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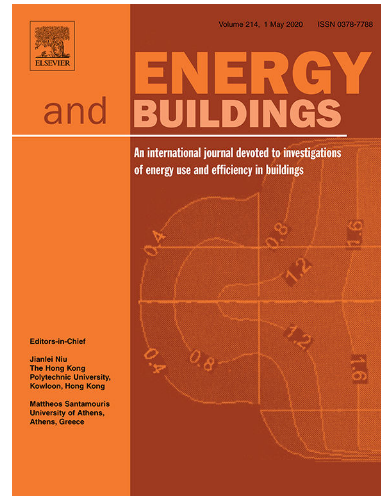

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What we know and do not know about New Zealand's urban microclimate: A critical review

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Abstract

Despite the remarkable contribution of urbanisation to socio-economic development, it has complicated negative impacts on the environment. The growth of urbanisation has noticeable adverse impacts on urban microclimate and parameters generating the urban heat island (UHI) effect. These impacts, exacerbated by the gradual influences of global warming over time, make urban microclimate changes more complex. The future urban development and climate change adaptation plans in New Zealand (NZ) show almost no evidence of considering the status of future urban microclimate, UHI and outdoor thermal comfort. An initial literature review showed a relatively small number of papers and grey literature on urban microclimate in NZ. This motivated the authors to explore the status of studies on the urban microclimate and the following impacts on UHI and outdoor thermal comfort in NZ. The results showed a relatively small body of knowledge on urban microclimate studies in research articles published and governmental reports in the context of NZ. Likewise, the inconsistency of research parameters and methods studied and the lack of validation in the available studies, plus the neglection of future urban development and urban morphology, limit the clarity of the scientific understanding of changes to the urban microclimate in NZ. The results of this study address the missing links and provide new insight for future studies. This study suggests providing models that consider the continuous changes to the urban microclimate considering the uncertainty of climate change impacts on weather factors such as temperature and airflow. Assessment of the impact of current and future urban morphology on UHI is necessary to develop optimised urban design guidance. ***Keywords:*** *Urban microclimate, Urban heat island, Outdoor thermal comfort, Climate change, Urban development*

1 Introduction

The increase of urbanisation [1] [2], human modifications of land cover (e.g. changing green spaces or water bodies to the built environment) [3]–[5] [6], and anthropogenic activities [7] influence the airflow and thermal balance in a city area [7],[8],[9]. The imbalance of natural airflow and temperature in urban areas has negative impacts on urban microclimate, altering wind flow patterns, exacerbating the urban heat island (UHI), and significantly affecting outdoor thermal comfort [3]–[5], [10]. The phenomenon of higher temperature in high-density urban areas than in the surrounding low-rise buildings and green spaces around the cities is known as the urban heat island effect [11] [9] [28] [30]. The UHI effect has been documented in more than 400 cities around the world [15]. All cities experience UHI effects regardless of climate differences, but UHI affects cities differently [12]. UHI can have noticeable negative impacts on outdoor thermal comfort and city dwellers' health and wellbeing [5],[16], urban air quality [3], and energy use of buildings [3], and exacerbates the negative impacts of climate change [3]. There is a need to examine case studies to estimate the current microclimate, understand the dependency of UHI on different factors in different case studies, and then explore and target efficient mitigation plans to control UHI [11].

Regarding the importance of urban microclimate for improving air quality [3] and outdoor thermal comfort in cities, considering factors affecting urban microclimate in the planning and design process is crucial [17]. The effectiveness of any proposed strategies for mitigating UHI in a city relies on the local climate and the urban morphology of that specific context [5]. Thus, the urban planning regulations used in other countries are sometimes ineffective if used without being tailored to the local climate and sometimes might be inflexible [17].

The negative impacts of urban growth and climate change on the urban microclimate of cities in New Zealand (NZ) motivated the researchers to conduct a critical literature review to explore the status of urban microclimate studies that lead to future potential research to mitigate these effects. Climate change is increasing both the average and maximum temperature in NZ. The extremely high temperatures and heatwaves are also expected to become more likely [18]–[20]. The number of days with a temperature exceeding 25 degrees Celsius is expected to increase significantly [20] [19]. The severe impacts of climate change, significant population growth in the large cities of NZ, and the urgent need for urban development magnify the adverse effects on urban microclimate characteristics in NZ cities [21]. New legislation might not comprehensively consider the climate change impacts on the urban development areas and major development projects [22]. This highlights the significance and the need for a well-structured, long-term, and holistic approach to considering the environmental impacts of urban microclimate in urban development plans and climate change risk assessments.

This paper aims to provide a state-of-art review of the urban microclimate in NZ. Also, the status of the urban microclimate in Auckland (the largest city in New Zealand with a fast growth rate compared to other regions in New Zealand) [23] which will be greatly affected by CC [24], will be explored specifically. The objectives of this study are 1) presenting an overview of all studies on urban microclimate, UHI, and outdoor thermal comfort in NZ, 2) exploring the impact of climate change and future urban development on urban microclimate in NZ, 3) Highlighting the knowledge gap neglected in impact assessment of urban microclimate in the case studies and the need for further assessment and analysis to improve it in NZ 4) provide recommendations for the future research.

1.1 Significance of study

The rapid rate of urbanisation and exacerbating impacts of climate change are negatively affecting the urban microclimates in recent years [25]. The findings of this study uncover the gaps in the urban microclimate study in NZ and provide a basis for neglected but critical aspects of urban microclimate and UHI for future studies. The results will give a broader insight into the role of urban microclimate and UHI for urban planners, climate change policymakers, and city councils in NZ. The importance of considering urban microclimate in climate change adaptation and mitigation plans and future development plans of urban areas in NZ will be highlighted for urban development and climate change plans. One of the areas of strategies and policies of the NZ government for emission reduction is the integration of emissions into urban planning and development. The total emission contribution of urban areas in NZ is still unknown. However, rapid urban growth in many parts of NZ has led to poor function of urban morphology and higher emission [26]. Moreover, changes to urban microclimate have undeniable effects on the health and well-being of city dwellers, outdoor thermal comfort of urban areas, and energy efficiency in the built environment at a large scale.

2 Urban microclimate

An urban microclimate is defined as the local climate of an urban area that can be different from the climate of the surrounding areas, including rural areas [25]. The climatic features of urban areas, such as temperature, heat balance changes, and airflow, are different from the surrounding rural areas [25]. The air over cities is two main layers, the canopy layer (the air between buildings) and the boundary layer (the air above the average height of buildings). The reflection of solar radiation from the ground and building façade changes canopy layers. The urban boundary layer is affected by heat transfer, pollutant emission, evaporation, transpiration, and overall urban development effects [27]. Urban microclimate has major impacts on the variation of air temperature [28] and wind flow [29], air pollution patterns [30], energy performance of buildings [31], [16], and thermal comfort [32].

Changes to urban microclimate impose adverse environmental, economic, and social effects on cities [2]. Higher temperature increases the demand for cooling energy and CO2 emissions, raises health and mortality risks and changes outdoor activities and socialisation [2]. Another major impact of temperature imbalance in urban areas is the formation of urban heat islands (UHI) [25].

Design guidelines and urban climate zoning have an essential role in achieving desired microclimate conditions [1]. To provide guidelines and plan for climate-sensitive urban forms, and to mitigate the negative impacts imposed by microclimate, an accurate microclimate assessment is necessary [1]. Due to the complexity of the urban environment, providing a database that includes the needed city features for an evaluation of the urban microclimate in a city is considerably complicated. On the other hand, theoretical atmospheric models are not flawless. Hence, there is no unique assessment method for microclimate [2].

2.1 Contribution of the urban microclimate to outdoor thermal comfort

The urban microclimate is one of the most critical factors affecting outdoor thermal comfort [33], the urban life quality [9][17][24], the utilisation of the outdoor public spaces [33] [35] [36], and the liveability and sustainability of cities [14], [8], [37]. There are several thermal comfort indices developed, considering the relationship between microclimate and thermal sensation. These indices, such as the Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) [38], help to predict outdoor thermal comfort [39]. Recent work in Wellington and Christchurch, New Zealand, has demonstrated that, in the field, these indices are less reliable than might be hoped because they don't incorporate human expectation or behaviour and mostly rely on the clothing rate or activity level [37]. Air temperature, thermal radiation, and wind speed are the most important microclimate parameters for thermal comfort in urban outdoor spaces [33]. Air temperature is more important in summer and thermal radiation in winter. However, it should be noted that human thermal comfort is the condition of psychological [40] and physical satisfaction with the thermal environment. Theoretical thermal comfort indices describe urban microclimate based on the energy balance and how people perceive space during outdoor activities regarding the human variables, including clothing and metabolic activity [40]. In practice, field tests reveal these factors are significantly affected by people's adaptation behaviours: it is difficult to find people outdoors wearing unsuitable clothing or when these indices suggest people would be uncomfortable. An adaptive outdoor comfort index [37] has been developed in two New Zealand cities that are far more nuanced in terms of people's behaviours than these theoretical indices. Further development would enable the sound design of shading and green spaces [41] and climate-responsive geometrical features of urban spaces [42] to enable effective management of air and surface temperature and improve thermal comfort [41]. Outdoor thermal comfort is a crucial factor in quantifying the quality of urban microclimate [40],[43]. Taking outdoor thermal comfort into account can give a holistic view of sustainable urban development [40].

2.2 Urban heat island effect

There is a worldwide increase in the temperature of microclimatic urban areas compared to the surrounding countryside causing the urban heat island phenomenon [11] [9] [28] [30]. UHI effect is caused due to urbanisation, industrialisation [44], and lack of vegetation in the urban environment [11] [25]. UHI can generate up to 12 °C surface temperature differences in the urban and surrounding rural areas [12], [45]. The intensity of UHI is influenced by geography [11], urban morphology, meteorological conditions [11], [12] using dark colours in paving and buildings [46], [47], the form of buildings [48], [49], lack of adequate vegetation [12], [14] and waste heat from energy-consuming activities in cities [50]–[55] [44]. UHI effect magnified by climate change is likely to increase urban heat extremes [14] [43]–[45]. The increase of urban surfaces, such as building facades and pavements, leads to higher absorption of solar radiation and reduction of convective cooling [59]. This has the potential to affect the outdoor thermal comfort of city residents significantly.

UHI imposes negative impacts on urban areas' physical and socio-economic [12] and economic aspects [60]. UHI increases energy consumption and greenhouse gas emissions and decreases outdoor thermal comfort [44] [9] [28]. The severe changes to outdoor thermal comfort cause a high risk to public health and wellbeing [13], [57], [61], [44], and heat-related mortality rate in urban areas [62] [63], especially for vulnerable city dwellers [9] [28], older adults [12], young children, and people with chronic respiratory and cardiovascular diseases [64].

The assessment of the UHI is critical for urban designers and policymakers due to the several negative effects on urban life [60]. Estimating and analysing the intensity and magnitude of UHI is needed to improve the environment in cities and establish policies and plans for prediction and coping with the damaging effects of UHI [58]. The awareness of citizens and urban planners about UHI and considering climate-responsive design can decrease the magnitude of UHI and increase outdoor thermal comfort [65]. The size, spread, and geometry of green urban spaces have the potential to reduce the adverse effects of UHI. Also, the synergy of benefits of using blue and green spaces in future urban growth enhances the mitigation of UHI negative impacts [59].

3 Research Method

The objective of this study was to map the literature on urban microclimate, urban heat islands, and outdoor thermal comfort in NZ. First, the research objectives were defined. Second, relevant studies were identified. Third, relevant studies were selected based on inclusion and exclusion criteria, then the data was charted, and finally, the results were summarised and reported.

The Scopus and Web of Science search engines were used to identify peer-reviewed articles, conference papers, and book chapters. The search query included "urban microclimate," "urban heat island," "outdoor thermal comfort," and "New Zealand" and major cities of NZ, including "Auckland," "Wellington," and "Christchurch," and the related terms. Searches were limited to articles and reports written in the English language. Additionally, the snowball method was employed in the literature review to find relevant governmental and academic reports. The title and abstract of papers were screened, and irrelevant studies were excluded. Journal articles, conference proceedings, books and governmental and academic reports were included in the search. Duplicated and irrelevant papers were removed. The scope of the research was the impact of urban microclimate, urban heat island and outdoor thermal comfort in urban area and built environment. The studies focusing on the natural environment (e.g. native trees and forests) were excluded from the results. Studies that contain the case studies located in New Zealand have been included in the results. Studies that have referred to a location in New Zealand without any research on the case study have been excluded from results.

The result of the search in Scopus was 18 papers, and only eight papers met inclusion criteria and were in the scope of this research. The initial result of searching Web of Science database was 11 papers. Only two papers from the database that were common between Scopus and Web of Science met the inclusion criteria of the search [66], [67]. Other research found on Web of Science was out of the scope of this research. Papers focusing on indoor thermal performance [68] or forests and natural environment [69].

The resulting full texts of eligible documents were examined. A data charting form was developed to extract data from papers. A pilot data extraction was tested to check the consistency of the data extracted with the research question. Charting data was continually updated. The charting table was developed to record the methodological approach, implemented area, publication year, and the key findings of the studies.

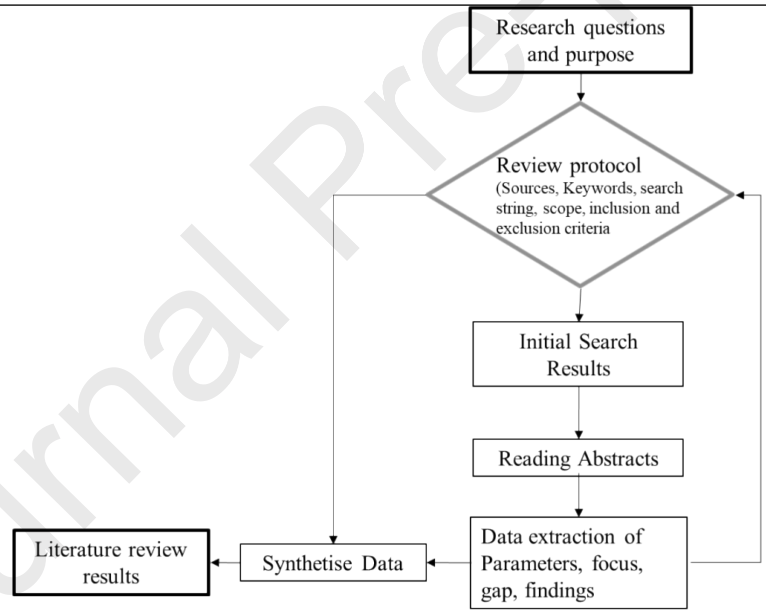

Figure – The process of research method

4 Urban microclimate studies in New Zealand

4.1 Overview of the climate of New Zealand

New Zealand is an island country in Southern Hemisphere with a moderate maritime climate, weather, and temperatures with no wide temperature range [70]. It has been recognised for its unique environment, with its nature remaining more intact than in many other parts of the globe [70]. Most cities in NZ lie close to the coast, which means mild temperatures, moderate rainfall, and high sunshine hours [70]. The climate of NZ differs from warm subtropical in the far north [71] [70] to the cool temperate climates in the mountainous areas in the far South [71]. The average temperature in the warmest month of the year (January) varies from 15ºC-21.1ºC in Wellington, 12.2°C-22.8°C in Christchurch, 16-20ºC and in winter, 5-14ºC and in the coldest and month of the year (July) varies 2.2°C-15.6°C in North and -2.2°-12.8°C in South. The warmest months are December, January, and February, and the coldest are June, July, and August [72]. Most areas in NZ have 600 to 1600 mm of rainfall [71] and receive at least 2000 sunshine hours annually [71]. There are relatively small differences between summer and winter temperatures in NZ [71]. The midday summer solar radiation index is very high in most areas and extreme in northern New Zealand and the mountainous regions [71].

4.2 A critical review of urban microclimate studies in NZ

An overview of peer-reviewed research on urban microclimate in NZ indicates the rise of temperature in urban microclimate and increase of UHI. Nevertheless, generally, an acceptable level of outdoor thermal comfort in public spaces and adjustment of people with the impacts were reported.

An analysis of a network of stations in Australia and New Zealand by Chambers and Griffiths [73] to assess the effects of urbanisation on extreme temperature showed that the daily temperature range was strongly influenced by urbanisation. Still, the results need further exploration due to data limitations. Both rural and urban areas experienced rising hot days and warm nights and decreases in cool days and cold nights. However, rural stations had less significant increasing trends in warm extremes. Urbanised areas showed more significant hot day increases. Similarly, a critique by Boretti and Watson [74] of a National Institute of Water and Atmospheric Research paper argued that the NIWA observed average 0.9^{o}C warming of 7 New Zealand meteorological sites could be better ‘explained’ by UHI effects rather than anthropogenic global warming. They provide no experimental data but rather argue that the NIWA observations over 100 years indicate that heat island build-up has impacted these temperature changes. On the other hand, a few studies explored the microclimate in NZ’s urban forests to investigate the relationship between environmental conditions and the plant community in the urban forest. Urban microclimate can also affect the diversity and density of native trees [75].

Moving beyond, a holistic search on microclimate and outdoor thermal comfort studies in NZ indicated a relatively small body of peer-reviewed literature concerned with urban microclimate. Most research on urban microclimate has been carried out in the case study of Christchurch, the third-largest city of NZ, located on the east coast of South Island.

Spronken-Smith et al. [76] reported measurement and modelling of energy fluxes in wintertime in suburban areas of Christchurch, New Zealand. They examined the heat and moisture at local and mesoscale levels. The application of a research methodology to estimate storage fluxes in urban spaces in wintertime conditions was explored. On-site measurements of humidity and temperature were recommended to avoid any inaccuracy in results.

Tuller [77] explored the difference between the amount of required clothing insulation to balance body heat with no changes to body heat storage in Christchurch. Results were presented in terms of the amount of needed clothing insulation to balance the body heat of a standing person with no change in body heat storage. Measurements were made at 18 separate locations along two transects across the city on cool, clear winter nights. Urban areas had warmer human thermal environments than the surrounding rural areas, and different clothing was required in the urban area and surrounding areas, including the hill slopes. It was concluded that the warmer human thermal environments in urban areas could cause thermal discomfort during hot weather. The effect of hills and ocean were of a similar scale to that of urbanisation. The most related climatic elements to the clothing requirements were air temperature and environmental thermal radiation.

On another side, Tavares et al. [78] aimed to identify how people adjust their culture and lifestyle values and expectations to the actual microclimatic conditions in Christchurch. Investigating the socio-cultural concept of urban comfort and people's perception in a post-earthquake setting may be valuable to understand better their experience of adaptation to dynamic urban landscapes. It was inferred that the integrative methodology of combining ethnographic methods with microclimate could be employed to explore how people adjust their culture and lifestyle values and expectations to the urban microclimate. The particular context for the study was a physical landscape under rapid change due to earthquakes.

Also, Perera et al. [37], [79] reported outdoor thermal comfort and thermal adaptation by 1100 interviewees in public parks in Wellington and Christchurch. A model was developed to test the adaptation aspects involved in thermal comfort. The influence of adaptation on thermal comfort assessment was examined based on peoples' thermal expectations and preferences. The study reported that the standard physiological models of UTCI and PET could not be applied reliably to different climates to predict comfort levels in the field for different thermal expectations. The evidence that people adapt their clothing, behaviour, and expectations to the outdoor thermal environment points to the need to calibrate generic physiological models like UTCI and PET more carefully to the climate. They concluded that generic physiological models are too rigid. An adaptive comfort model for the outdoors is required to capture the richness of local adaptation.

Tapper et al. [66] tested an energy balance model to measure surface temperature in Christchurch during winter. It was expected that the energy balance model would give acceptable predictions of surface urban heat islands in winter. There was a more than 1C difference between simulated and observed temperatures. Measured rural and Central Business Districts (CBD) temperatures on a cold clear winter night showed a 4^{o}C warmer CBD than the neighbouring rural area. The research only tested this 'surface' temperature in winter. No information was collected at different heights in the same location, though some measurements were made within the neighbouring hills.

In Auckland, the most populated city in New Zealand, Nouri [67] provided a framework for the international history of built and conceptual projects that address the level of thermal comfort in urban public spaces focusing on the case study of Auckland. Regarding future increases in both urban density and climatic impacts. The analysis reported an expected increase from 20+ to 60+ days when the temperature would exceed 25^{o}C; the effects of UHI need to be considered further. The research results indicated that the extracted solutions could shape potential measures and considerations in Auckland's local policy and design guidelines. Considerable increases in the population, urban density, and CO_2 emissions in future years will increase the need to address microclimate concerns in Auckland, and adaptation to the effects of climate change in the urban area for the next decades is essential.

Table 1 - Summary of urban microclimate studies on the case studies in New Zealand *

Ref.	Study area	Study focus	Method	Findings	Year published
[77]	Christchurch	Thermal bioclimatic effects	Quantitative – fieldwork and numerical analysis	Urban areas create warmer human thermal environments than do surrounding rural Areas. The ordering of urban-rural land use zones from lowest to highest clothing requirements was CBD, light industrial-commercial, residential, and rural.	1980
[66]	Christchurch	Urban heat island	Energy balance modelling	There are spatial variations of temperature in CBD and vegetation areas.	1981
[76]	Christchurch	Energy storage fluxes	Quantitative- In-field measurement and modelling	The factors affecting mesoscale energy fluxes of surface layer and atmospheric boundary layer	2006
[73]	Australia and New Zealand	Extreme temperature		The observation of a more significant increase of warm extremes in urbanised sites compared to rural stations and the additional influence of broadscale climates, such as NINO3.4 and MSLP2 on warm extreme trends.	2008

[74]	New Zealand	Temperature rise analysis	Quantitative- Analysis of the measured temperature records	The global cooling and local warming trends in NZ and observation of the formation of heat islands from the individual analysis of the raw temperature data from different measuring stations	2011
[67]	Auckland	Thermal Sensitive Urban Design- UHI	Case study	The need for further consideration of UHI regarding the increase of urban density and climatological impacts was identified. A range of benchmarks was developed from other cities facing similar present and future microclimatic issues in Auckland.	2015
[78]	Christchurch	microclimate and urban comfort	Qualitative- Interview and on-site microclimate measurements	The importance of investigating the socio-cultural concept of urban comfort in a post-earthquake setting to understand better people's experience and adaptation to dynamic urban landscapes changing for other reasons.	2019
[79]	Christchurch	Outdoor Thermal comfort and adaptation	Qualitative- Field survey methodology	The drawbacks of physiological models in predicting what people feel and prefer in outdoor environments and the need for calibrating physiological models to various climates where people have different perceptions and expectations of thermal environments.	2020

* The Scopus and Web of Science search results were included in this table.

From this literature, it appears that previously published studies on Urban Heat Islands are limited to the two cities, Auckland and Christchurch, and a few governmental reports on Wellington [80]. Furthermore, the numerical models used in these studies are relatively simplified and lack the accuracy to make decisions. Overall, the review of these studies highlights the need for more in-depth investigation towards exploring the urban microclimate in NZ, especially focusing on a broader network of meteorological data stations and advanced simulation tools. Moreover, short-term studies such as those reported in this section do not necessarily show urban microclimate changes over time until recent years precisely. Likewise, no study examined the level of UHI intensifying in the key cities in NZ.

Jing et al. [81], [82], [16] demonstrated that, when modelling the thermal performance of naturally ventilated buildings in dense urban areas, the model must account for: the effect of UHI within the urban canopy layer; the influence of the vertical structure of the wind within the urban boundary layer; the wind flows between buildings within the urban canopy layer; and the dynamics of the vertical variation, the lapse rate, of the air temperature. By testing the same exemplar dense urban area in London, Beijing, Singapore and Wellington climates, the study demonstrated that no one factor is more important and that the relative importance of each varies with the type of climate. The research demonstrated the importance of this multi-layered approach to modelling building thermal behaviour. In the temperate Wellington climate, the effect was a difference in annual energy use of up to 25%.

4.3 Climate change impact on urban microclimate in New Zealand

The climate change risk assessment by the Ministry of Environment of NZ indicated higher day and night temperatures in future decades [83]. The historical temperature records in Wellington and Masterton showed the increase of extreme temperature at night and the decrease of cold extremes at day and night due to the impacts of climate change [84]. The temperature increase in NZ under a high emissions scenario is expected to reach 1.0°C by 2040 and 3.0°C by 2090, and 3.7°C by 2110 relative to 1995 (Figure 1) [22]. Climate change would impact the expected number of days exceeding 25°C in Auckland, Wellington [84], and Christchurch [85]. Until 2050 the number of days exceeding 25°C will increase to 31-81 days in Auckland, 5–21 in Wellington, and 32–64 days in Christchurch [85]. Changes in temperature will increase overheating and air-conditioning load in New Zealand [85]. For the year 2030, the increasing percentage of living area overheating is expected to be 61%, 32%, and 15% for Auckland, Hamilton, and Christchurch, respectively. Until 2080, the percentage increase in overheating compared to today is projected to be 254%, 160%, and 61%, respectively. These considerable changes show Auckland will shift from an urban area that demands energy for heating to a cooling-dominated climate until the end of this century [85]. These changes have a significant impact on people, economies, and the natural environment [84].

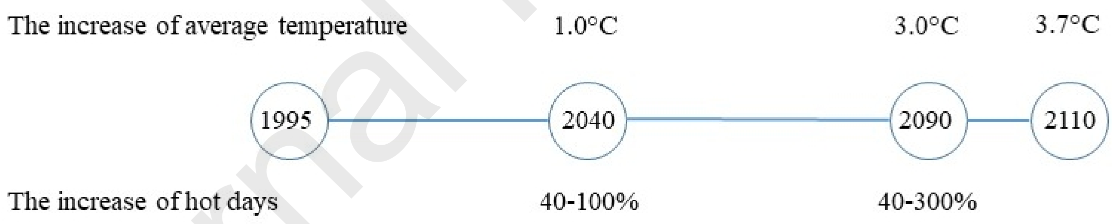

Figure 1 - The timeline of the increase of average temperature and number of hot days in New Zealand

4.4 Reports on urban heat islands effect in New Zealand

There is a high chance of intensified UHI effect in NZ due to climate change impacts on the built environment [85]. Extended summer heatwaves might not be an issue in some coastal cities in NZ (for example, Auckland), but the rapid urbanisation, the increase in aged population, and a rise in average temperature, the health risk to residents of coastal urban areas will increase in future [86]. Boarin et al. [21] point out that urban areas with intensive development are at more risk of UHI effects. They suggest that in the temperate climate of NZ, UHI affects energy usage, air conditioning load, weather patterns, and population health. They argue that conducting a Post Occupancy Evaluation of an urban area, including UHI measurement, can help develop an understanding of the effects of UHI in urban areas.

Their report notes that the provision of green and open spaces and neighbourhood design has been shown in other climates and cultures to contribute to UHI mitigation and improve wellbeing and liveability in cities. However, there is a lack of policies and guidelines to address the UHI phenomenon in local policies and guidelines [59] and even in the national climate change policy published by the Ministry of Environment. It is not clear how the international solutions to UHI might be applied to New Zealand's urban climates.

Jing et al. [81] demonstrated that the effect of UHI on the need for cooling ventilation requires a careful understanding not only of the density of buildings and roads in the urban environment but also of the effect of these buildings on wind flows and temperature variations between the buildings. There is a dearth of these studies internationally [16]. The current focus of New Zealand codes and standards development is on increased airtightness and insulation to address what is seen as a national problem of "cold, damp houses". To avoid these developments leading to a rise in summer mortality due to heat stress, New Zealand needs far better empirical data on the structure of sun, wind and temperature within the urban environment.

5 The urban microclimate of Auckland

5.1 Overview of the selected area

Auckland is the largest city in New Zealand, with a 1.4 million population. It is located on the North Island (Figure 2) and has the fastest growth rate among all regions in New Zealand [23]. The city is characterised as an attractor of business, tourists, and migrants and contributes almost 40% of the country's GDP [87]. The NZ urban system is strongly dominated by Auckland. The national economic trend towards concentration in Auckland has further increased since the 1980s in response to wide-ranging economic and state sector reforms to deregulate the New Zealand economy [88]. Auckland is a metropolitan region consisting of several districts [23], [89]. Although Auckland is relatively small in the global league of metropolitan cities, it shares concerns comparable with some more prominent cities in developed countries [90].

Auckland experiences a subtropical climate with warm and humid summers, mild winters, and a few touches of frosts each year. Rainfall is typically plentiful all year round. Most regions of Auckland receive around 2000 hours of bright sunshine per year [91]. Most of the Auckland region has mean annual temperatures between 14 °C and 16 °C. The eastern areas of Auckland are generally warmer than the western areas [91].

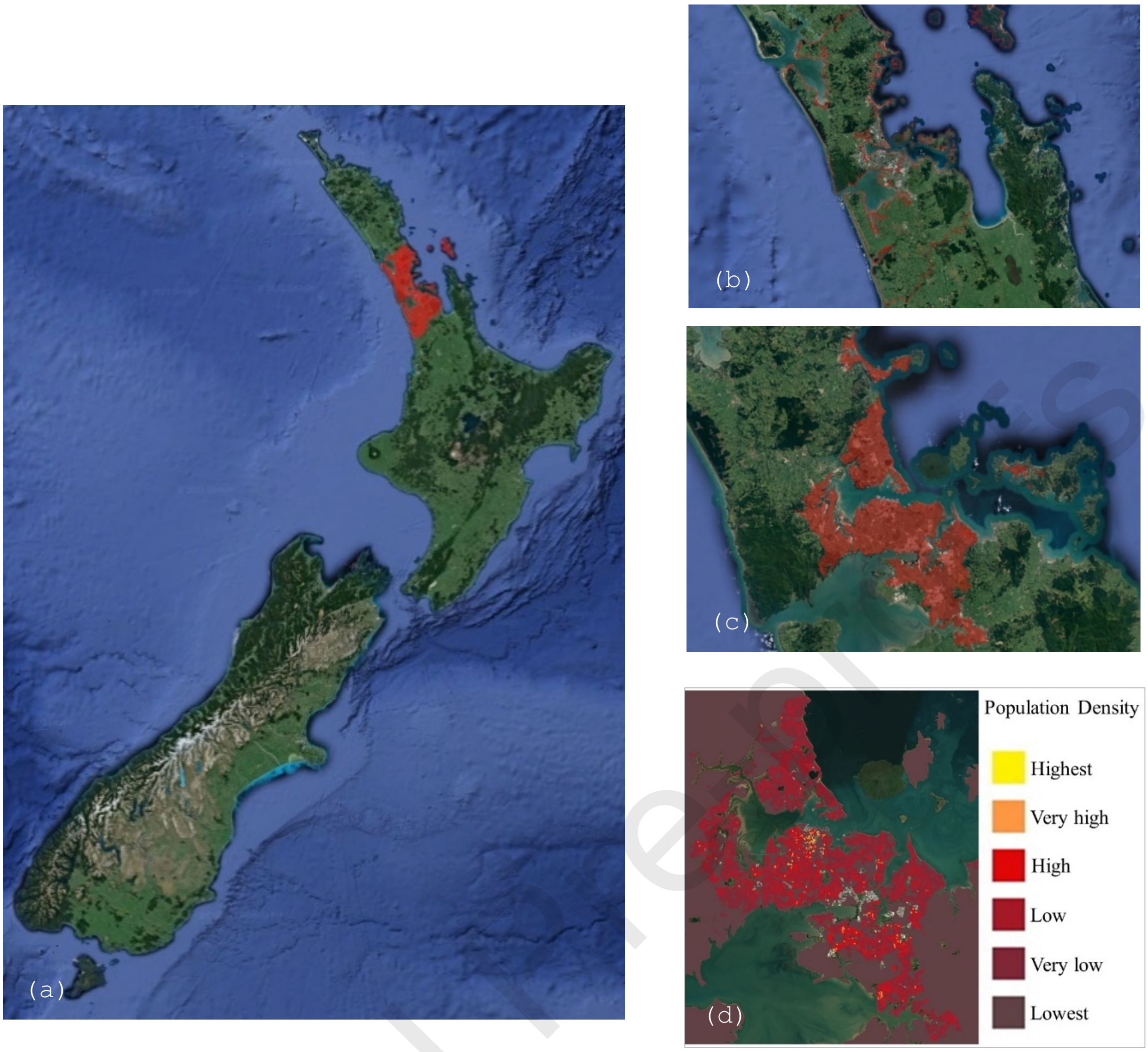

Figure 1 - (a) Map of New Zealand (b) Location of Auckland region (c) Map of Auckland urban area (d) Map of population density in Auckland city (Source: www.arcgis.com)

Auckland is a windy city. It experiences much more wind every month of the year than ‘windy’ North American cities like San Francisco and Toronto or the UK city of Leeds. It is a little less windy than in Boston. Examining the UHI changes as the effects of anthropogenic climate change are experienced will require a sound data-driven understanding of the spatial variations (vertically and horizontally) of temperature, humidity, wind flows, and solar radiation.

5.2 Impact of climate change on the future urban microclimate of Auckland

Climate change will affect the future urban microclimate of Auckland considerably [24]. According to NIWA, the criteria for a ‘hot day’ in Auckland is days with a maximum temperature higher than 25 degrees. All climate change scenarios indicate considerably warmer temperatures (above 25 degrees

Celsius) and the probability of extreme heat weather events in Auckland in future years [24] [92]. Mean annual and maximum temperatures are estimated to increase during the 21st century. The frequency of warm extremes will rise, and the number of cold nights and frosts will decline. Most of Auckland is projected to experience over 70 more hot days per year (days > 25°C) by 2110 under RCP8.5 and 30-40 more hot days per year under RCP4.5 [92].

Auckland experiences 20 hot days per year, contributing to the 14 heat-related deaths per annum recorded for the elderly age group in Auckland and Christchurch [18]. Based on the heat vulnerability assessment of at-risk community groups in the local council in Auckland, the Central Business District (CBD) of Auckland and the South of Auckland are high-risk areas in Auckland. The condensed architecture of tall buildings (Figure 3), high vehicle traffic volume, and densely populated urban street canyons (Figure 4) increase the heat vulnerability in the CBD of Auckland. The report emphasised social infrastructure and growing green spaces to reduce the heat vulnerability in Auckland [93].

The Climate Change Risk Assessment technical report series produced by Auckland Council identified the key risks to the region [24]. Temperature changes will alter anthropogenic air pollution emissions in Auckland. The higher temperature is expected to increase the air conditioning load in urban areas in Auckland and is assumed to decline wood-burning emissions due to warmer winters. Solar radiation is expected only to change a little [92].

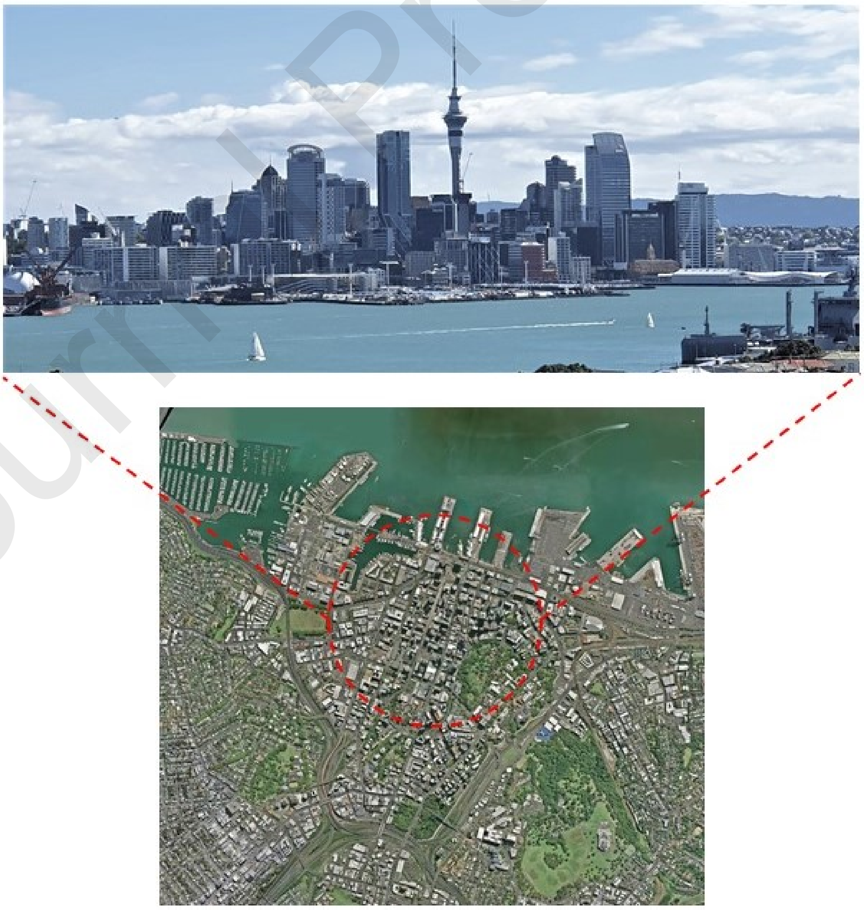

Figure 2 – (a) Central Business District of Auckland region (Source: Authors) (b) Satellite image of Central Business District of Auckland region (Source: data.linz.govt.nz)

Figure 4 - Street-level photos of CBD of Auckland (Source: Authors)

Figure 5 - The vegetation map of Auckland and the green urban spaces
(Source: (a): [94], (b): [95], (c): [96], (d): [97])

5.3 Future urban development of Auckland and land use patterns

Currently, there are around 1.66 million people in Auckland ,and the predictions show that Auckland's population will grow to 2.4 million in the next 30 years [98]. Auckland's population is distributed over a large land area with a remarkably lower density compared to the population distribution in European and Asian cities. The cultural preference of Aucklanders is currently low-density living (See Figure 8), relying on high private mobility that affects historic spatial urban growth patterns in Auckland [89]. However, over the 30 years from 2017–2047 [99], the Auckland City Council proposes that urban growth will likely occur in the existing urban area. As a result, the density of the city centre will increase remarkably (Figure 7) [99]. The degree to which UHI is an issue is a delicate, climate-specific balance between climate plus green surfaces and street canyons (Figure 4) that reduce wind speeds and increase the temperature, as well as increase the reflection of radiation from facades. In addition, the higher population density leads to more human activities and traffic, which both risk increasing the microclimate's temperature [100].

This significant growth requires a development strategy to understand the needed investment in planning and infrastructure [101]. Integrating climate knowledge into future planning is crucial to provide a foundation for developing climate-conscious urban development for Auckland and considering the impacts of urban development on the microclimate of Auckland. According to the Auckland City Council Climate Plan [24], noticeable population growth will significantly change Auckland's built environment by increasing the thousands of new homes, infrastructure, and commercial buildings. The plan argues that the integration of future climatic risks in the planning system for this development could produce more resilient and sustainable regions. It sees the assessment of performance and function of existing and future built environments as critical for the success of Auckland's climate goals.

Climate-aware urban design must balance the potential UHI effects of densification, the localised increases in wind speed to uncomfortable or even dangerous levels, the need to ventilate streets to avoid pollution and the sun shading effects that increase winter discomfort. Following Jing et al.'s demonstration that international climate lessons do not apply [16] locally, understanding Auckland's microclimates requires understanding the spatial distribution of temperature, wind, and sun across the region correlated with the terrain and building density data.

Figure 6 - Land use changes of Auckland city from 1985 to 2020 (Source: Google Earth)

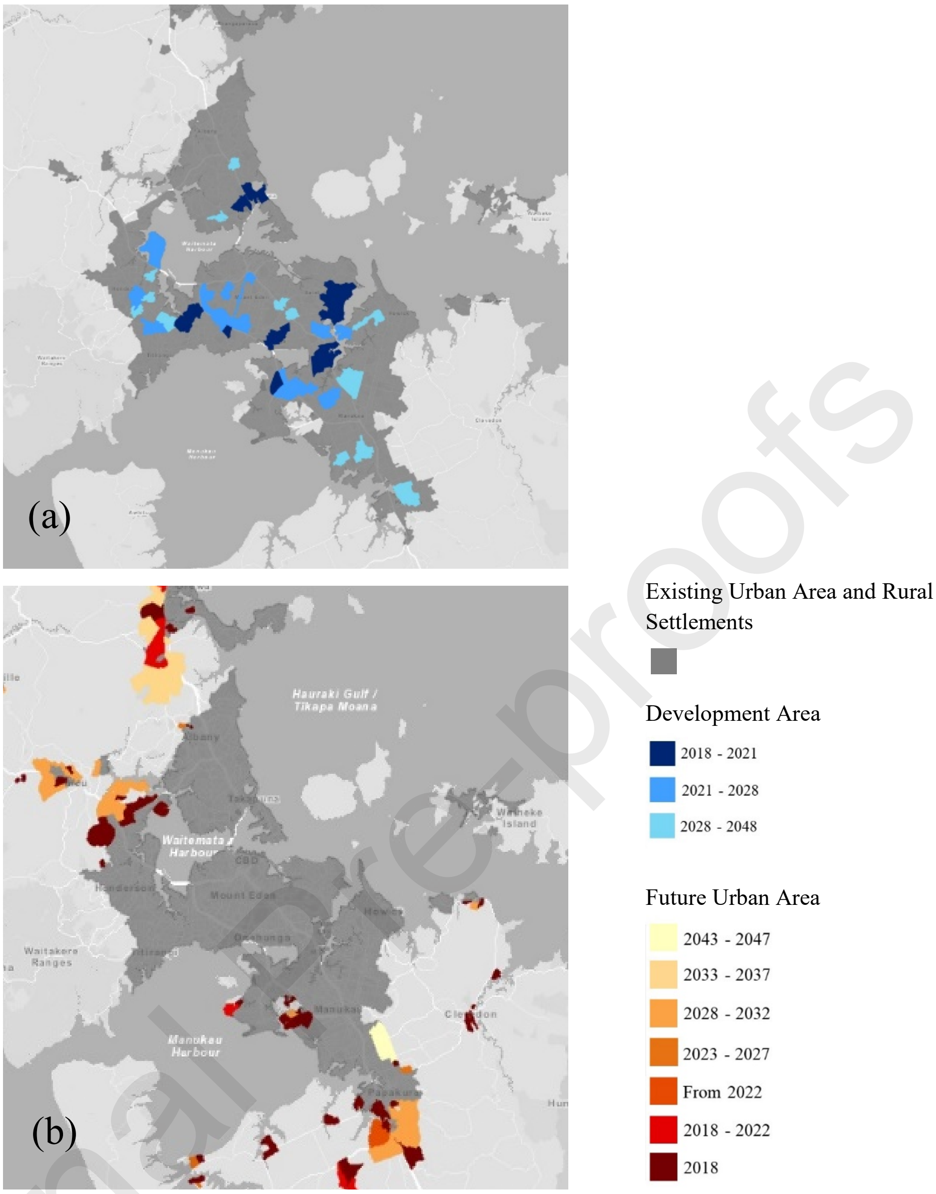

Figure 7 – The map of (a) development of current urban areas and (b) Addition of future urban areas (Source: www.aucklandcouncil.govt.nz)

Figure 8- Low-density residential areas in Auckland (Source: Authors)

6 Discussion

This review of studies focused on urban microclimate in New Zealand has demonstrated that very little measured data exists. This restricts understanding of urban microclimate status, UHI intensity, and the relative impacts on outdoor thermal comfort.

One of the most common themes in the presented papers is the analysis of meteorological data to find the temperature change in a specific location. The increase of the UHI effect is addressed in the literature by the numerical analysis of meteorological data on locations in cities and rural areas. The main weakness of these New Zealand studies is in the quantification of urban-rural temperature data on a few particular, extreme days from meteorological measurement stations without considering other factors such as climate change or annual climate patterns. The available work suggests that the UHI effect may exist in some urban areas at particular times in winter but does not address the intensity, magnitude, and duration of UHI. The reported analyses thus far have been based on regional weather measurements from NIWA and the Meteorological Service and a single set of microclimates measurements along two transects through Christchurch on a cold night during the 1970s [77].

Understanding UHI, wind, and solar effects on the environment between buildings and hence on the Indoor Environmental Quality of the adjacent urban buildings need reliable data. Models for these urban microclimate factors exist. However, they require good quality calibration data that does not yet exist.

If Computational Fluid Dynamics models of airflow, and urban energy balance models, are to be linked reliably to long-term weather records for a region, then we require time-series records of the key parameters from a range of intra-urban locations that can be correlated against the weather recorded at the extra-urban locations of standard meteorological weather stations. This would ensure that, in

combination with standard energy performance simulation tools, they might eventually become reliable predictors of the urban microclimate.
A few studies investigated the impacts of urban microclimate on the human thermal comfort of city residents through employing qualitative data collection and analysis [78], [79]. The outdoor thermal comfort was tested on a limited case study of urban space in Christchurch [73]. The limitations of the method and the case study make it difficult to expand the results to further cases or urban environments in NZ. Moreover, investigation of the adverse effects of UHI on the health conditions of city dwellers, primarily through measurement of the outdoor thermal comfort criteria, is neglected.
Conducting research that establishes an approach based on the standards of outdoor thermal comfort, ISO 7730 [102] could provide a basis to assess and compare the status of outdoor thermal comfort.
Looking at the whole analysed documents, a significant time gap between the conducted studies on the topic is revealed. The publication years of the previous studies show some research assessing the UHI effect was carried out decades ago [66]. Moreover, those studies with measured microclimate data typically have a record that lasts 1 – 2 days. Given the constant changes to the urban microclimate and the dynamic nature of the factors affecting the urban microclimate, the results of these studies are unlikely to be reliable for identifying the status of the urban microclimate in NZ. Using technologies such as sensor network and incorporating the ideas of Internet-of-Things to support microclimate modelling would assist with analysing patterns of urban microclimate [103].
Among the limited studies, the focus has been on Christchurch, with a small amount of data available on Wellington and Auckland. Likewise, limited coverage of case studies and data acquisition is another weakness. Micro-scale urban elements and their effect on thermal comfort are addressed minimally in Auckland. The existing urban plan has been considered for the assessment. The variables of future urban morphology and urban development as the factors that would affect the results have not been considered in the studies.
The methods and approaches of assessment focus on the existing condition of urban microclimate rather than predicting the future condition and trying to analyse and compare the existing conditions to the future scenarios. Climate change will have significant effects on the urban microclimate in NZ [85], and analysing the climatic data in a wide timeframe could illustrate the flow of changes to the urban microclimate. This is specifically important due to the tangible effects of global warming on the number of hot days and heatwaves that will be intensified in future years.
The impact of climate change and the uncertainty of its impact on future temperature rise and heat-related extreme events such as heatwaves are among the factors that have not been addressed in the past research. Underlying this whole field are laboratory, rather than field-based, assumptions about comfortable temperatures, air speeds, air quality, and solar radiation conditions. Most of this data about 'comfort ranges' is based on office-style activities for working-age adults. Choices and behaviours at home and outdoors are too often erroneously assumed to be consistent with these sedentary tasks [37], [104]. For example, it is common to report temperatures greater than 25^{o}C indoors are too hot for

comfort and health in much of the literature that has been sourced on New Zealand when the standard Fanger office-based comfort measures would suggest that this is a temperature most would find reasonably comfortable.

The lack of any reliable and accurate New Zealand UHI intensity analysis hinders the investigation of appropriate approaches for and mitigation osf UHI. No research on specifically exploring or testing appropriate mitigation strategies of UHI was identified.

7 Conclusion

This review has identified a knowledge gap related to urban microclimate conditions in New Zealand cities through investigation of the methodological approach, main findings, and context of studies regarding the chronological order of studies. Urban development and CC impacts as the two main factors affecting the urban microclimate were explored. This research provided an overview of the impacts of CC on the urban environment and the necessity of considering the importance of urban microclimate importance on urban development.

Urban morphology is a crucial factor that should not be eliminated from the urban microclimate models. Only land-use changes are assessed in old studies, and the effects of urban morphology are neglected. This becomes more critical when looking at the studies on CBDs. We can find almost no studies working on the CBDs as one of the most vulnerable sectors of a city under the effect of UHI due to urban morphology characteristics such as density of people per square kilometre, height and spacing of buildings and effects of the local terrain. An example of local terrain effects can be found in the early Christchurch studies, which focused on pollution and queried cold air drainage from hills to pools in valleys, eventually 'draining' to the sea.

Auckland city is the largest and most populated city in NZ and is under rapid urban development. This makes consideration of an environmentally friendly future urban microclimate in the development plan urgent. It is necessary for most urban spaces, not only in New Zealand. However, the size and intensity of development in Auckland, and the predicted increase in summer overheating events due to anthropogenic climate change, suggest it should be the starting point in New Zealand for the study of the impacts of urban development and climate change. The focus needs first to be on outdoor thermal comfort and safety in extreme winds.

The dynamic behaviour of factors affecting microclimates, such as temperature and airflow, makes it necessary to provide models that consider the constant changes to the urban microclimate. Armed with empirical data on urban microclimate, and as a result, trusted models of microclimate, it will be possible to model comfort and health inside buildings during the design process or as part of any policy development. The factors that need to be measured, and hence modelled, are the differences both horizontally across the city and vertically at representative points:

- of the temperatures, focusing on regions representative of different intensity levels of building development (near and away from water bodies; near and away from parks of different scale; near and away from tall narrow streets;
- of wind focusing on regions very similar to the focus for temperature but recognising exposure to prevailing winds;

And solar radiation, focusing on the effects of vegetation vs. solid surfaces; trees as shade vs open tarmac. The goal is to provide: 1) holistic, context-based UHI, airflow, and radiation measurements that can be used to develop tools that can be used to design mitigation strategies and solutions; 2) information on the way to examine the effects of future development of cities on UHI; and 3) develop optimised urban design guidance for New Zealand.

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