-driven rain and façades with vertical greenery.

Figure 4. (**a**) Wind-driven rain penetrated into a sheltered studying area on a university campus. (**b**) Corrosion on the metal frame of a sheltered walkway due to moisture induced by wind-driven rain.

3.5. Vertical Greenery

Vertical greeneries, or green walls, have become more common and warrant special attention as a separate section. Although vertical greeneries have many advantages, such as providing cooling effects and aesthetics [69,70], they can accelerate the deterioration of façade materials [71,72]. In addition, vertical greeneries require additional supporting structures [73,74], which are prone to corrosion and thereby increase the risk of falling objects, as shown in Figure 5. As a "City in a Garden" [75], Singapore has been adopting vertical greeneries for both residential and commercial buildings [76]. However, there is a lack of studies of vertical greeneries in the equatorial climate [77]. The impacts of climate change on vertical greeneries, for example, whether a chosen plant species can adapt well to the projected changes in temperature and rainfall patterns, remain unknown. Heavy thunderstorms with strong winds can cause accidents due to tree failures [78,79], as shown in Figure 5c. On the other hand, a long dry spell can wither the plants, thus increasing the risk of falling branches. There are currently no detailed guidelines for the inspection or failure detection of vertical greeneries or green walls. As Singapore continues to incentivize and mandate new development to incorporate urban greenery [75], the associated risk with climate change should not be overlooked.

Figure 5. (**a**) A rooftop garden and vertical greenery on a residential building in Singapore. (**b**) Additional structure is required to support vertical greenery; the red arrow indicates corrosion on the supporting structure. (**c**) Fallen tree branches after a heavy rain; the red arrow indicates the point of failure.

4. Limitations

Climate change projections are inherently uncertain and extremely difficult to predict [80,81]. Singapore's climate change projection [34,35] was conducted by downscaling nine GCMs from CMIP5 used by IPCC's AR5 [36]. Therefore, uncertainties in the GCMs are propagated to the downscaled regional models used for climate change projection in Singapore. Subsequently, the impacts of climate change derived under a projected climate change scenario could be inaccurate. However, since the RCP8.5 corresponds to the highest level of emission [82], it provides a conservative prediction of the impacts of climate change.

The uncertainty of the impacts of climate change, specifically on building façades, is also a huge unknown. The coupling of different meteorological parameters, such as temperature and humidity, is even more complex. For example, as discussed in Section 3.1, a higher temperature can accelerate the rate of corrosion, but at the same time, it can also accelerate drying on wet façades after a rainfall and thereby reduce the rate of corrosion. While these issues can be addressed in accelerated experiments performed in laboratories to mimic environmental effects, a façade exposed to real environmental conditions over a long period may not behave exactly the same as that tested under accelerated experiments [83]. The testing conditions in a laboratory are highly controlled, whereas real environmental conditions fluctuate with time and can deviate significantly from laboratory testing conditions. For example, the properties of the steel–concrete interface in laboratory corrosion tests may not be representative of those of real reinforced concrete [84]. Therefore, it is impossible to predict the exact impacts of a changing environment due to climate change, even in a highly controlled laboratory.

This paper focuses only on the climate change projection in Singapore, a tropical coastal city. This discussion should not be generalized to other climate zones, since the climate change projection can be very different. Winter and snowfall are not considered in this paper, but climate change can have a huge impact on both, for example, the duration of extreme cold during winter and snow cover. Nevertheless, this paper can still contribute to the literature, as the issue of falling objects from a height is also faced in other cities in the tropical and sub-tropical climate zones, for example, Kuala Lumpur, Shanghai, and Hong Kong [85–87].

5. Conclusions

This paper studies the potential impact of climate change on building façades in Singapore, a tropical coastal city. Singapore enacted the Periodic Façade Inspection (PFI) regime in 2020, where all buildings above 13 m and exceeding 20 years old are required to undergo façade inspections by competent persons every 7 years. Based on the Second National Climate Change Study conducted by the Centre for Climate Research Singapore (CCRS), the projected mean (dry-bulb) temperature in Singapore could reach 32.0 °C, while the maximum temperature could reach 36.7 °C by 2100, with an increase in the frequencies of warm days and warm nights. Relative humidity is projected to drop slightly from 83% to 80% by 2100. The number of extreme rainfall events is projected to increase, and rainfall intensity is also projected to increase. The projection of mean 10-m wind speed was inconclusive, but wind gust speed is projected to increase by up to 10%.

The common root causes of façade defects that can be impacted by climate change are identified, namely corrosion or degradation, material fatigue, adhesion failure, biological attack, and humidity or dampness. Some key concerns due to climate change are as follows:

- A projected higher temperature can accelerate corrosion or degradation, material fatigue, and adhesive failure;
- A projected higher rainfall intensity and an increase in the number of extreme rainfall events can increase the period of water contact on façades and its components, thereby accelerating corrosion or degradation and adhesive failure, as well as increasing local humidity or dampness and the chance of biological attack;
- A projected higher wind gust speed can increase the penetration of wind-driven rain, which can induce corrosion or degradation, adhesion failure, biological attack, and humidity or dampness;
- How climate change will affect vertical greeneries is not well-understood. Heavy thunderstorms, high wind gust speeds, and long dry spells can cause the plants used in vertical greeneries to fail and fall.

The PFI regime enacted in Singapore in 2020 is relatively new and does not consider the impacts of climate change. While the uncertainties in both the climate change projection and its impacts on building façades remain large, this paper provides a first insight into the key concerns to focus on, as listed above, for the future revision and improvement of the PFI regime.

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