Building and Environment 243 (2023) 110627

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Impact assessment of climate change on energy performance and thermal load of residential buildings in New Zealand

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ARTICLE INFO

Keywords:
Climate change
Residential buildings
Heating and cooling energy demand
Climatic zones
Energy performance

ABSTRACT

While it is evident that climate change will have an impact on the energy demand for heating and cooling in buildings, the exact extent of this impact is not yet fully understood. Quantification of future cooling and heating need in buildings provides a basis for taking appropriate measures for building climate change adaptation. The focus of this study is to examine how future climate change scenarios will impact the heating and cooling of residential buildings across different climatic regions in New Zealand. The future weather data under changing climate were generated for six climatic zones of New Zealand employing the statistical downscaling method. The study used various climate change scenarios, which represent concentration pathways (RCPs), to generate weather data. Specifically, the RCP8.5 and RCP4.5 scenarios were employed in the building performance simulations for different prototypes of residential buildings. The results showed there would be a significant change in the thermal performance of residential buildings, with a noticeable increase in cooling load and a decrease in heating load. These changes include a maximum thermal load change of 3 kWh/m^2 in Auckland by 2090, 2.7 kWh/m^2 in Hamilton, 8.3 kWh/m^2 in Wellington, 4.2 kWh/m^2 in Rotorua, 11 kWh/m^2 in Christchurch, and 11.6 kWh/m^2 in Queenstown. The warmer climatic zones are expected to change from a heating dominated to a cooling-dominated zone. The results indicated the importance of considering present and future climatic conditions in design and establishing a foundation for actions for the resilience of buildings to climate change.

1. Introduction

Climate change adaptation and mitigation of the adverse impacts of climate change is one of the hugely significant challenges of the world in the twenty-first century [1]. Global warming, as an important threat, will have a noticeable influence on the building's energy performance [2] regarding higher average outdoor temperatures in future decades [3–5]. The impact of climate change on the indoor environment of buildings has been classified in prior studies into three categories: "heating and cooling demand," "HVAC system" (referring to heating, ventilation, and air conditioning systems), and "power peak demand." [1]. Climate change is predicted to significantly affect the cooling and heating in buildings because of changes to the weather features in future years [6–8]. The impacts of climate change on buildings' energy consumption could be both negative and positive [9]. The extent of these effects is still unclear [10]. The useful life span of the buildings is for decades, which means that even the gradual effects of climate change, like temperature rise, can affect the performance of the buildings in the long term [11,12].

Understanding the impacts of climate change on buildings to prepare for the future, adapt to the effects, and take appropriate actions and measures to adapt to negative impacts is crucial [7]. One of the crucial factors in assessing climate change's impact on a building's energy consumption is the thermal load which has a noticeable proportion of the building's energy performance for cooling and heating systems [1].

The consequences of the effects of global warming are considered to be underestimated by building designers [5]. Studying alternative features in buildings is required to perform more effectively in contemporary and future climates [13]. Most previous research on climate change in the building sector has been around mitigation plans and actions [14], and there is a knowledge gap on managing risks and adapting to climate change in the building sector [13,15].

The previous studies on the impact of climate change on energy consumption in buildings were reviewed to identify trends, patterns, and gaps in the existing literature. The articles are selected to encompass various geographic locations, climate change scenarios, residential

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https://doi.org/10.1016/j.buildenv.2023.110627
Received 28 March 2023; Received in revised form 15 July 2023; Accepted 17 July 2023
Available online 17 July 2023

building types and the timeframe of the study. Furthermore, previous investigations have served as valuable references in shaping the methodology employed in this present study, contributing to its development and refinement.

Shourav et al. [16] created models using historical data and climate variables such as temperature and rainfall to examine how the energy performance of buildings may change in the future due to the effects of climate change. According to the findings, the increase in temperature resulting from different climate change scenarios would have a significant impact on residential energy consumption. The study analysed the peak energy demand and overall energy demand of residential buildings in Dhaka city under four RCP scenarios. This suggests that the effects of climate change on buildings can be substantial and require attention to reduce their potential negative impact on energy consumption [16].

Ciancio et al. [4] conducted research to investigate the effects of climate change on energy performance in 19 cities across various latitudes and climatic regions in Europe. The research findings revealed that, as a result of climate change, the energy requirements for winter heating in buildings tended to decrease, while the energy demand for summer cooling was projected to increase, particularly in the southern regions of Europe. The research suggests that the increase in cooling demand resulting from climate change is expected to be greater than the decrease in heating demand. As a result, the overall energy demand for buildings is likely to increase, which has important implications for energy consumption and greenhouse gas emissions [4].

Rodríguez et al. [5] aimed the estimation of the energy performance of a minimum energy building in three time periods of present, past, and future in a subtropical climate, which is typical of coastal cities climate in the south of Spain. The research utilised climate data from various time periods, including historical periods as well as projections for the 2020s, 2050s, and 2080s. The climate data was based on four different emission scenarios, which were B1, B2, A2 and A1F1. These scenarios represent different levels of greenhouse gas emissions and their potential impact on climate change. Scenario B1 the scenario describes a future world with a focus on global sustainability, environmental protection, and social equity. Scenario B2 presents a future world that emphasises local and regional sustainability, with moderate population growth and intermediate economic development. Scenario A2 depicts a future world characterised by high population growth, slower economic development, and a focus on regional self-reliance. Finally, the A1F1 sub-scenario specifically focuses on fossil fuel-intensive development, assuming a reliance on coal, oil, and gas as primary energy sources. Electricity needed for heating was estimated to diminish, and electricity required for cooling was expected to increase considerably. Overall, the current energy consumption will change for the worse due to the impacts of global warming [5].

The results of studies conducted to investigate the relationship between climate change and energy consumption suggest an increase in overall energy consumption due to climate change. Tootkaboni et al. [17] utilised the morphing methodology to develop future hourly weather data for different climate change scenarios, with the aim of assessing the risk of overheating in Milan, Italy. The study analysed the energy performance of buildings in both the short-term (2021–2040) and long-term (2081–2099) periods and found that heating energy consumption would decrease by approximately 30.9% while cooling energy consumption would experience a significant increase of 255.1%. Furthermore, the study revealed an alarming rise in the risk of overheating of up to 155%. These significant changes in building energy consumption underscored the need for the inclusion of climate change factors in future energy consumption assessments of buildings. The study highlights the importance of considering the potential impact of climate change on building energy consumption and taking appropriate measures to mitigate the risks associated with climate change-induced changes in energy consumption patterns [17].

Kishore [18] conducted a study on the impacts of climate change on the bioclimatic potential of a residential building using EnergyPlus energy simulation engine. They used weather data for future years based on the A2 climate change scenario and found a strong correlation between the bioclimatic winter and summer thermal discomfort hours and yearly heating and cooling energy consumption. The results showed an increase in annual cooling energy consumption by 18–89% in 2020, 32–132% in 2050, and 58–184% in 2080 for five cities, compared to the base case, assuming no changes in the operation of the residential buildings in the future. These findings highlight the importance of considering climate change impacts in future energy consumption assessments of buildings [18]. Understanding and incorporating climate change factors are essential for developing strategies to mitigate risks and improve energy efficiency in buildings.

D'Agostino et al. [19] focused on the impact of climate change on building energy needs, specifically heating and cooling loads, cost-optimal efficiency measures, and renewable energy production. Eight European locations (Stockholm, Milan, Vienna, Madrid, Paris, Munich, Lisbon, and Rome) were examined to highlight climate variations and weather datasets were evaluated for changes in climatic parameters. Future climate scenarios for 2060 were analysed, revealing significant changes in energy balance: heating will decrease by 38%–57% while cooling will increase by +99%–380% depending on the location. Improved energy efficiency measures will be essential, enabling renewable energy to meet building needs and reducing peak demand [19].

Hosseini et al. [20] assessed the future energy performance of two representative residential buildings in an urban area in Southeast Sweden. Future climate data synthesised from 13 climate scenarios and microclimate data considering urban morphology were incorporated. The findings reveal that microclimate can lead to a 17% increase in cooling degree-days (CDD) and a 7% reduction in heating degree-days (HDD) on average compared to microclimate. Over successive 30-year periods, CDD increases by 45%, and HDD decreases by 8% under typical weather conditions. The study also demonstrates that annual cooling demand can become four to five times larger in 2040–2069 and 2070–2099 compared to 2010–2039. Additionally, the annual overheating hours can increase by up to 140% in the future. These findings highlight the importance of considering climate variations to avoid maladaptation or insufficient adaptation of urban areas to climate change [20].

The overview of the available literature shows that geographical locations will have a crucial role in the evolution of energy requirements in the future years [4,21]. For countries with similar climatic zones, noticeable differences have been reported [1]. The findings of studies related to this topic are heavily influenced by several factors, including the projected climate change scenario, the type of building being studied, and the geographical location [11,17]. This makes performing a regional and localised analysis necessary [17]. The extent and nature of the impact of climate change on building energy consumption may vary significantly based on these factors, which highlights the importance of taking a localised and context-specific approach when developing strategies to mitigate the potential effects of climate change on building energy consumption.

Existing and future building stock performance is expected to be affected by climate change in New Zealand [15,22]. Climate change adaptation in New Zealand is scoped mainly at the city and neighbourhood level, and there is still a gap in climate change adaptation at the individual building level [13]. The potential impacts of climate change on housing energy performance in New Zealand have been explored by considering different scenarios [16]. Changes in intense weather events and temperature are the major factors affecting the buildings in New Zealand [13]. Quantifying the climate change impacts and the risks of climate change to the energy consumption of buildings improves the establishment of threshold criteria for climate change adaptation [23]. This can accelerate the investigation of prospects of adaptation and intervention in buildings [24]. Taking early actions toward climate change impacts will generate an effective and lowest-cost response to protect buildings against [15]. Developing policies and strategies to reduce long-term risks to new and existing building stock accelerates a precautionary approach to the effects of climate change [15].

The risk of overheating and increasing thermal load in buildings can be reduced by taking adaptation intervention actions [25]. Quantification of the impacts facilitates the realistic assessment of the potential impacts [25] and provides the feasibility of a standardised approach that integrates climate change into the building design [6].

In New Zealand, the impact of climate change on the energy performance of housing and the need for climate change adaptation at the individual building level are areas that require attention [13]. By exploring climate change impacts in all climatic zones and major housing typologies in New Zealand, the research seeks to understand the patterns of change in energy consumption and provide recommendations for strategies to help the building sector adapt to climate change. This study contributes to the development of threshold criteria for climate change adaptation and informs building design approaches to protect buildings from overheating and increased thermal load. Overall, it aims to facilitate a standardised approach that integrates climate change into building design and enables effective and low-cost responses to climate change impacts.

The primary objective of this paper is to quantify and analyse the potential impact of present and future climate change scenarios on the heating and cooling requirements of residential buildings located in six different regions across New Zealand, representing all regional climates in the country. Identification of potential patterns of change in building energy consumption under different scenarios and residential building typologies provides valuable insights into the potential implications of climate change through assessing vulnerabilities and helping to set performance targets. This will potentially lead to the development of recommendations for strategies to help the building sector adapt to climate change.

2. Materials and methods

This study investigates the potential impacts of climate change on the thermal performance of residential buildings from 1999 to 2015 to 2090. The available historical weather data (1999–2015) was used to assess the current buildings' cooling and heating demand. Future climate data for six cities in New Zealand, each representing one of the country's six climatic zones, were generated based on the Coupled Model Intercomparison Project Phase 5 (CMIP5). According to the statistical downscaling method and the historical hourly weather data, weather data of two climate scenarios were acquired by Meteonorm software for use in the building performance simulation. Meteonorm software was selected because of data accuracy and reliability, wide geographic coverage and providing comprehensive meteorological data parameters [26].

The assessment looks into climatic projections for four future periods of 2030, 2050, 2070, and 2090 following two RCPs of 4.5 and 8.5. The two scenarios being considered are RCP8.5, which represents the highest level of carbon emissions, and RCP4.5, which is an intermediate stabilisation scenario that assumes the implementation of conservative greenhouse gas reduction plans [27].

As a case study, the research considers two typologies of residential buildings based on a report on the update of the energy efficiency building code of New Zealand [28]. A six-stage methodology, as shown in Fig. 1, was undertaken to study the behaviour of these buildings and their performance assessment following the phases of (i) Generation of

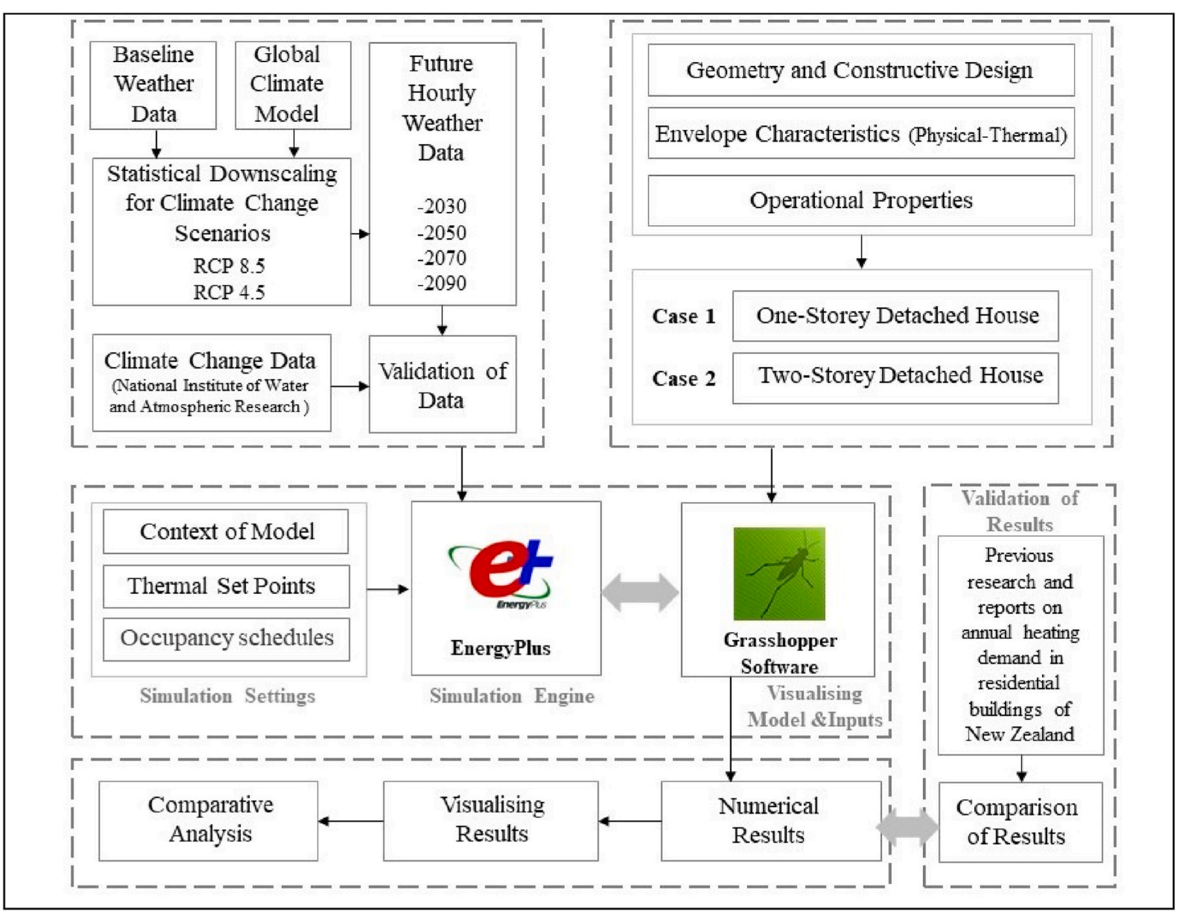

Fig. 1. Flowchart of the employed methodology.

future weather data based on locations, Bioclimatic zone characterisation and climate change projections, (ii) Introducing reference buildings characteristics; (iii) Visualising model and simulation settings; (iv) Validation of the results; (v) Reporting and visualising the results.

2.1. Generation of future weather data

In order to simulate the future behaviour of the building prototypes, it is necessary to generate future weather data. Obtaining accurate and dependable current and future climate weather data is essential in order to enhance the quality and reliability of research outcomes related to climate change [29]. This study used EnergyPlus Weather file (EPW) and typical metrological year (TMY) hourly weather files that are compatible with the simulation engine used in this study [30]. The data used as the baseline for the simulation includes several parameters such as relative humidity, dry bulb temperature, wind speed, wind direction, sky cover hours, sunshine hours, days of frost, and solar radiation intensity [31]. In this study, the baseline scenario for the weather file refers to weather data from 1999 to 2015, which is one of the common default data files used in building performance simulations. This information was obtained from the “OneBuilding” website.

After reviewing existing climate change weather datasets and methodologies for their generation, statistical downscaling was identified as appropriate for this research [32]. Statistical downscaling is a technique used to estimate local or regional climate variables using larger-scale climate data. It can be implemented through deterministic or stochastic approaches, depending on whether random variability is explicitly accounted for by including a noise term. In the past, statistical downscaling has been favoured over dynamical downscaling due to its simplicity and the challenge of interpreting results from the latter method [32].

The baseline weather files, including International Weather for Energy Calculations (IWEC) files, were uploaded to Meteonorm software to obtain forecasted future weather conditions for each targeted location. In order to conduct a more comprehensive analysis of the simulation, the time periods of 2030, 2050, 2070, and 2090 were chosen to facilitate a more precise comparison of the results. Meteonorm software is predominantly based on the statistical downscaling method to estimate climate variables at the local level using available meteorological data. The software utilises the CMIP5 climate model and integrates multiple data sources, including satellite data, reanalysis data, and ground measurements, to build a comprehensive climate database. Meteonorm establishes empirical relationships between large-scale meteorological variables and local-scale parameters through statistical downscaling. It employs regression-based techniques and statistical models to downscale the available climate data to the desired location, taking into account factors such as latitude, altitude, and geographical characteristics to enhance accuracy. The tool relies on Global Climate Models (GCMs) as specified in the IPCC assessment report to provide data and information [31].

2.2. Location and climate

New Zealand is located at 88° 01′ E − 92° 41′ E longitude and 20° 34′ N - 26° 38′ N latitude [33]. New Zealand belongs to the tropical region climatically [34]. Based on the building code of New Zealand, there are six climatic zones in New Zealand (Fig. 2) [33] (see Fig. 3).

In this study, six cities that are among the largest cities of New Zealand, and each belongs to one of the climatic zones, are considered as the case study. Location information of each city and climatic zones are presented in Table 1.

2.3. Reference buildings

In New Zealand, detached houses are the most commonly built type of residential building [14]. An examination of the database of building consent applications for housing in New Zealand indicates that over 80% of residential buildings in the country are in the form of detached houses [36]. A study conducted by Viggers et al. [36] shows the percentage of detached housing compared to non-detached houses, townhouses and apartments. The analyses of statistics in New Zealand by their research show the floor area of most detached housing is from slightly less than 150 m^2 to more than 200 m^2. So, to cover a wide range of residential buildings, detached one-storey and two-storey buildings were selected

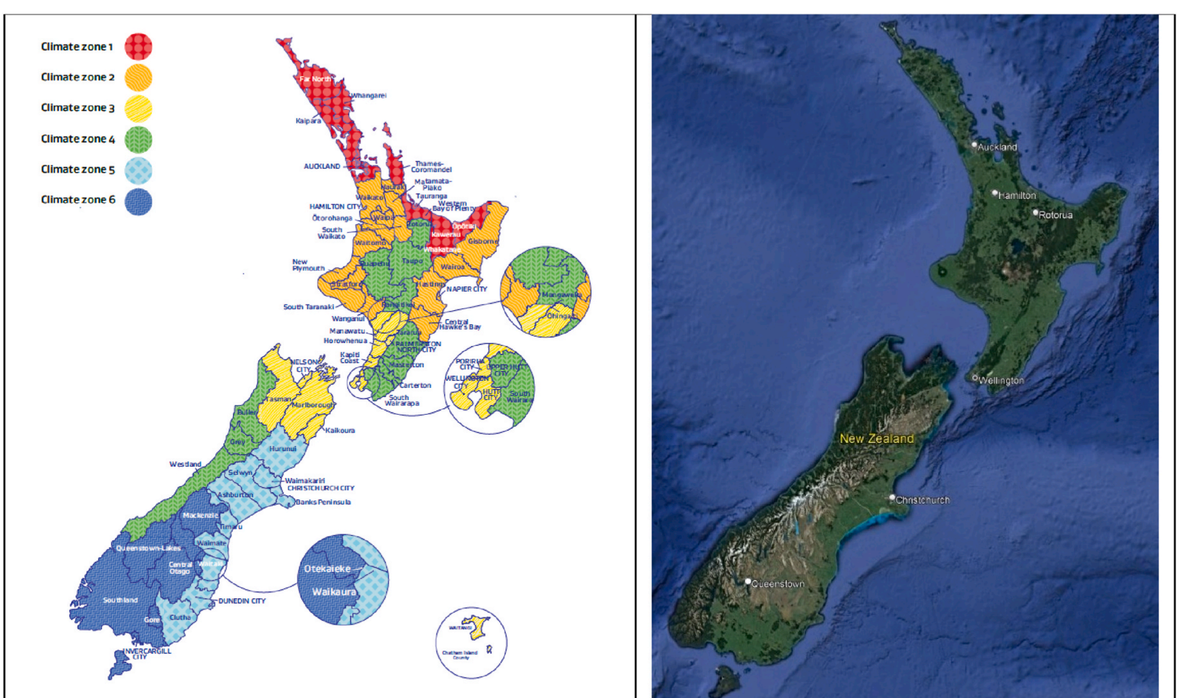

Fig. 2. Map of New Zealand’s six climate zones (Source: [33]).

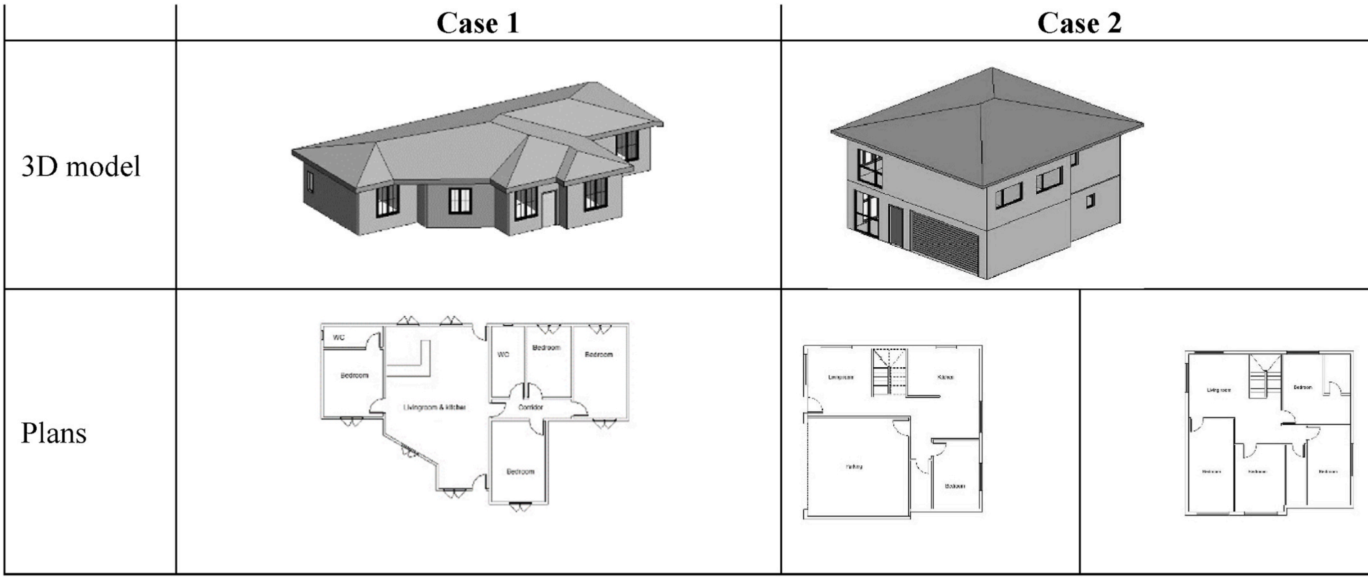

Fig. 3. Plan and perspective view of simulated models. Source: Authors.

Table 1
The climatic zones of selected locations (Source: [33,35]).

	Climatic zone	Description of climate zone	Average temperature	Altitude (m)	latitude (°)
Auckland	1	warm, humid and changeable without extremes of temperature	Summer: 14–24 °C Winter: 7–15 °C	196	−36.8509° S, 174.7645° E
Hamilton	2	Mild and temperate with moderate rainfall	Summer: 22–26 °C Winter: 10–15 °C	40	−37.7826° S, 175.2528° E
Wellington	3	Temperate marine climate, relatively windy	Summer: 17–21 °C Winter: 9–10 °C	10	−41.2924° S, 174.7787° E
Rotorua	4	Mild temperate climate	Winter: 9–12 °C Summer: 12–22 °C	280	- 38.1446° S, 176.2378° E
Christchurch	5	Warm, dry summers and cold winters.	Summer: 22.5 °C Winter: 11 °C	20	−43.5188° S, 172.5836° E
Queenstown	6	Cool summers and short and very cold winters	Summer: above 16 °C Winter: below 8 °C	310	−45.0106° S, 168.7203° E

as the model for simulation.

All models meet the minimum R-Value based on the update of the NZ building code. The minimum R-values of the exterior building components in the NZ building code for all six climatic zones are presented in Table 2.

The characteristics of the prototypes are represented in Table 3.

2.4. Building energy simulation settings

EnergyPlus was utilised as the simulation software to conduct the simulation. EnergyPlus is a building energy simulation software developed by the United States Department of Energy (DOE). EnergyPlus is a

Table 2
Update of Construction minimum R-values for housing and buildings up to 300 m^2 based on New *Zealand Building Code- Energy Efficiency - Source:* [33].

Climatic Zone	Building components				
	Roof	Wall	Floor (Slab-on-ground floors)	Floor (other than slab-on-ground)	Glazing
Zone 1	6.6	2.0	1.5	2.5	0.46
Zone 2	6.6	2.0	1.5	2.5	0.46
Zone 3	6.6	2.0	1.5	2.5	0.46
Zone 4	6.6	2.0	1.5	2.8	0.46
Zone 5	6.6	2.0	1.6	3.0	0.50
Zone 6	6.6	2.0	1.7	3.0	0.50

Table 3
Building construction properties.

Building element	Material (layers)	Total R-value (m^2·K/W)
Exterior Wall >2.2	30 mm Weatherboard 30 mm Cavity 0.2 mm Flexible underlay 90 mm Insulation and framing 10 mm interior lining	2.0
Roof >6.6	30 mm corrugated metal roofing 0.2 mm Flexible underlay 45 mm purlins 90insulations and rafter spacing 10 mm plasterboard ceiling	6.6
Floor (Slab-on-ground floors) > 1.7	20 mm Flooring 150 mm Concrete floor slab DPM under slab insulation Sand blinding and hardfill	1.7
Floor (other than slab-on-ground) >3.0	Flooring Floor joints and Insulation Lining	3.0
Window >0.50	LowE1/Clear (Argon) (Double) Frame: uPVC	0.5 Heat Gain SC:0.89

software used for simulating the energy consumption and environmental impact of buildings and their systems, such as HVAC, lighting, and renewable energy systems. EnergyPlus is one of the most reliable tools for energy simulation and is validated by the Standard ASHRAE 140–2014 [37]. The input of the simulation includes the geometry and construction types of the models, weather files under future climate change scenarios for the six locations, cooling and heating set points, the occupancy schedule of the models, and the neighbourhood and context of the models.

The building model was created using separate thermal zones for each individual room and space. The cooling and heating set points based on the New Zealand energy standard are set at 25 °C and 18 °C, respectively. The simulation run timesteps are based on the hourly steps of the calculations for an entire year. The occupancy schedule of the models is considered as residential buildings, which were considered between 6 a.m. and 10 p.m. in the living room and between 10 p.m. and 6 a.m. in the bedroom.

The terrain type that the models sit in is "Urban". The terrain type determines the wind profile of the context in which the model is based. The energy performance of the building is affected by the neighbourhood and the context that the model sits in. The context of the simulation is an urban area with similar buildings lower than 10 m and trees around.

3. Results and discussion

3.1. Validation of the results

3.1.1. Validation of weather data

To validate the generated data, weather data for future years up to 2090 in Auckland was compared to similar climate change data obtained from the National Institute of Water and Atmospheric Research (NIWA). This was done for the purpose of ensuring that the generated data is accurate and reliable [38]. The average monthly dry bulb temperature (dbt) was selected as the main parameter affecting the results.

The R-squared quantity is the square of the correlation and indicates the proportion of variation of the variables (see Fig. 4). The R-squared value R^2 range is from 0 to 1, and the higher value for R^2 shows more similarity in the datasets. As shown in Fig. 5, R^2 is equal to 0.9675 and in the acceptable range and shows the reliability of the generated data.

3.1.2. Validation of energy performance simulation

The simulation results were validated using a comparative analysis by comparing the outcomes of the study with the results of other independent studies [36]. The available research results on the cooling and heating of residential buildings in New Zealand were extracted and sorted to compare with the obtained results of this study.

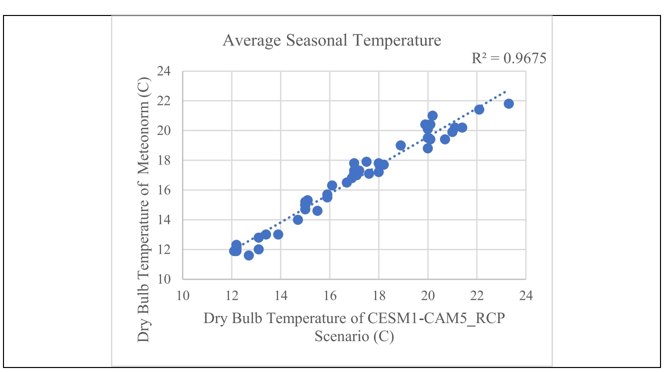

Fig. 4. Validation of the generated average monthly dbt.
CESM1-CAM5_RCP: The Community Earth System Model version 1 (CESM1) incorporates the Community Atmospheric Model version 5 (CAM5). Source [39].

Fig. 5 shows the space heating energy use for the samples of each city based on a study from the Building Research Association of New Zealand (BRANZ) on sustainability and housing in New Zealand [40] reported the requirements for space heating and a comfortable indoor temperature based on an evaluation of 70 selected buildings in 2012 in Christchurch. The results showed an approximate 25 kWh/m^2, 41 kWh/m^2 and 75 kWh/m^2 for heating demand for residential buildings in Auckland, Hamilton and Christchurch, respectively [40].

Viggers et al. [36] investigated the thermal performance and the heating demand in residential buildings in Wellington as a case study. The case studies included detached houses with different floor areas. The approximate energy needed for heating the buildings is around 39 kWh/m^2 [36].

Table 4 summarises the results of similar studies on New Zealand residential buildings simulation and the results of simulation using the building codes before 2021 updates in this study. The studies in question evaluated the energy performance of residential buildings prior to the year 2020 without any emphasis on their energy performance in the future.

The comparison of similar case studies and locations with the results of this study for the baseline weather data is aligned. The outcomes shown in Table 4 are based on the settings of the existing residential buildings in New Zealand. Regarding the time frame of the similar studies, the R-values and schedules used as inputs of the simulation were deprived of the New Zealand energy building code before the update in 2021 to be comparable with those studies.

3.2. Future weather data features

This section presents the findings of the study on future weather projections in New Zealand and compares them to current conditions to provide an overview of the expected changes in climate. The variation in the dry bulb temperature is the most important factor affecting residential building cooling and heating energy use [41]. The values presented in Table 5 display the rate of increase in monthly average temperatures of the year 2090 under RCP 4.5 and 8.5 compared to the weather data of 1999–2015 used as a baseline to analyse the temperature rise.

Comparing the forecasted future weather data with historical data suggest higher dry-bulb temperatures for all locations. Table 5 displays the monthly outdoor dry-bulb temperatures for future weather projections created by applying the statistical downscaling method to historical baseline climatic data. The table represents a consistent increase in monthly average temperatures for the future in terms of outdoor dry-bulb air temperature. Climate change impacts were recognised in the future weather data generated.

The baseline weather file and the period directly affect future weather file generation results. As shown in Table 5 the values of temperature rise until 2090 (RCP 8.5) range between 2.2 °C and 4.8 °C compared to baseline temperature data. The future weather files predict a mean temperature increase of 2.7–5.8 °C in summer and 2.4–4.1 °C in winter compared to the baseline period (1999–2015 baseline). The cities of Hamilton and Wellington are predicted to have the highest delta temperature values in 2090 (compared to historical measured data) and require special attention.

Under RCP 4.5, the average monthly temperature increased by approximately 6.6%–22.6% across the months, comparing the 2090 temperature data with the baseline data (Table 5). This value ranges from 18.6% to 34.9% for scenario RCP 8.5 by 2090.

Fig. 6 reports the annual degree days of heating and cooling for future weather data. Heating degree days (HDDs) represent the number of degrees below 18 °C that the building requires heating while cooling degree days (CDDs) indicate the number of degrees above 18 °C that require air conditioning. The overall trend in the future is expected to be a reduction in heating degree days and an increase in cooling degree days. Fig. 6 indicates a sharp rise in cooling-degree days, while heating-

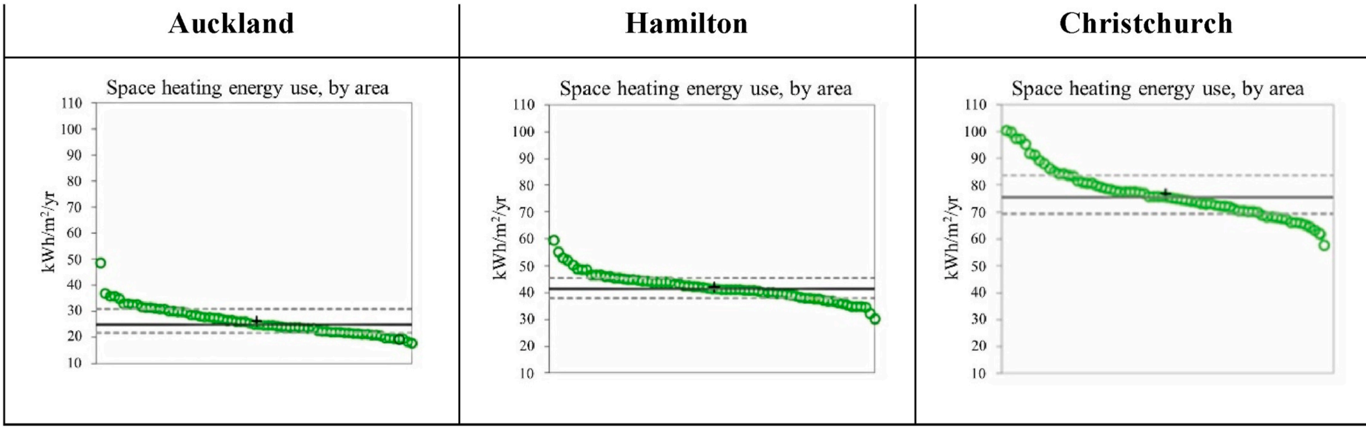

Fig. 5. The results for annual heating demand in 70 built-houses in Auckland, Hamilton and Christchurch (Source: [40]).

Table 4
The summary of the annual heating demand in residential buildings in similar studies.

Case study	Location	Results of similar studies (kWh/m^2)	Simulation results of the present study (kWh/m^2)	Ref.
One-storey detached residential buildings	Wellington	39	41	[36]
	Auckland	25	24.7	[40]
	Hamilton	41	41.6	
	Christchurch	75	68.9	

degree days are projected to decrease moderately.

During the baseline period, the average HDD value was 1321–2889 for Auckland and Queenstown, respectively. These values indicate the heating requirements for buildings in these cities under current climate conditions. Under the RCP 4.5 scenario, the HDD values are projected to decrease over time. By 2090, HDD is expected to be 709 and 2615 for Auckland and Queenstown, respectively, indicating a reduction in heating demands compared to the baseline period. The average CDD is reported to be 19–73 for Auckland (which is in the warmest climate zone) from the baseline period to 2090 under RCP 4.5 scenario conditions. This value varies from 20 to 24 for Queenstown, located in the coldest climate zone of New Zealand. These projections suggest that climate change will likely result in increased cooling requirements and decreased heating requirements in New Zealand cities.

3.3. Building energy simulation results

In this research, weather data was generated and utilised to evaluate the influence of climate change on two building prototypes and their thermal load. The primary goal was to investigate the behaviour of these buildings under changing climatic conditions over time. The study analysed various values for each location and scenario, including but not limited to:

i) The average amount of energy used for heating and cooling on an annual basis
ii) The cooling and heating demand required to maintain set temperature points throughout the year

The results of the analysis indicated a similar trend for both scenarios in terms of the quantities studied, demonstrating a decrease in energy consumption for heating and an increase in energy demand for cooling. Fig. 7 shows the cooling and heating values over the years. As expected, based on the results of temperature rise and cooling and heating degree days in the previous section, for most cases, the heating load experienced a slight decrease, while the cooling load exhibited a more substantial increase over the research period.

The study observed a significant difference in the heating and cooling requirements from 2030 to 2090, with a continuous increase in the cooling load. The results showed an increase in the annual cooling requirement of New Zealand cities such as Auckland (75% by 2090), Hamilton (53% by 2090), Wellington (79% by 2090), Rotorua (61% by

Table 5
Average monthly dry-bulb temperature under RCP4.5 and RCP 8.5 climate change scenarios by 2090.

Location	Climate change scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Auckland	Baseline	19.8	20.0	18.8	16.0	13.4	11.0	10.2	11.2	12.5	14.3	15.9	18.1
	RCP 4.5–2090	22.0	22.5	20.7	18.0	16.0	13.6	12.7	13.4	14.6	16.0	17.5	20.2
	RCP 8.5–2090	24.1	24.4	22.5	19.7	17.5	14.9	14.0	14.7	15.9	17.4	18.8	21.9
Hmailton	Baseline	18.5	18.7	17.4	14.3	11.4	8.9	8.3	9.7	11.2	13.1	14.7	16.9
	RCP 4.5–2090	22.4	22.5	20.2	17.2	15.0	12.2	11.0	12.2	14.3	16.4	18.2	20.9
	RCP 8.5–2090	24.7	24.5	22.0	18.9	16.4	13.4	12.3	13.5	15.6	17.6	19.3	22.6
Wellington	Baseline	18.1	17.9	16.7	14.1	11.9	9.7	8.9	9.6	11.0	12.7	14.3	16.5
	RCP 4.5–2090	19.8	20.2	18.7	16.1	14.7	12.4	11.5	11.9	13.1	14.2	15.8	18.3
	RCP 8.5–2090	22.1	22.1	20.6	17.9	16.2	13.9	13.1	13.5	14.5	15.7	17.0	20.1
Rotoroa	Baseline	17.9	17.8	16.5	13.3	10.3	7.9	7.3	8.5	10.1	12.2	14.0	16.3
	RCP 4.5–2090	20.6	20.6	18.1	14.7	12.5	9.7	8.8	9.7	11.6	13.6	15.7	18.7
	RCP 8.5–2090	22.5	22.3	20.0	16.5	14.1	11.2	10.2	11.2	13.1	15.1	17.0	20.4
Christchurch	Baseline	17.5	16.8	15.4	12.0	8.7	5.9	5.4	6.9	9.2	11.8	13.8	16.2
	RCP 4.5–2090	19.5	19.1	16.9	13.3	11.1	8.2	7.5	8.8	10.8	12.5	14.8	17.8
	RCP 8.5–2090	21.6	20.8	18.7	15.0	12.4	9.4	8.8	10.3	12.0	13.7	15.8	19.6
Queenstown	Baseline	16.7	16.5	14.6	10.9	7.3	4.3	3.8	5.7	8.2	10.7	12.8	15.2
	RCP 4.5–2090	17.8	17.6	15.3	11.2	8.6	5.6	4.8	6.5	9.0	11.1	13.2	16.0
	RCP 8.5–2090	19.8	19.3	16.9	12.8	10.0	6.9	6.4	8.0	10.1	12.2	14.2	17.5

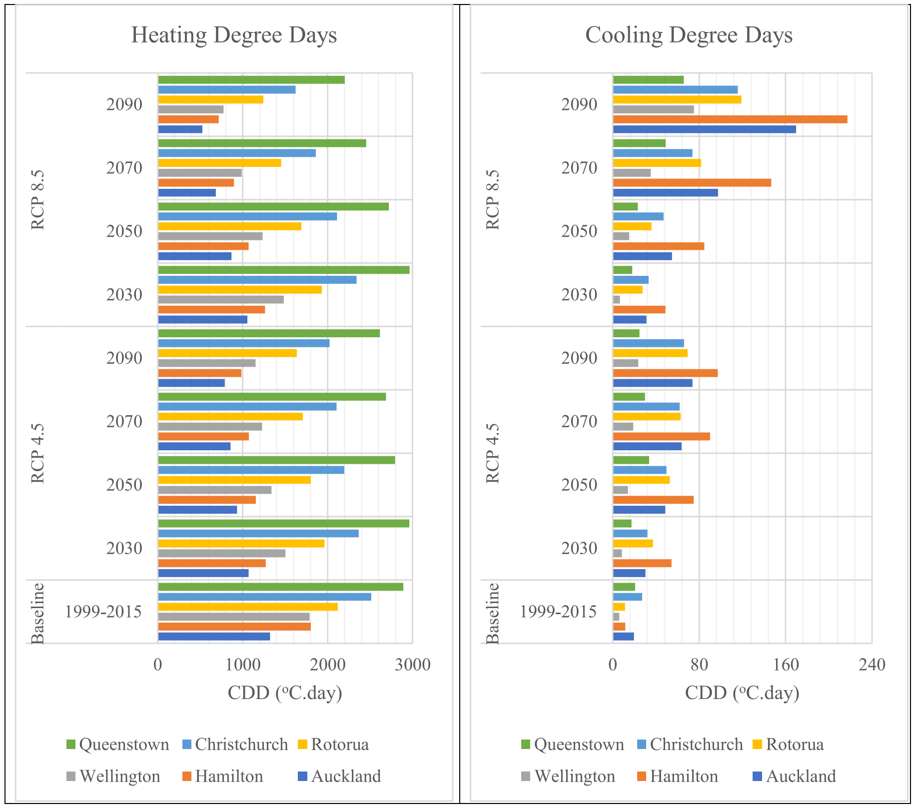

Fig. 6. The comparison of heating and cooling degree days of the case study in the six climatic zones.

2090), Christchurch (68% by 2090) and Queenstown (40% by 2090) for the one-storey detached building based on RCP 4.5. Similarly, for the case of scenario RCP 8.5, the increase in average cooling energy ranged between 184% and 380%, and the average decrease in heating energy ranged from 32% to 71%. The most considerable relative variation of the heating load was witnessed in Auckland around 9 kWh/m^2 decrease compared to the historical data (1999–2015).

The same conditions for the time frame and climate change scenario could potentially lead to a reduction in the annual heating requirement of New Zealand cities, including Auckland (38% by 2090), Hamilton (35% by 2090), Wellington (32% by 2090), Rotorua (22% by 2090), Christchurch (20% by 2090) and Queenstown (15% by 2090). The highest relative difference variation rate of the heating load was noticed in Auckland, with around a 71% (approximately 4 kWh/m^2) fall from 2030 to 2090. The minimum decrease of heating energy was for Queenstown (zone 6), with a 15% decrease from 2030 to 2090 based on RCP 4.5. In all scenarios examined, the research revealed a notable shift in the demand for heating and cooling between 2030 and 2090, with a rise in cooling load and a decline in heating load.

Fig. 7, which presents the annual thermal load results, shows a shift in the main share of thermal load from heating to cooling loads in some locations. By comparing the change range of thermal load, it is evident that in cooler climatic zones (zones 5&6), a decrease in thermal load in future is likely. Compared to the baseline data, thermal load in the case of scenario RCP4.5 decreased between 1.8 and 9.1 kWh/m^2 and decreased between 1.8 and 11.8% based on RCP 8.5 by 2090. The total energy use indicated a downward trend in colder climates of zone 5 and 6 (Christchurch and Queenstown), whereas more moderate climate zones (zone 1 and 2) experienced an upward trend in total energy use.

The results imply that the intensity of variation in heating and cooling is also impacted by the typology of buildings. The maximum increase of cooling in case 2 was 268% compared to 386% in case 1. Also, for heating, case 2 had a maximum of 67% (9.1 kWh/m^2) decrease compared to 71% (9 kWh/m^2) in case 1. The comparison of the results of two different typologies is consistent with the report of the Building Research Association of New Zealand (BRANZ) [28] on the heating and cooling demand of different residential building typologies.

The study findings indicate that the impact of climate change on heating load varies across different regional climatic zones in New Zealand, with warmer zones experiencing a more pronounced decrease in heating load. On the other hand, the change in cooling load does not align consistently with the climatic zones. Among the zones, zones 1 and 3 show a more significant increase in cooling load, while zones 2 and 6 exhibit the least increase.

The shift in cooling and heating is present in all climate change scenarios and building typologies. However, the magnitude of changes in heating and cooling in future years varies. The effect of changing the variables of building design, such as glazing ratio, R-values of building components and the thermal set points, can change the ratio of change in cooling and heating. The presented results quantified the exposure of residential buildings in different climatic areas of New Zealand to climate change.

Climate change adaptation plans and actions must be tailored to the building characteristics of different locations not only based on the current climate but also on future weather. The values obtained from the simulation are crucial for the development of the climatic categories and, subsequently, the energy needs and the minimum requirements for the buildings.

3.3.1. *Comparative analysis of findings with prior studies*

A review of similar studies' findings was conducted to provide a comparative analysis of the findings with similar studies. All presented studies used residential buildings as a case study (Table 6).

Table 6 presents a compilation of findings from various studies analysing the impact of climate change on energy demand in different regions around the world. Due to the differences in the studied time-frame and construction types used worldwide, a precise comparison of the study results with studies around the world might not be feasible.

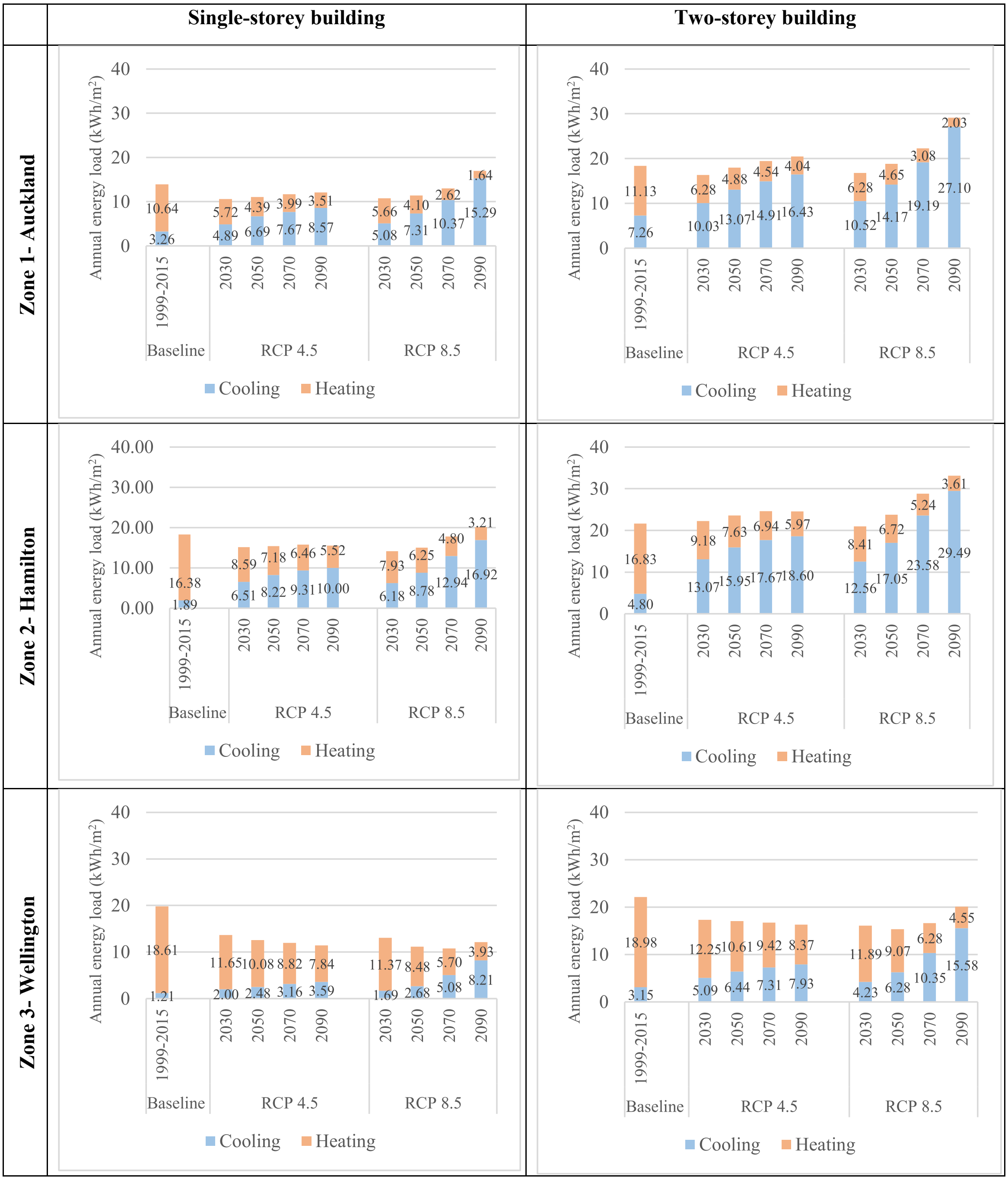

Fig. 7. Heating and cooling energy demand in six climatic zones of New Zealand for two different residential typologies.

This limitation motivated location-specific research in New Zealand. However, drawing comparisons between the outcomes and findings of other studies can offer valuable understanding regarding the extent of energy demand fluctuations caused by climate change.

The majority of the studies indicate a significant increase in cooling energy demand due to climate change. Brazil, Taiwan, and the United Arab Emirates, for instance, are projected to experience notable rises in cooling needs, with percentages ranging from 19% to 185%, depending on the study timeframe.

The cooling demand in New Zealand was expected to increase by approximately 75% by 2090, which is consistent with locations in Brazil (112%–185% in 2080) and Taiwan (82% BY 2080). Heating demand is expected to decrease by 40% in Finland by 2100; this value is about 38% by 2090 for New Zealand.

Similar studies in Turkey investigating the effect of climate change on four different climatic zones and an office building case study show some consistency in the ratio of the variation in cooling and heating load. The average cooling energy demand is expected to increase by 111%, while the average heating energy demand represents a decrease of 51% based on the weather data from the year 2080 compared to historically recorded weather data. The results show that in the coldest region, the overall cooling and heating demand will decrease by up to 17% [54]. These results are consistent with the variation in the trend of cooling and heating demand in colder climatic zones of New Zealand.

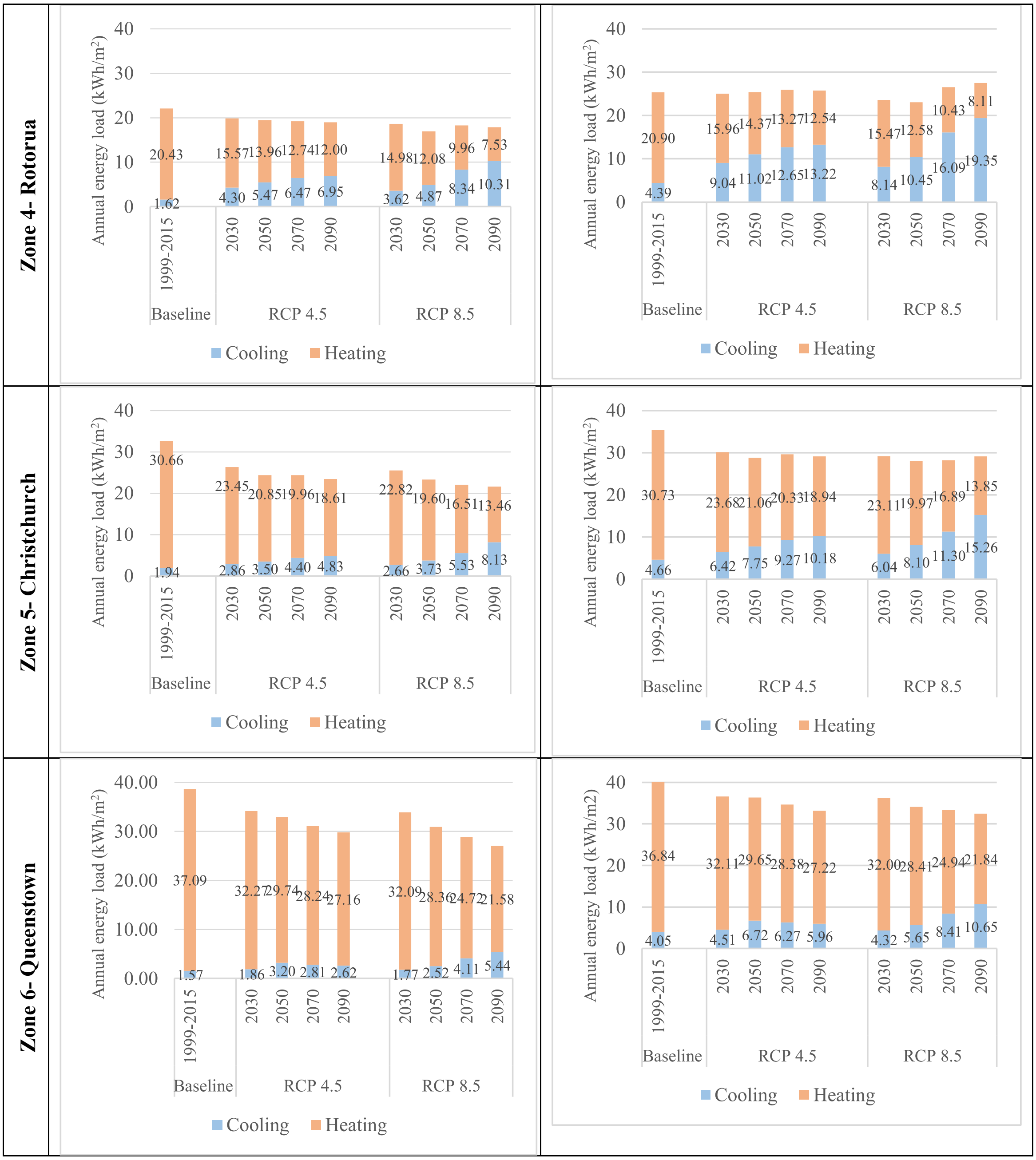

Fig. 7. (*continued*).

4. Conclusion

In this paper, the thermal behaviour of different typologies of houses with minimum requirements of building codes for R-values of building components was analysed under different time periods and climate change scenarios. This research quantified the impacts of various climate change scenarios on cooling and heating loads as well as building energy use across New Zealand. The study found that the models exhibited different thermal behaviours for each climate change scenario, indicating that future weather conditions will have a significant impact on the thermal performance of buildings throughout New Zealand. Additionally, the study noted that the effects of climate change on heating and cooling demand would vary across different climatic zones. The comparison of the results in different climatic zones suggests that climate change is narrowing the energy usage gap between residential buildings in cold and hot climate regions of New Zealand.

The climate projection results indicate that, over the next 70 years, the housing sector in New Zealand is expected to experience a significant increase in cooling energy and a reduction in heating energy, on average. For different climatic zones, different changes in thermal load were observed. In the colder climatic zones (zones 5&6), the overall thermal load will decrease, while in the warmer zones (zones 1&2), the thermal load will increase due to the greater changes in the share of cooling load. A bigger reduction in heating loads associated with winter heating and changing from heating dominated climate to cooling dominated climate is expected in Auckland and Hamilton. The predicted changes are significant in all scenarios and periods, showing a maximum change of 3 kWh/m^2 in total thermal load in Auckland until 2090, 2.7 kWh/m^2 in Hamilton, 8.3 kWh/m^2 in Wellington, 4.2 kWh/m^2 Rotorua, 11 kWh/m^2 in Christchurch, and 11.6 kWh/m^2 in Queenstown. The role and share of cooling and heating load are different for each climatic zone and location. Due to global warming, the overall thermal load in some

Table 6
A summary of the results of previous research on the impact of climate change on cooling and heating.

Ref	Study area	Findings	Period
[42]	Brazil	The cities' annual cooling energy needs are expected to rise significantly, with an increase of 19%–65% in 2020, 56%–112% in 2050, and 112%–185% in 2080.	2020, 2050 and 2080
[43]	Taiwan	Increase in cooling energy demand between 31% and 82% are observed for three future time slices, i.e. 2020, 2050 and 2080.	2020, 2050 and 2080
[44]	Netherlands	Cooling energy demand can be limited between 59% and 74% by application of external solar shading and additional natural ventilation as passive measures.	2035, 2065 and 2090
[45]	Sweden	13–22% decrease in heating demand and a 33–49% increase in cooling demand	2050–2100
[46]	Finland	20–40% decrease in heating demand and 40–80% increase in cooling demand	2030–2050–2100
[47]	Australia	Total heating and cooling energy demand is projected to vary between −26% and 101% by 2050 and –48% and 350% by 2100.	2050 and 2100
[48]	United Arab Emirates	23.5% increase in cooling demand	2050–2100
[49]	Hong Kong	12.3e21.6% increase in cooling loads. Mitigation: raise SST, doubling glazing and wall thermal insulation.	2010–2039, 2040–2069 and 2070–2099
[50]	Spain, València	Total energy demand will increase by around 25% by 2090–2100.	2011–2020, 2051–2060 and 2091–2100
[51]	Mexico	Energy consumption will increase by consumption will increase 20% and 35% by 2050 and 2090, respectively.	2050 and 2100,
[52]	Montenegro	Applying the best retrofit combinations would reduce the total energy demand by 75% under the current climate and by 66% and 59% at the end of the 21st century	2026–2045, 2056–2075 and 2080–2090
[53]	China	The energy demand of the residential sector in the hot-humid area can rise by 102.2%.	2100
[54]	Turkey	The average cooling energy demand is projected to rise by 111%, while the average heating energy demand is expected to decrease by 51%.	2080

locations will increase and, in some locations, will decrease.

The study's findings have added to the existing knowledge on building performance analysis by highlighting the importance of incorporating future weather data in building simulations and quantifying the effects of temperature increase on the indoor environment of residential buildings. The results also demonstrated that the impact of global warming on each location is unique, with different regions being affected differently.

The results lay a foundation for future plans and actions for the resilience of the building sector to climate change. These results indicate that the design of future buildings should consider both present and future weather data and climatic conditions. The result of this paper encourages architects and building engineers to review their design solutions considering the uncertainties of future climate. Additionally, the comparison of the two main typologies of residential buildings illustrated how different design options could influence the energy performance of buildings in future.

The results of this study suggest potential energy-saving advancements in future building codes and technologies, shedding light on how existing heating in buildings may function under future climate conditions. The method used in this research can be further applied to investigate different building types in various climate zones, enabling predictions of future energy consumption for each building type and offering localised guidelines for building design and energy usage. These findings pave the way for further research in understanding the interplay between buildings and climate change and guiding energy-efficient practices in the construction sector.

It is important to ensure that short-term economic or sustainability goals do not compromise the long-term energy performance of buildings. The study's results can be utilised to identify adaptation measures for buildings that can help mitigate the negative impacts of climate change. Quantifying climate change effects on building performance can suggest a data-driven performance regulation in the building and construction sector.

This study was limited to housing in New Zealand and focused on major residential typologies to understand the thermal load patterns in the typologies. Future forecasting of energy performance in buildings is prone to complexity and uncertainty. The specification of the construction of different buildings needs to be included in future research, so future development of this research is recommended to consider the variation of construction types across the country. So further research is required to address some of the limitations.

In order to conduct a more accurate evaluation of building performance, future research should explore various techniques for generating future weather data and verify their precision. Additionally, investigating the impact of urban microclimates is vital as they have the potential to magnify or alleviate the consequences of climate change. Conducting a comprehensive study on different design settings like window-to-wall ratio, R-values, construction systems, and passive strategies to overcome the adverse impacts of climate change is one of the future research pathways.

Although the impact of climate change on the categorisation of climate zones in New Zealand was not within the scope of the current research, it is an important area for future research. Understanding how climate change may influence the existing classification of climate zones is crucial for accurate and effective climate assessments, planning, and decision-making.

CRediT authorship contribution statement

Zahra Jalali: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Asaad Y. Shamseldin:** Writing – review & editing, Supervision, Conceptualization. **Amir Ghaffarianhoseini:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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