Auckland Council

Auckland Urban Heat Assessment

Technical Report

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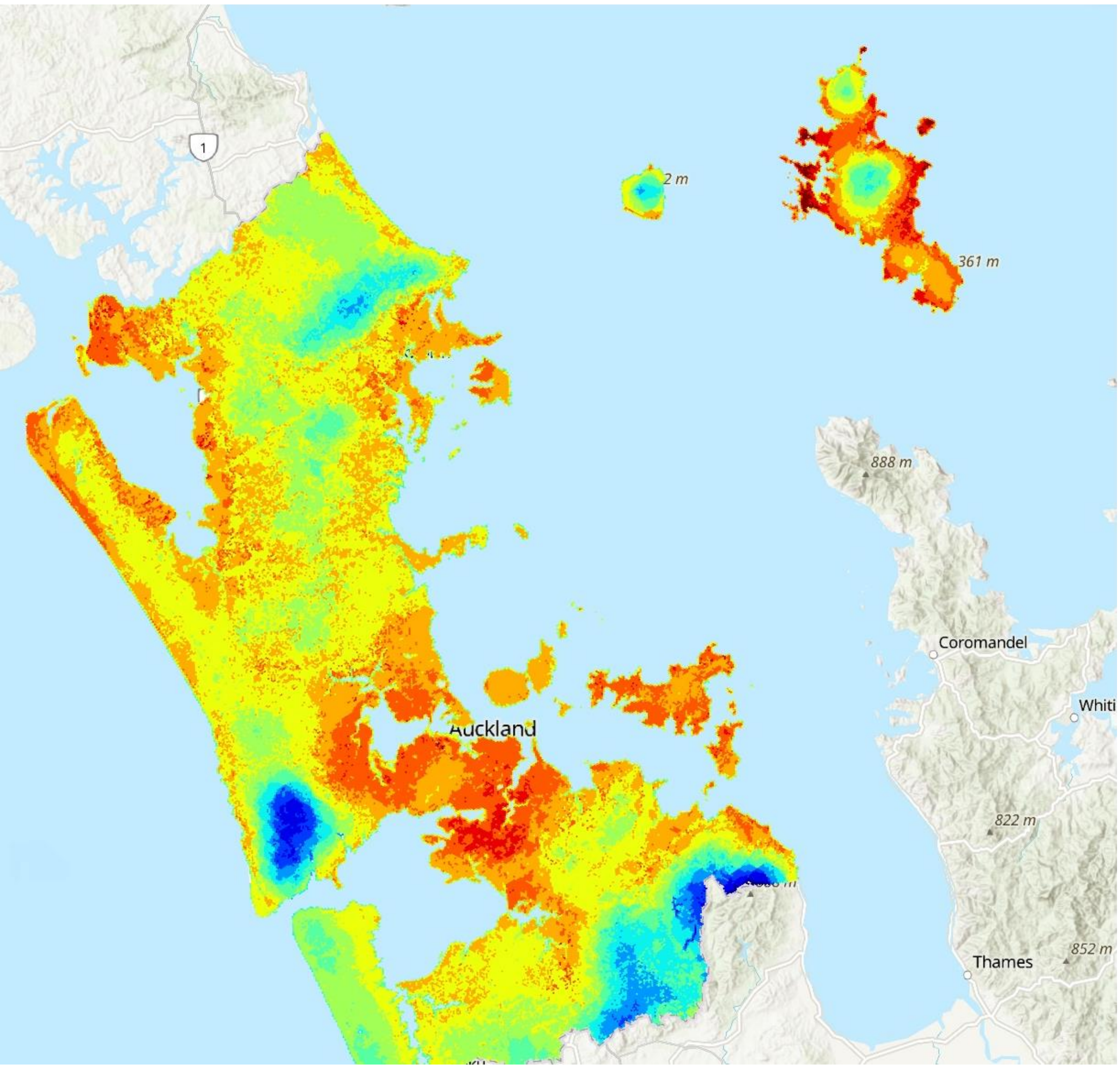

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Executive Summary

Urban heat risk is a growing concern for Auckland. Rising temperatures, urban expansion, and socioeconomic vulnerabilities are expected to increase heat-related impacts for its citizens. This includes not only heat-related illnesses and deaths but also other significant effects such as reduced productivity, strain on infrastructure and critical services, and indirect issues like ecological and environmental deterioration, similar to what has been observed in other cities globally.

Auckland Council commissioned Arup to produce a heat dataset, which would provide insight into how temperatures vary across Auckland, including the Auckland urban area and the wider Auckland region encompassing rural areas; referred to as the Area of Interest (AOI) in this assessment. The intention of the dataset is to support communication on heat related hazards and to inform decision making for Auckland Council. Furthermore, there is potential for this heat dataset to find synergies in heat and carbon mitigation solutions, for example implementing nature-based solutions in hotspots, etc. The data can also inform climate change risk assessment for Auckland.

Method

Arup have used a novel approach to deliver this dataset, involving the coupling of two state-of-the-art climate modelling tools: WRF (weather research and forecasting) and UHeat.

- WRF enabled the regional variation in climate across Auckland to be incorporated, particularly wind, which can significantly affect the urban heat island effect. Due to the large geographical area and Auckland's specific geographical and topographical characteristics, representing large scale climate was important in producing an accurate dataset.

- UHeat predicts the urban heat intensity across cities at a high resolution, accounting for the parameters that influence the urban environment such as land surface cover, building massing, heat emissions and albedo.

Key Findings

This resulting dataset consists of temperature predictions near street level (2m above ground) for the period from November 2021 to March 2022 (Auckland’s hottest summer on record to date) at a high resolution of 300 x 300m for the AOI. The data has been aggregated in this report to show how daily minimum, average and maximum temperatures vary across the AOI providing insights into the climate variations across the region as well as the magnitude of the urban heat island (UHI) effect in the city centre.

Key insights from the UHeat modelling:

- Auckland’s city centre experiences an UHI effect. A nighttime UHI effect is predicted, with temperatures up to 3°C warmer than rural areas.

- Daytime cooling of the city centre. The data shows this area is sometimes cooler than some surrounding regions during the day, likely due to local wind patterns.

- Temperature variation in the Auckland city centre area. Up to a 3°C variation was predicted within different locations in the city during a peak temperature day.

Conclusions

The UHI effect, as demonstrated by the dataset, combined with increasing urbanisation and the impacts of climate change indicate the need for heat planning and adaptation for Auckland to ensure present and future resilience.

This project has provided a valuable first step for both short and long-term planning in response to the potential impacts of heat and extreme temperatures for Auckland. The dataset can be utilised in a number of ways:

- Publications and data sharing: Make the data publicly available for stakeholders like public bodies, private sector, and the community. An interactive web portal can enhance accessibility.

- Data layering to understand risk: Combine the heat dataset with other data to create detailed heat risk maps, aiding decision-making.
- Community engagement: Use the data to inform and support communication on heat-related hazards and resilience, involving the community in mitigation strategies.
- Gaining insights: Further analyse the data to understand hot and cool spots and the potential for heat mitigation.
- Planning and development: Use the dataset to inform adaptation programmes, targeting areas most affected by heat to improve climate resilience .

There are also several avenues that can be explored to build on this work. Key follow-up steps include:

- Incorporating updates to understanding change: Use the latest geospatial data to refine the analysis and evaluate changes with time.
- Producing heat stress maps: Create detailed maps highlighting areas most affected by heat stress, accounting for other contributing environmental factors.
- Scenario testing: Evaluate the effectiveness of various heat mitigation strategies.
- Climate change projections: Integrate climate change projections to inform adaptation planning.

Beyond this project, Auckland can review adaptation measures and heat mitigation solutions other cities have successfully implemented to establish their own programmes. The challenge is to identify the most effective strategies for Auckland, focusing on heat mitigation and holistic benefits. The heat dataset produced in this project is crucial for prioritising efforts, communicating with stakeholders, and driving action on heat.

This report provides a detailed overview of the methodology, a summary of the results from the UHeat model, and further discussion about use of the dataset and potential next steps.

Glossary of Terms

The following words and terms are used throughout the report, and a definition of these is provided below.

Area of interest (AOI)	The geographical area selected for assessment. In this case, the AOI coincides with the Auckland Council boundary (referred to Auckland region in this report).
Auckland region	The extents of the Auckland Council boundary, marked in grey in Figure 1.
City centre	The commercial and business centre of Auckland.
European Centre for Medium-Range Weather Forecasts (ECMWF)	An independent intergovernmental organisation serving as both a research institute and a 24/7 operational service, producing global numerical weather predictions and other climate data.
ERA5	This is a climate dataset produced by the ECMWF. It provides detailed hourly estimates of multiple climate variables from 1950 to present day. This dataset is widely used for climate research and weather forecasting
Forcing data	The meteorological data used to drive land surface models such as WRF and SUEWS. This can include data on temperature, precipitation, wind speed, and other meteorological variables.
Network common data form (NetCDF)	A format for storing multi-dimensional geoscience data such as climate data.
Sea surface temperature (SST)	The temperature of the sea close to the surface, typically a few millimetres below the surface.
Surface Urban Energy and Water Balance Scheme (SUEWS)	An open-source, academically developed physics-based model that simulates the variation of urban climate with the site characteristics and meteorological conditions.
T2	Air temperature at 2 metres above ground level. Weather stations typically measure air temperature at this height.
UHeat	An Arup tool that combines influencing parameters of urban heat (e.g., land surface classification, building massing and surface albedo) with SUEWS to obtain climate predictions at a high resolution (up to 300 metres)
Urban heat island (UHI)	Urban Heat Island (UHI) refers to the phenomenon where urban or metropolitan areas experience higher temperatures than their rural surroundings due to human activities. This temperature difference occurs because urban structures like buildings, roads, and other infrastructure absorb and retain heat more than natural landscapes, such as forests or water bodies. The lack of vegetation, extensive use of heat-absorbing materials (like concrete and asphalt), and energy consumption for transportation, industry, and residential purposes contribute to the UHI effect (United States Environmental Protection Agency, n.d.).
Weather research and forecasting model (WRF)	WRF is a mesoscale climate model, developed by the US National Centre for Atmospheric Research (UCAR). It is used to simulate and predict weather patterns and atmospheric conditions over a wide range of scales, from meters to thousands of kilometers.

1. Introduction

Extreme heat and increasing temperatures are a growing concern globally. The impacts of heat are exacerbated in cities by the Urban Heat Island (UHI) effect which is influenced by the way we design and build our urban areas. Urban heat risk is an ever-growing concern for Auckland. Rising temperatures, urban expansion, and socioeconomic vulnerabilities are expected to increase heat-related impacts for its citizens. This includes not only heat-related illnesses and deaths but also other significant effects such as reduced productivity, strain on infrastructure and critical services and indirect issues like ecological and environmental deterioration, similar to what has been observed in other cities globally.

Auckland Council commissioned Arup to produce a heat dataset, which would provide insight into how temperatures vary across Auckland, including the city centre and the wider region encompassing rural areas. The intention of the dataset is to support communication on heat related hazards and to inform decision making for Auckland Council. Furthermore, there is potential for the urban heat dataset to inform climate adaptation planning and input into a climate change risk assessment for Auckland.

1.1 Scope of assessment

The main objective of this assessment was to provide Auckland Council with an urban heat dataset for the Auckland region (approximately 4,940 km^2), shown by the Auckland Council Boundary in Figure 1 below. This is referred to as the ‘Area of Interest’ (AOI) for this assessment.

Figure 1: Auckland Council boundary. Source:https://geomapspublic.aucklandcouncil.govt.nz/viewer/index.html

Arup combined two tools designed to support UHI assessments:

- **Weather Research & Forecasting model (WRF)** – This is a state-of-the-art mesoscale model of large-scale weather patterns, including wind advection across cities. In this project, the outputs from WRF have been used as input parameters to UHeat. Due to the large geographical area and Auckland's specific geographical and topographical characteristics, large scale climate features which can be captured by WRF are important in producing an accurate high resolution urban heat dataset. In particular, wind is a pivotal element within the urban environment and can significantly affect the UHI effect, necessitating the use of the WRF model to accurately represent this impact.

- **UHeat** – An Arup tool that combines influencing parameters of urban heat with an academically developed model (SUEWS) to obtain predictions of air temperatures and other important climate variables across the region. UHeat accounts for the influence of parameters such as land surface cover, building massing, and heat emissions on urban heat intensity across the city at a high granularity (approximately 300m).

Both the WRF and UHeat analysis was carried out for a five-month summer period from November 2021 to March 2022. The models were coupled one way with the output of the WRF model used as input for the UHeat model. Further details about the technical implementation are provided in Section 2 and Appendix A.

1.2 Urban Heat Island (UHI) effect

The Urban Heat Island Effect (UHI) describes the phenomenon where urban areas experience warmer temperatures than the surrounding rural areas. This is illustrated in Figure 2 below.

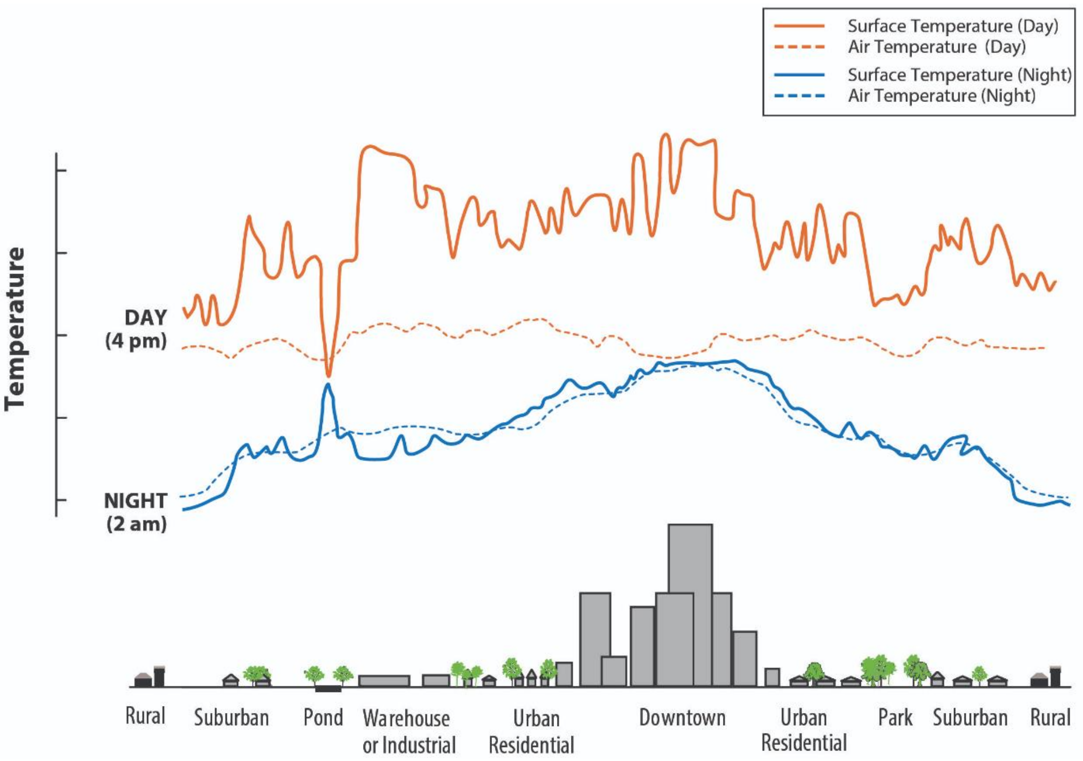


Figure 2: Elevated temperatures in cities compared to rural areas for daytime and nighttime (U.S. Environmental Protection Agency, 2024).

UHI is caused by several factors:

- Urban Form – this includes features such as building density, building massing (height to area ratio) and street layout. The geometry of cities also impacts wind flow behaviour, particularly narrow spaces between tall buildings can block wind and trap heat (MIT, 2021).
- Urban Fabric – buildings and other manufactured surfaces tend to absorb and re-emit solar radiation due to their low albedo. This makes surroundings warmer. Man made surfaces also prevent water from being absorbed changing the natural water balance.
- Anthropogenic heat emissions – for instance human-induced activities such as cooling buildings and using cars increases the heat generated and emitted in urban locations.
- Reduction in greenery and vegetation – intensive urbanisation leads to changes in the natural terrain type, for example roads and buildings displacing trees, grass, soil which help moderate air temperatures. Trees

and other plants, for instance, can lower air temperatures by providing shade. Additionally, this vegetation, along with soil and water, helps cool nearby air through evaporation.

- Weather and terrain topography – UHI is generally more severe under calm and clear weather conditions as there is maximum solar radiation reaching the ground and minimum wind to disperse the heat away. Geographical features such as mountains can influence UHI by changing the wind patterns experienced within cities.

UHI has multiple potential adverse impacts on people and the environment:

- Health risks – the elevated temperatures can impact health, wellbeing, and levels of comfort, especially for the most vulnerable in society such as the elderly or those with existing health conditions.
- Increased energy consumption – both peak and total energy demand increases. It is estimated that with every two degrees of temperature increase air conditioning demand increases by between 1-9% (U.S. Environmental Protection Agency, 2024)
- Air pollution- high temperatures can accelerate chemical reactions in the atmosphere reducing air quality.
- Impaired water quality due to higher water temperatures. For instance through stormwater runoff from heated surfaces (Auckland Council, 2013).

While New Zealand has relatively mild summer temperatures, Auckland currently experiences 20 hot days over 25°C each year, which contribute to a proportion of the 14 heat-related deaths per annum (Golubiewski, 2019). The NIWA projections for Auckland predict that the number of hot days over 25°C will rise in the coming decades, increasing fourfold (to over 90 days per annum) by the end of the 21st century (Jennifer L R Joynt, 2019). This will lead to a significant increase in heat related deaths from the current baseline of 14 heat-related deaths per year up to 88 deaths per year with a three-degree rise in global temperatures (Jennifer L R Joynt, 2019). In addition, Auckland is also expecting to grow significantly over the next 30 years with an estimated 520,800 more people expected to live in Auckland increasing the population to 2 million (Auckland Council, 2023). The Auckland Heat Vulnerability Index acknowledges that certain demographics are more susceptible to the risks associated with high temperatures. These include individuals over 65, children under 5, those with limited understanding of the local language, ethnic minorities, low-income households, and renter households. The index illustrates the variation in these vulnerabilities across the city (Jennifer L R Joynt, 2019).

The rising temperatures, together with the expansion of urban areas and the presence of various vulnerabilities across the city, highlight the need for a heat dataset. This dataset will offer valuable insights into the factors influencing the formation of hot and cool spots, such as land cover, building density, and albedo, across Auckland’s urban centre. By aiding in future planning, this dataset will help mitigate the impacts of extreme temperatures, thereby ensuring the health and safety of citizens and enhancing the resilience of the city.

2. Method

An overview of the method is provided in this section with more detail presented in the Appendices. The project stages are set out in Figure 3 below.

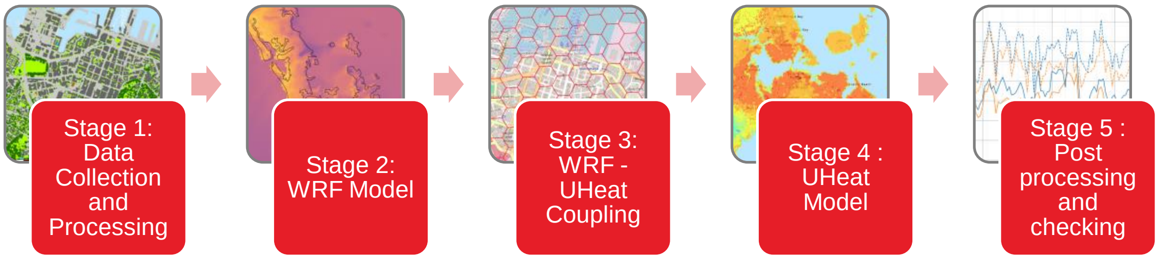


Figure 3: Project stages

2.1 Data collection and processing

2.1.1 Geospatial data

Geospatial data fundamentally underpins the creation of the heat dataset. Multiple geospatial datasets are combined to give a single dataset that defines the urban environment at each grid within the AOI. This incorporates information about land classification, surface cover, tree cover, surface albedo, building heights, massing, and population density.

High quality geospatial datasets are crucial to produce meaningful results from UHeat. Table 1 summarises the geospatial datasets utilised for this project, many of which were provided by Auckland Council.

Table 1: Summary of geospatial datasets used for this project.

Dataset	Source / Date of Extract	Description	File reference
Hexagon grid (Hex grid)	Auckland Council	Covers an area of 27450km^2. Hexagon grid with a resolution of 270 to 280m for long edge of the hexagons.	Hexagon_grid_5ha.gdb (Auckland Council)
Land cover	Auckland Council **Date:** 2022	Vector file, covering an area of 4600 km^2.	AucklandData_RFI_Arup.gdb (Auckland Council)
Canopy height	Auckland Council **Date:** 2016-2018	Raster derived from LiDAR at 1m resolution.	URBAN_FOREST_LIDAR20162018_1MCHM_CLASS.tif (Auckland Council)
Population density	Stats NZ portal **Date:** 2018	Vector file, using 2018 NZ Statistical Area 1 data, which is finest available resolution.	2018 Census Individual (part 1) total New Zealand by Statistical Area 1 (LINZ Data Service, 2016) (LINZ Data Service, 2019)
Digital surface model (DSM)	Land information NZ (LINZ) portal **Date:** 2016-2017	LiDAR data of the southern Auckland Region captured between 2016 and 2017, generated for Auckland Council. 1m resolution.	Auckland South and North LiDAR 1m DSM (2016-2017) (LINZ Data Service, 2016) (LINZ Data Service, 2019)
Digital elevation model (DEM)	Land information NZ (LINZ) portal **Date** 2016-2018	LiDAR data in the northern Auckland Region captured between 2016 and 2018, generated for Auckland Council. 1m resolution.	Auckland South and North LiDAR 1m DEM (2016-2018) (LINZ Data Service, 2021) (LINZ Data Service, 2019)

Dataset	Source / Date of Extract	Description	File reference
Water bodies	Auckland Council	Includes the inland water regions.	AucklandData_RFI_Arup_OpenWater.gbd (Auckland Council)

https://us-west-2.console.aws.amazon.com/s3/object/uheat?region=us-west-2&bucketType=general&prefix=data/Cities/Auckland/IrrigatedLand/irrigated-land-area-raw-2020-update.shp

The following data processing steps were carried out to prepare the geospatial data for input into UHeat:

1. **Hex Grid and AOI preparation.** A comparison was made between the hex grid provided by Auckland Council and the AOI to ensure that appropriate bounds were utilised.
2. **Combining datasets to produce full land cover dataset.** Individual land cover datasets were combined to create a complete dataset which consists of the six landcover types used in UHeat (trees, grass, paved, buildings, bare soil, and water). Figure 4 shows the geospatial datasets before combination, and Figure 5 shows the combined land cover dataset.
3. **Quality checking and supplementing data.** Quality checks on the land cover data found that there were a number of areas where the land cover data was missing or classified incorrectly. This included:
   - Missing data for Birds Beach Reserve, building footprints and features beyond the shoreline (e.g. mangroves) and inland water bodies.
   - Misclassification of building shadows.

   Several measures were implemented to supplement or rectify this data, ensuring its accuracy for the subsequent stages of analysis.

A detailed discussion of the data processing steps taken are presented in Appendix A.1.

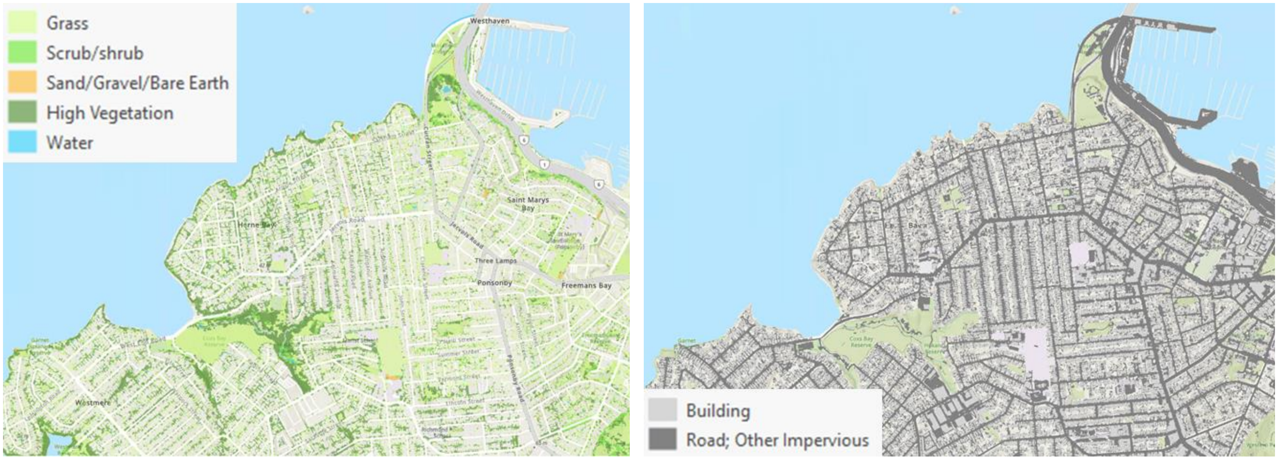


Figure 4: Visualisation of the land cover dataset provided by Auckland Council.

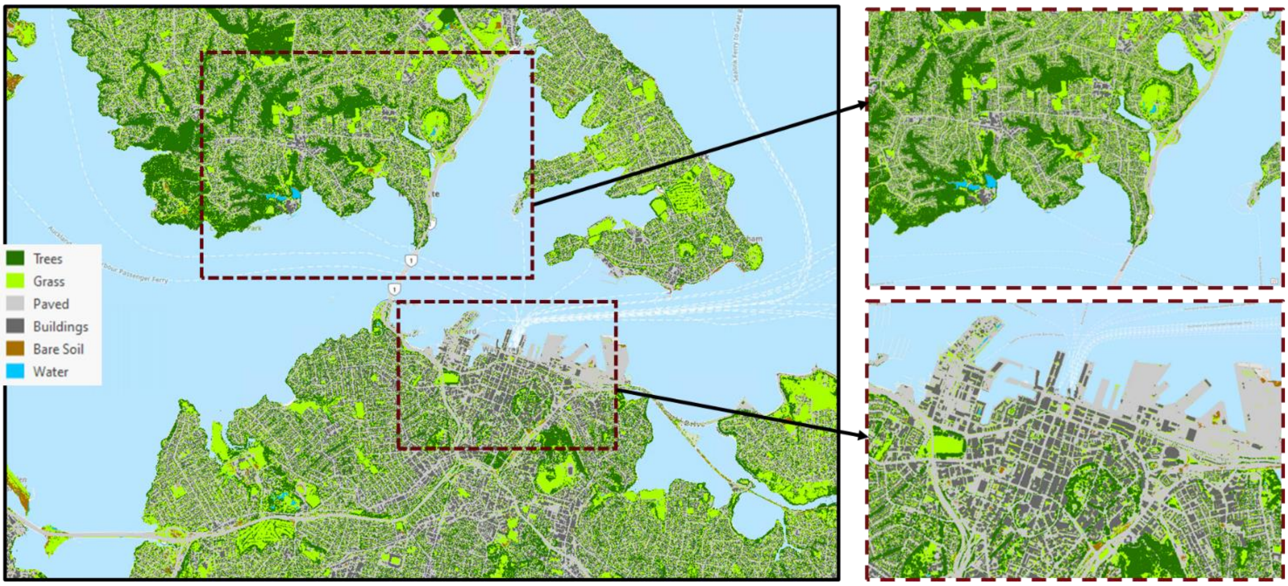


Figure 5: Visualisation of the combined land cover dataset to be used for UHeat modelling.

2.1.2 Forcing data

Forcing data, in the context of climate science, refers to the factors that drive changes in the climate system (NOAA, 2021) (University of Calgary, n.d.). These factors, known as forcings, exist outside of the existing climate system and can include variations in solar radiation levels, volcanic eruptions, changing albedo, and changing levels of greenhouse gases in the atmosphere (University of Calgary, n.d.). In the context of land surface models, forcing data can refer to the meteorological data used to drive the models (NASA, n.d.). This can include data on temperature, precipitation, wind speed, and other meteorological variables.

For WRF, ERA5 data is used as forcing data. This is an open-source dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and provides hourly meteorological data on an approximate 28km resolution global grid, up to an elevation of 80km.

ERA5 can also be used as forcing data for UHeat directly, however for this project outputs from WRF were used as the forcing data for UHeat (see Section 2.4). ERA5 was then used as reference information to check and diagnose the UHeat model at different stages of this project.

2.2 Weather Research and Forecasting model (WRF)

2.2.1 Overview

WRF is a mesoscale climate model, developed and published under an open-source licence by the US National Centre for Atmospheric Research (UCAR).

WRF is used to support short term weather forecasting and for downscaling; the process of taking climate data at a larger spatial resolution and calculating the climate conditions at a smaller scale, as illustrated in Figure 6. For this project WRF version 4.5 was used.

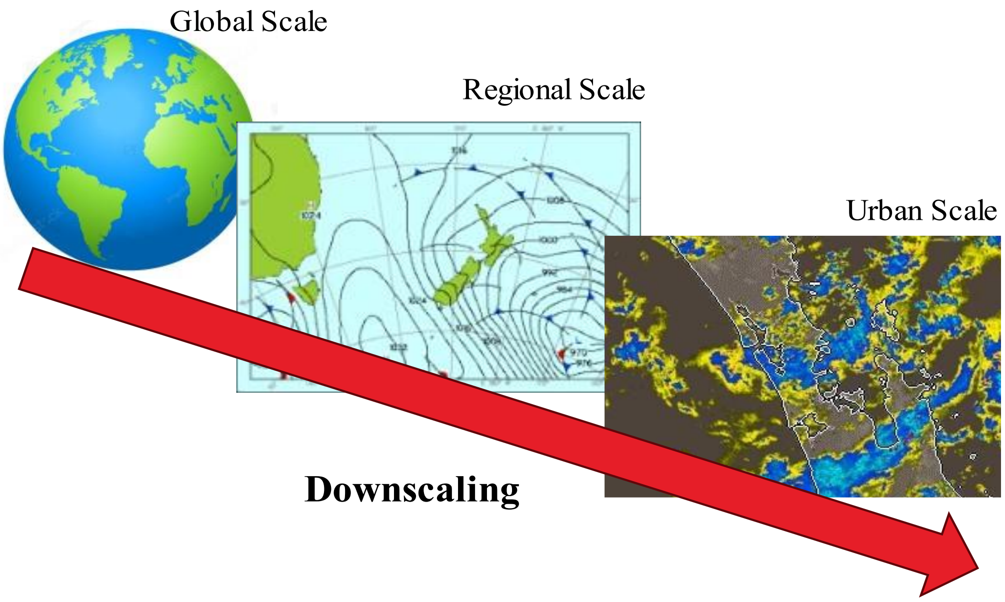


Figure 6: Illustration of downscaling.

Due to Auckland's unique geographical and topographical features, it is important to account for localised climate effects. Specifically, local wind patterns could play a significant role in driving the UHI effect, as they can cause large-scale heat advection across the city. In this project, we used the WRF model over the full analysis period November 2021 to March 2022, to downscale ERA5 data, which is lower-resolution climate data. This allowed us to capture the influence of geographical and topographical features and the resulting localised climate effects.

Figure 7 compares the prediction of air temperature at 2m above ground (referred to as T2) from WRF to ERA, demonstrating the increased spatial detail WRF provides.

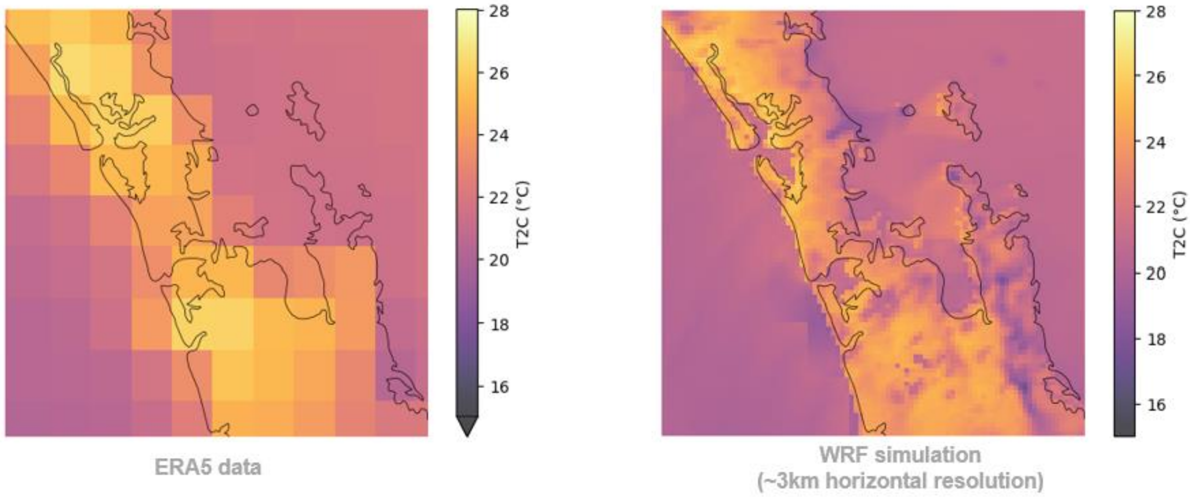


Figure 7: Comparison of the T2 temperature from ERA5 (left) and WRF (right).

2.2.2 Workflow

Figure 8 presents an overview of the WRF workflow, and Table 2 provides more detail about each of the steps.

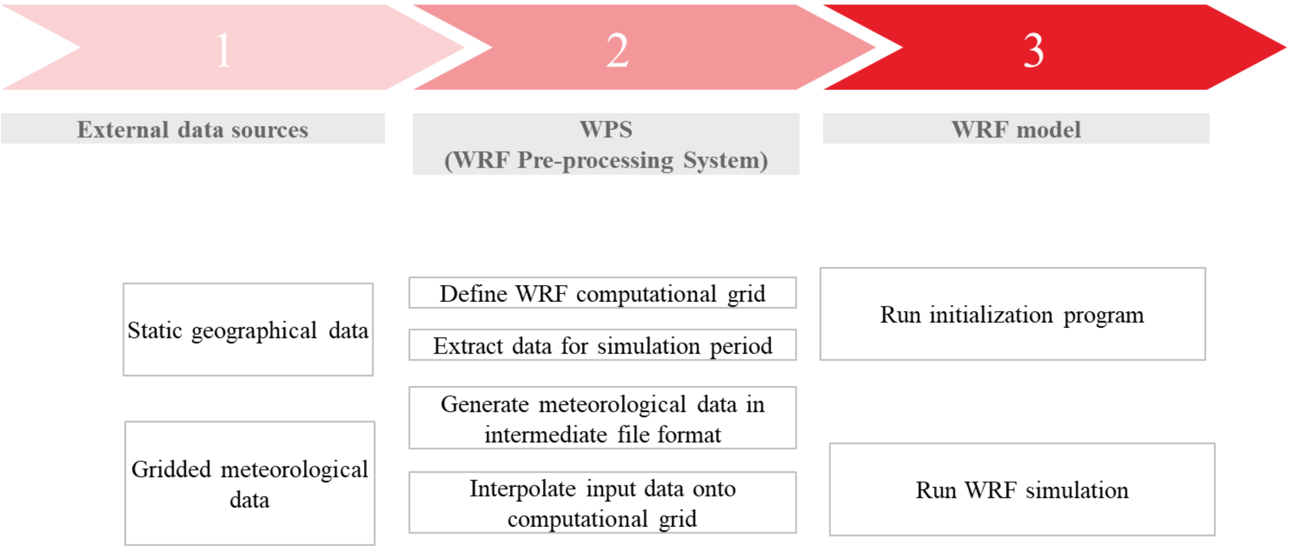


Figure 8: WRF workflow overview.

Table 2: Description of the different stages of the WRF workflow.

Stage	Task/Item	Description
External data sources	Static geographical data	Input data to represent the geographical domain e.g. land cover. This is static data over the WRF simulation.
	Gridded meteorological data	Input meteorological data e.g. climate data (ERA5) which changes over the simulation time at a temporal resolution set by the user.
WRF pre-processing system	Define WRF computational grid	The area of interest and the terrain data for the WRF run is defined, using the static geographical data.
	Extract data for simulation period	Climate variables required for the WRF run is extracted from the meteorological data for the defined simulation time period.
	Generate meteorological data in intermediate file format	The meteorological data is converted to an intermediate file format required for WRF.
	Interpolate input data onto computational grid	The meteorological data is horizontally interpolated onto the model domain.
WRF model	Run initialization programme	The meteorological data is vertically interpolated onto the model domain.
	Run WRF simulation	The WRF simulation is run, and outputs produced in netcdf format.

2.2.3 Input data

WRF inputs must be configured for specific applications. Consequently, using the model requires careful consideration of the model input settings, with an iterative process typically followed to determine the appropriate settings. This process was informed by previous experience with the model.

The primary model inputs include temporal resolution, simulation time, spin up period and spatial resolution (vertical and horizontal). There are also a range of physics-based parameters, such as different models to represent the land surface, ocean, and urban canopy.

Details of how model input data and parameters were evaluated and selected through sensitivity studies is presented in Appendix A.2.

2.2.4 Model review and checking

The input parameters used in WRF were reviewed by Dr Ting Sun at UCL (University College London). Outputs from the WRF modelling were reviewed qualitatively and quantitively, focussing on temperature and wind speed variables, as these are key inputs to the UHeat UHI calculation.

Spatial plots of the temperature and wind speed variation across the AOI were examined, including investigating hotter and colder areas across the AOI. Furthermore, the WRF predicted temperatures and wind speeds were compared to weather station data provided by Auckland Council to assess accuracy and suitability for using as input to UHeat. The comparison to weather station data is presented in Appendix C.

2.3 UHeat

2.3.1 Overview

UHeat is a tool developed by Arup to provide quantitative analysis of the UHI effect. It combines geospatial data and climate forcing data with an urban heat model ('SUEWS') for application over large geographical areas. It accounts for multiple factors that influence UHI such as building heights, surface albedos (reflectiveness), the amount of green and blue infrastructure, impervious surfaces, population density and the urban climate.

UHeat can output a number of different parameters; for this project, the principal output is a prediction of the air temperatures two meters above ground. This is a more accurate indicator of the UHI effect compared to more commonly reported surface temperatures, as UHeat considers energy fluxes (sensible and heat) and water fluxes such as evaporation and run-off which all impact urban temperatures.

The different processes embedded within the tool is shown in Figure 9 below. The preparation of the geospatial data is described in section 2.1.1 and Appendix A.1.

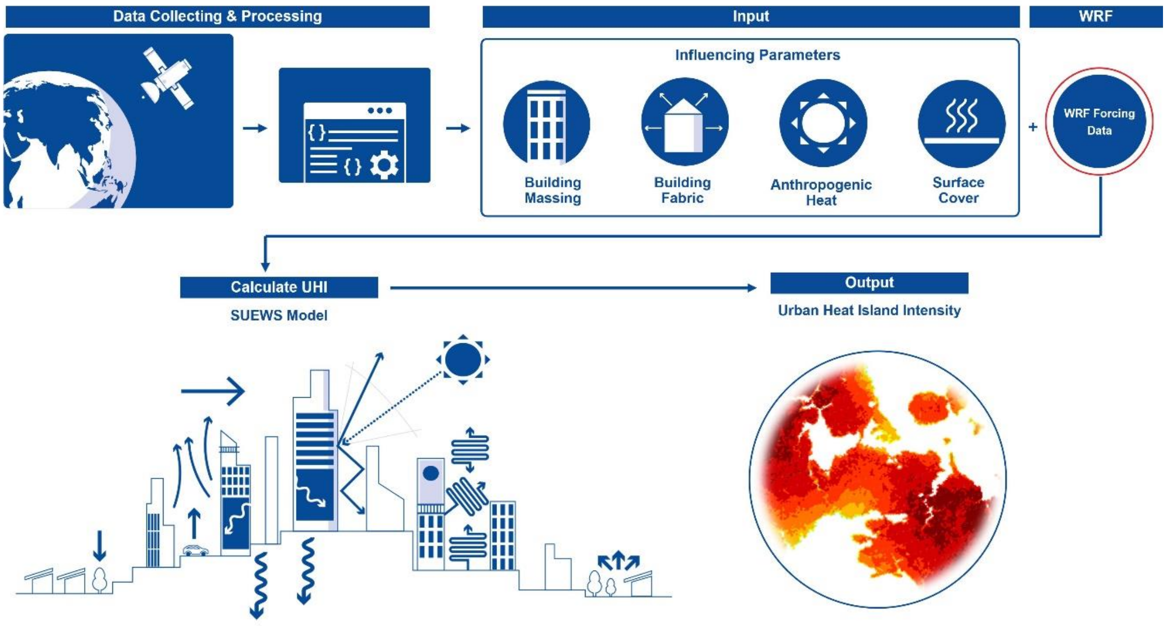


Figure 9: Overview of the UHeat process.

2.3.2 SUEWS model

UHeat uses the Surface Urban Energy and Water Balance Scheme (SUEWS) climate model, developed by Professor Sue Grimmond's team at the University of Reading (SUEWS dev team, n.d.). SUEWS is an open-source model that simulates the variation of urban climate with the site characteristics and meteorological conditions (SUEWS dev team, n.d.). For this project the following python version of SUEWS, supy 2024.8.2.dev0[1] was used (Sun, 2024).

SUEWS requires hourly data as inputs (referred to as 'forcing data'). The required input climate variables are:

- wind speed,
- relative humidity,
- air temperature,
- barometric pressure,
- rainfall and
- radiation (shortwave and longwave).

The forcing data is obtained at a 'forcing height'; a height above the urban canopy. For this project, the WRF output data is used as the forcing data for the analysis.

A more detailed description of the SUEWS calculation, model sensitivities, and limitations are provided in Appendix A.3.

2.3.3 Data resolution

Analysis is carried out at an approximately 300m diameter Hex grid resolution (presented in Figure 10) typically capturing neighbourhood-scale variations in temperatures. The input data is gathered and integrated into the model for each individual grid and the calculations are performed for each grid over the entire analysis period (five months). For this project, Auckland Council provided the Hex grid. An extract of the Hex grid is shown in Figure 10.

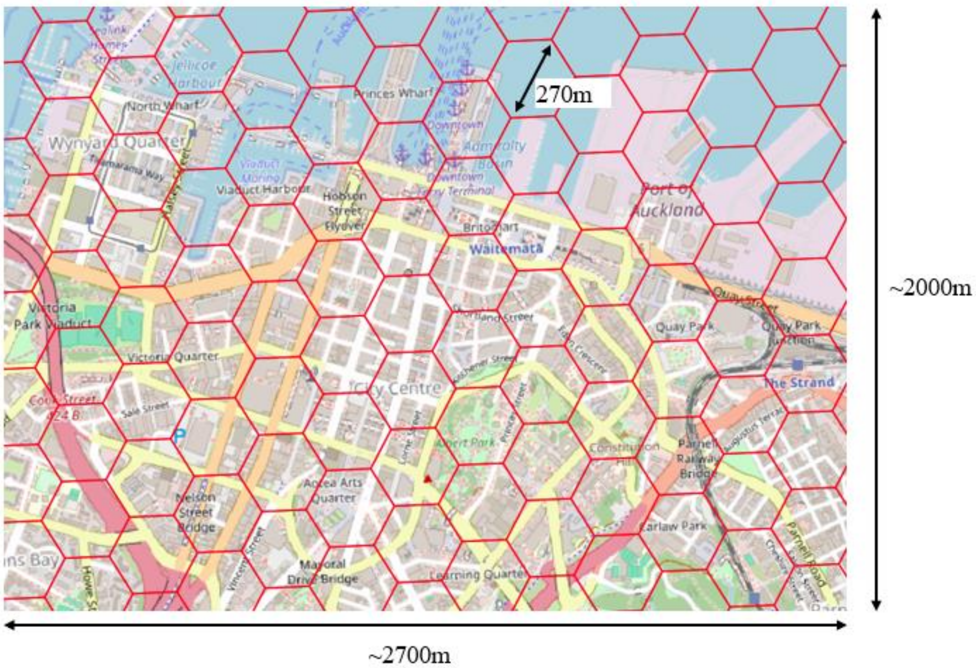


Figure 10: Screenshot of the hex grid provided by Auckland Council.

[1] More information can be found at: https://suews.readthedocs.io/en/latest/

2.3.4 Data outputs

The output of UHeat is an hourly temperature time series at each hexagon for the analysis period. In this report the output has been presented as a series of spatial plots (or maps) and time series charts. In some instances, the data has been aggregated over the analysis period to give daily mean, maximum and minimum temperatures. These are presented in the results section 3.2.1.

The aggregated data has been made available to Auckland Council in the form of a geodatabase file (‘*Arup_UheatDataResults_20240823.gdb’*).

Additionally, the time series data for air temperature at 2m (T2) at every hexagon has also been shared with Auckland Council. This consists of two data frames:

- The geospatial data attributes for each hexagon defining it urban characteristics.
- The timeseries of air temperature at 2m.

2.4 WRF to UHeat coupling

The heat dataset created for this project is derived from a one-way coupling of WRF and UHeat, where the WRF outputs are input as forcing data into the UHeat. The coupling between the models requires a couple of steps to ensure compatibility:

- **Extraction and processing of climate variables from WRF.** The forcing data consists of a number of climate variables: wind speed, relative humidity, air temperature, barometric pressure, rainfall, and incoming radiation (shortwave and longwave). This information is required at hourly intervals and specified at a defined vertical height in the atmosphere above the urban canopy. For some variables, the values were adjusted such that they are at the correct height for input to UHeat.
- **Mapping of data from WRF squares to UHeat hexes.** The analysis grid resolution differed between WRF and UHeat as shown in Figure 11. The WRF model used square grids with a resolution of 2.7 km by 2.7 km, while UHeat used hexagonal grids with a resolution of 300 m by 300 m (as provided by Auckland Council). The different resolutions necessitated a conversion to map WRF results onto the UHeat grid. Bilinear interpolation was used, where for a given UHeat hex, the values from the nearest four WRF squares were proportionally weighted.

Further details about the coupling is presented in Appendix A.4.

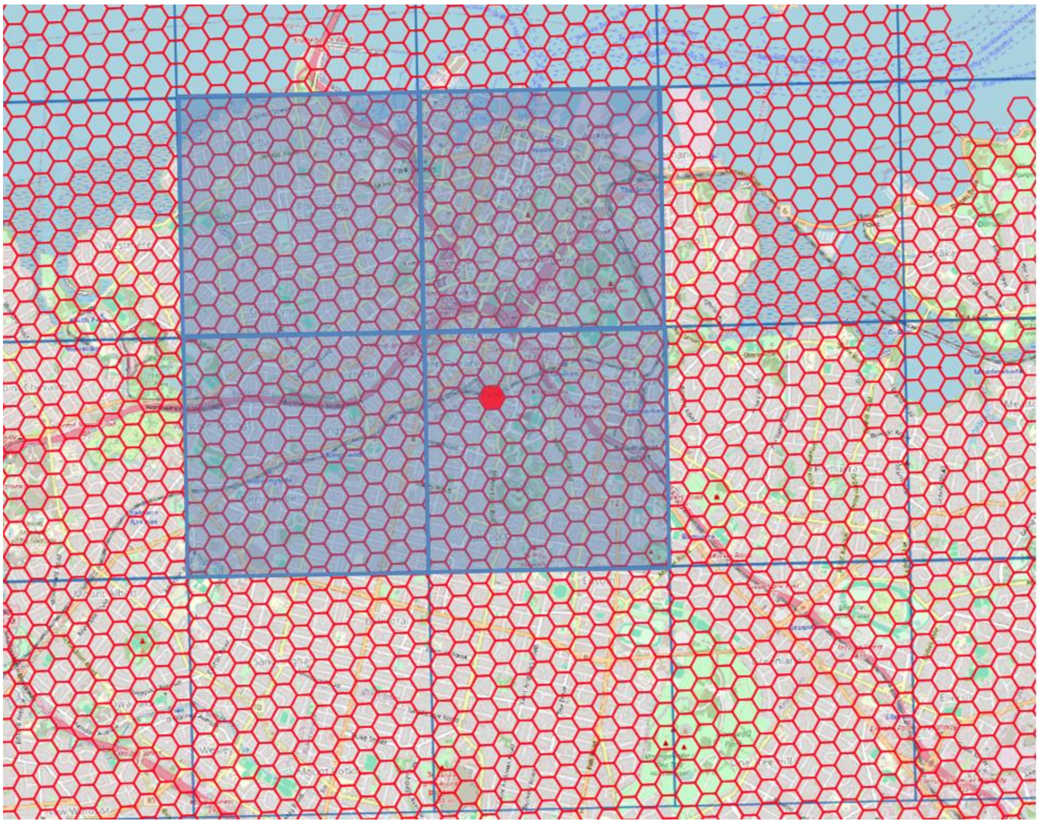


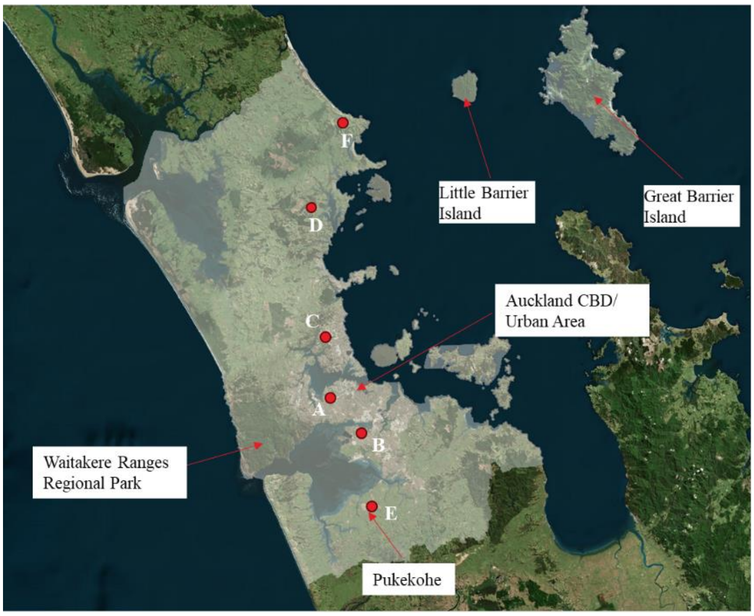
Figure 11: A single UHeat hex (highlighted in solid red) and its four nearest WRF squares (highlighted in solid blue). The values of the climate variables in the blue squares are combined using bilinear interpolation to gives the forcing data for the red hex.

2.5 Model review and checking

Extensive model review and output checks were conducted on UHeat. This was crucial to ensure accuracy and suitability of outputs. The specific checks carried out during this project are described below.

2.5.1 Benchmarking with recorded climate data

UHeat predictions were benchmarked against recorded climate data as a robust validation check. Data from several weather stations across Auckland, provided by Auckland Council, was used. This data consisted of time series information, including temperature, relative humidity, and wind conditions for the analysis period. The primary comparison focused on temperature, but other variables were also examined. The weather stations used for the UHeat result verification are shown in Figure 12.



Weather stations	
A	Auckland MOTAT EWS
B	Auckland Māngere 2 EWS
C	Auckland North Shore Albany EWS
D	Warkworth EWS – *no wind data*
E	Pukekohe EWS
F	Leigh EWS

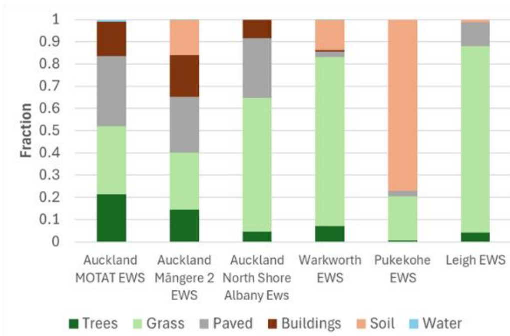


Figure 12: Weather stations used for UHeat result verification.

UHeat hexes coinciding with these weather station locations were selected for comparisons. Figure 13 compares the mean daily maximum temperatures at these locations. There is difference of between 1 to 1.5°C between UHeat and the weather station, with UHeat generally underpredicting the temperatures.

An exact match was not expected as we are comparing data for a single point against predictions over an entire hexagon. Additionally, there may be localised physical effects at the weather stations that are not accounted for in UHeat. Further comparison of the UHeat results and weather station data is included in the Section 3.2.3 and Appendix C.2.

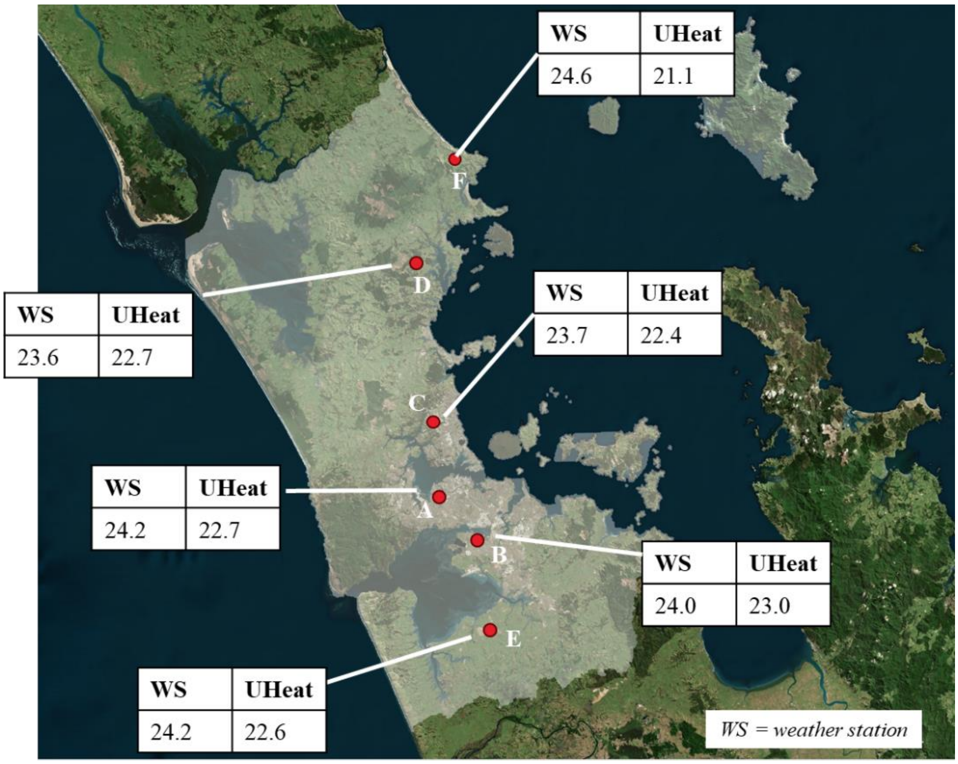


Figure 13: Comparison of the mean of the daily maximum temperature for weather station (Denoted WS) and UHeat for the full analysis period.

2.5.2 Benchmarking against satellite data

Remote sensing data from Sentinel 8-9 can be processed to obtain land surface temperature (LST) for a geographical region. This data is available at high resolution, with imagery captured approximately every two weeks. The LST data can be compared to the surface temperature output from UHeat to give additional confidence about the UHeat predictions. Note that the validity of this type of benchmarking depends on the quality of the remote sensing data, which may be adversely affected by uncontrollable factors such as cloud cover.

We obtained LST imagery for the analysis period, but quality checks on the data revealed that most of the imagery was of poor quality due to cloud cover or other interference. As such, this was deemed an unreliable source for data validation.

2.5.3 Comparisons against WRF outputs

Comparisons were made between WRF spatial plots and UHeat spatial plots for several time steps to check they broadly correlated. The UHeat spatial plots are expected to match WRF in terms of overall climate patterns. These checks helped justify temperature differences across larger areas, which could not be attributed to UHI effect.

2.5.4 Sensitivity tests and additional model checks

There is considerable uncertainty regarding the input parameters for UHeat. Informed estimates for these parameters were made based on available input data (e.g., land cover and forcing data) and expert judgement. Several small-scale sensitivity tests were conducted both before and after the analysis to assess the impact of varying a number of key parameters. Appendix B provides a comprehensive list of the parameters tested and the findings incorporated into the final UHeat analysis.

The review and validation processes were critical in this project, helping to identify the need for modifications and re-running analyses. Appendix B also provides a detailed log of the models executed prior to the final analysis, along with the modifications made at each stage to enhance accuracy and calibration of the model.

3. Results

In this section a subset of the analysis results for both WRF and UHeat is presented. This consists of:

- Spatial plots showing temperature and wind speed variation across the AOI for the 4th of January 2022, which corresponded to the peak temperature observed in the weather data.
- Time series plots showing the temperature variation for specific locations across the full analysis period (November 2021 to March 2022) and between 1st and 8th of January 2022, a period when daytime air temperatures were consistently above 25°C.

In some cases, the results have been aggregated across the analysis period to facilitate communication.

3.1 WRF

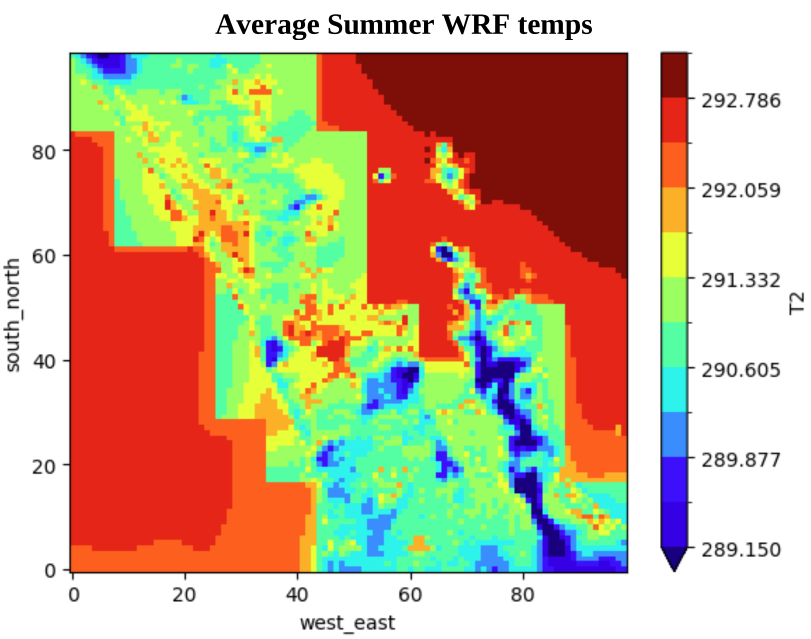
3.1.1 Temperature and wind speed spatial maps

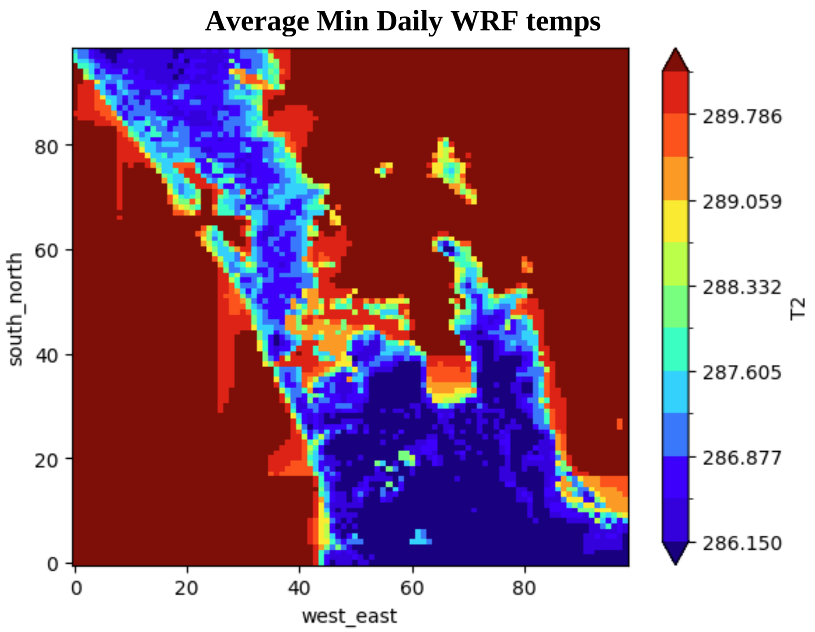
Figure 15 and Figure 16 show the WRF predicted air temperature at 2m and wind speed magnitude throughout the 4th of January 2022 for the full AOI, highlighting the large-scale climate variation across Auckland and climate movements through the course of a day.

Temperature fluctuations, wind patterns, and other climate variables across the AOI are influenced by climate variations inherent to such a large area. While the WRF model is not specifically an urban heat model, it does capture the UHI effect to some extent by accounting for landcover and urban features, albeit at a lower resolution compared to the UHeat model.

Note that distinct changes in resolution observed towards the northeast and southwest regions (the water areas) are due to the use of ERA5 data as input for land and sea surface temperatures separately. The WRF model interpolates between the land and sea surface temperatures to create a single temperature layer at 2m.

Figure 14 presents the aggregated WRF results for the analysis period, displaying the average (mean), maximum, and minimum temperatures. On average, the plots indicate that the northern regions are warmer compared to the southern regions. The average daily minimum temperatures reveal warmer sea temperatures surrounding the land, with a slight increase in temperature towards Auckland City Centre. Conversely, the daily maximum temperatures show cooler sea temperatures compared to the land.





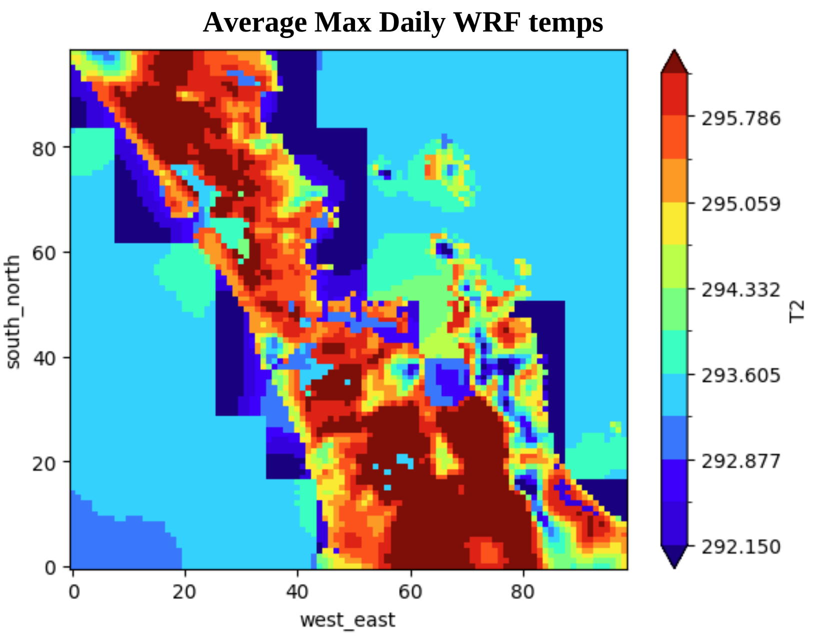
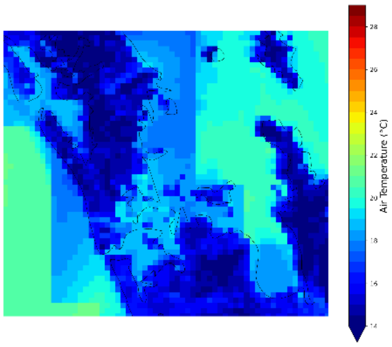


Figure 14 Aggregated WRF Results showing average, daily maximum and daily minimum temperatures over the analysis period

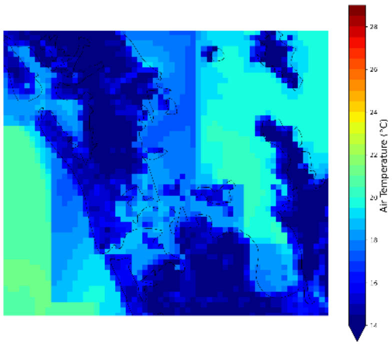
The temperatures presented in Figure 15 highlight the diurnal changes in heat patterns across the region. During the middle of the day when daily temperatures are at their peak, the hottest areas are not just limited to the Auckland urban zones but also span across some rural areas. For example, the highest air temperatures (26°C and above) at 15:00 are seen in the Auckland city centre and in some of the rural areas towards the north and south of Auckland such as Karaka and Kumeu. Later, during the night between 21:00 and 23:00 the urban area is warmer than the rest of the Auckland region, highlighting the UHI effect which is generally more prominent during nighttime. This diurnal pattern is seen across the period of analysis from November to March.

Figure 16 shows the variation in wind speed across Auckland. The plots are aligned with the prevailing wind patterns shown in Figure 17 which show distinct south-westerly and northeasterly winds. These patterns highlight distinct south-westerly and northeasterly winds. The WRF model predicts high wind speed regions in the southwest (Pacific Ocean) and northeast (Tasman Sea) areas. Compared to the ERA5 data resolution, the WRF model offers a higher resolution of these wind patterns across the AOI, providing crucial input for the UHeat model. Additionally, the WRF results indicate a relatively high wind speed zone just south of the city centre at 15:00, which corresponds to lower temperatures in this area. The winds in this region have a cooling effect.

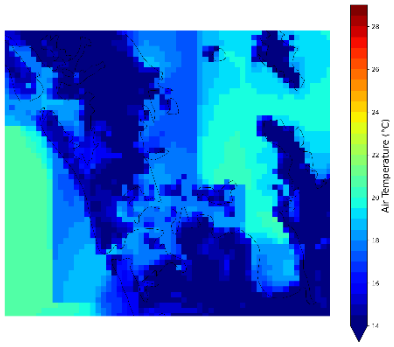
01:00



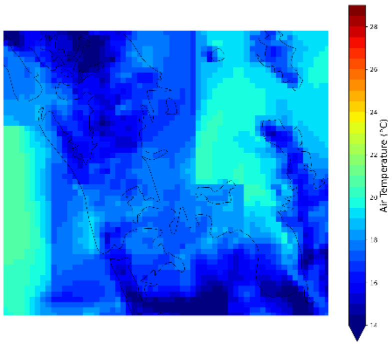
03:00



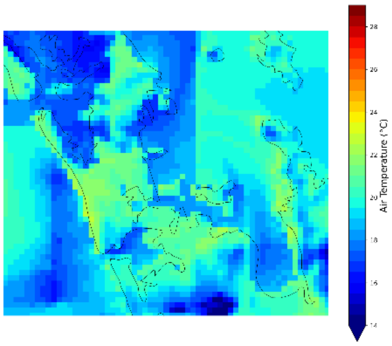
05:00



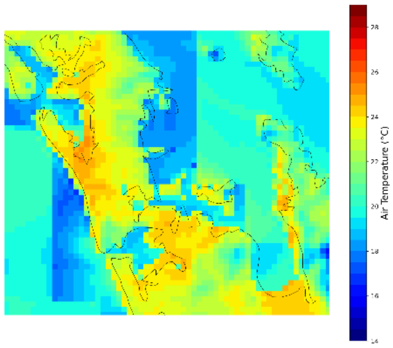
07:00



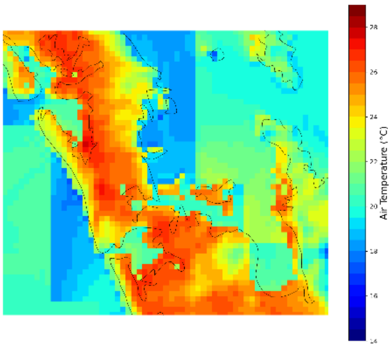
09:00



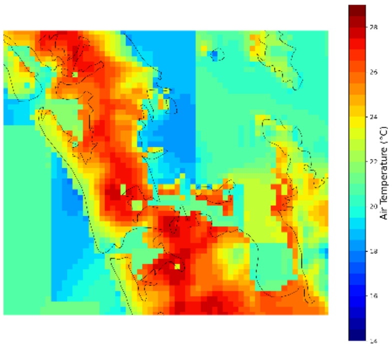
11:00



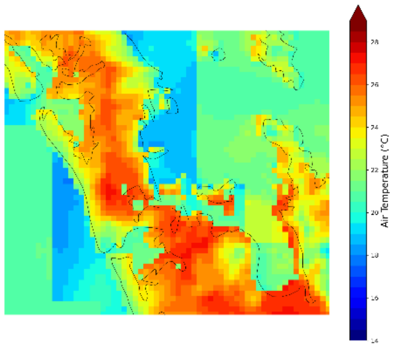
13:00



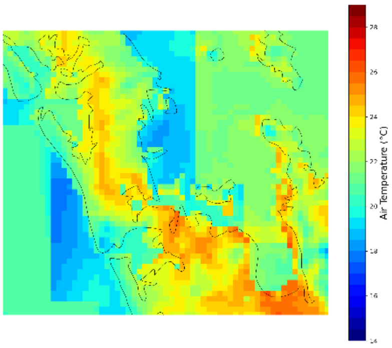
15:00



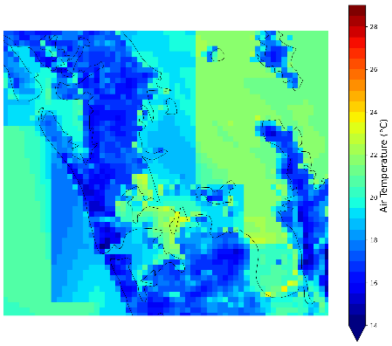
17:00



19:00



21:00



23:00

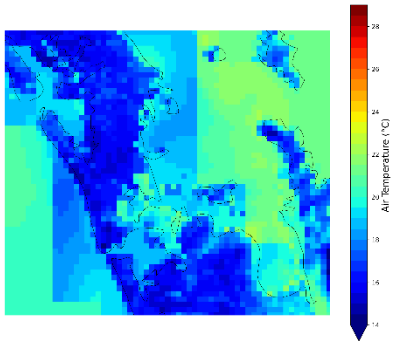
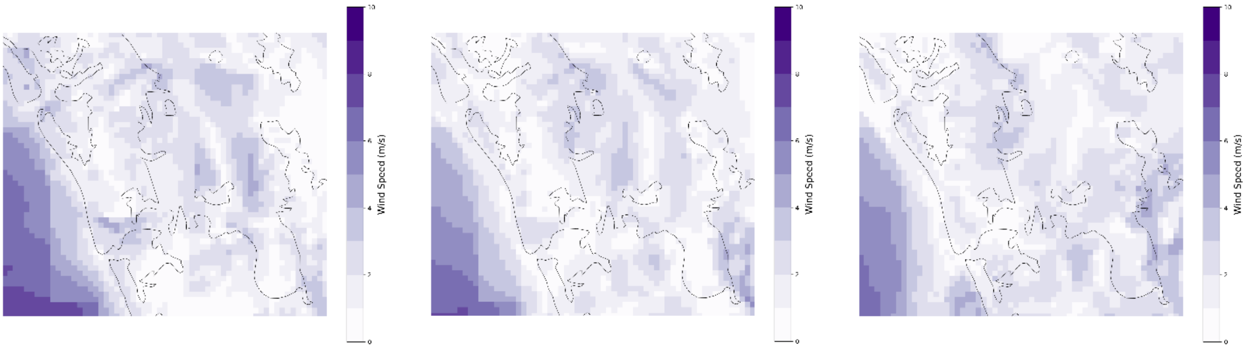
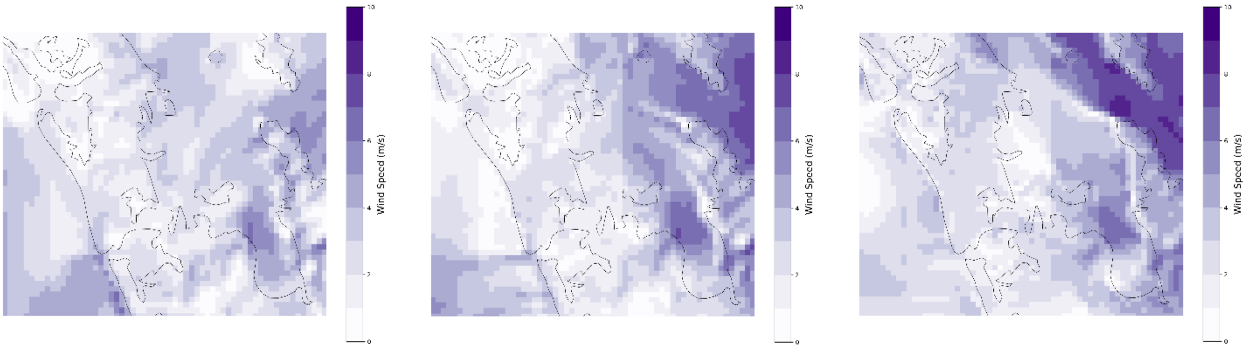


Figure 15: WRF predicted air temperatures at 2m above ground on 4th of January 2022.

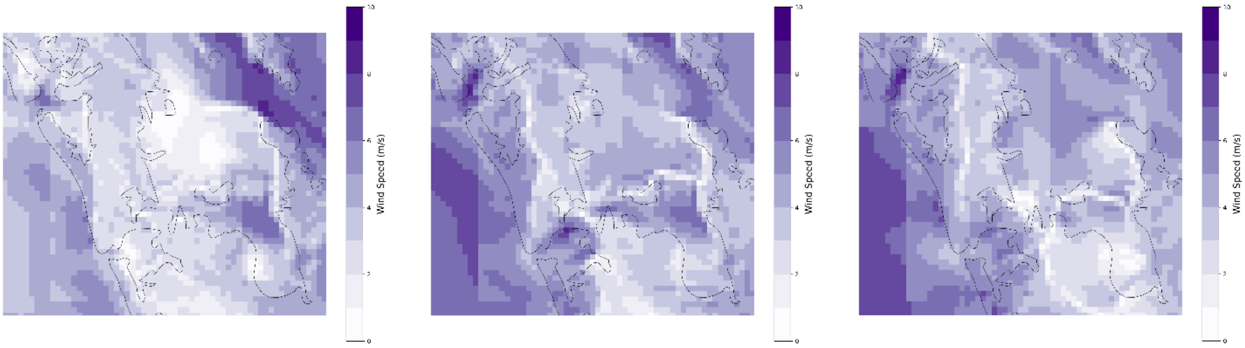
01:00 03:00 05:00



07:00 09:00 11:00



13:00 15:00 17:00



19:00 21:00 23:00

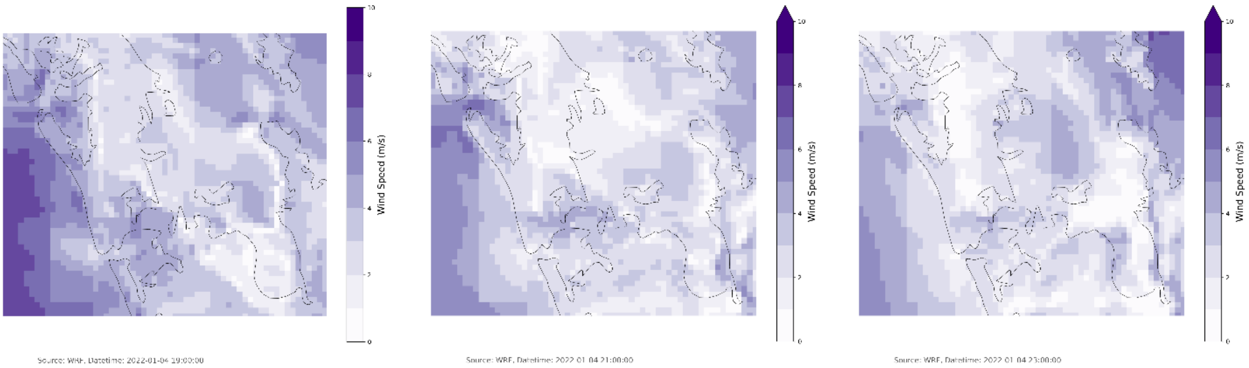


Figure 16: WRF predicted wind speed at 2m above ground on 4th of January 2022.

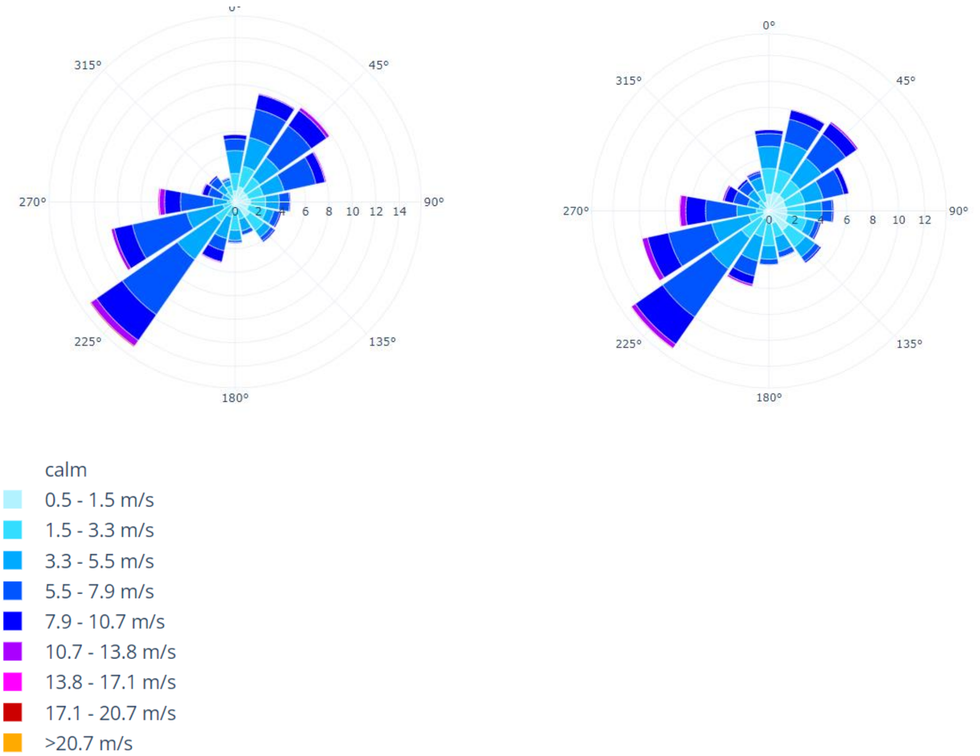


Figure 17 Annual (left) and Nov- March (right) wind rose for Auckland (based on EnergyPlus Weather file (EPW) climate file from the weather station located at Auckland International Airport)[2] (Betti, 2024).

[2] An EPW (EnergyPlus Weather) file is a standardized file format used in building energy simulation software. The EPW file contains a wide range of meteorological data, typically on an hourly basis, for a specific location over an entire year. It typically represents a "typical meteorological year" (TMY). This means it doesn't contain data from a single, specific year but instead compiles statistically representative weather data from multiple years. The goal is to create a dataset that reflects average or typical weather patterns for a specific location, excluding extreme weather events or anomalies. The TMY used to create this wind rose is based on climate data from 2004 and 2018 from the weather station located at Auckland international Airport.

3.2 UHeat

3.2.1 Aggregated temperature spatial maps

In this section the following aggregated temperature results from UHeat are presented to give overall observations on temperatures:

- Mean daily temperature for the full analysis period (Figure 18);
- Mean of the daily maximum temperature for the full analysis period (Figure 19);
- Mean of the daily minimum temperature for the full analysis (Figure 20).

As well as showing the aggregate temperatures across the AOI, the figures also focus Auckland city centre and surrounding areas.

The maps indicate relatively higher temperatures in the city centre when examining mean and minimum temperatures. This suggests that the UHI effect is evident during the night, aligning with findings from the WRF modelling. Auckland's UHI is about 2-3°C at nighttime. Note that an UHI at nighttime is expected and is due the larger proportion of impervious surfaces in urban areas that will absorb heat during the day and release it more slowly during the night compared to rural areas. The relative temperatures of the sea will also have an impact on the urban heat island in the city centre. As seen from the WRF modelling (Figure 14) the sea temperatures when looking at daily minimum temperatures tend to be warmer than the land. Given that the city centre is surrounded by the sea, this can contribute to higher temperatures compared to more inland areas.

In contrast, maximum air temperatures are predicted to be higher in areas outside the city centre, due to large-scale climate variations and the dominance of solar radiation during the day. In addition, during peak daytime temperatures, the sea may help cool urban areas. Unintuitively, grassy areas generally show higher temperatures in the model predictions during the daytime, which is attributed to low moisture levels in these areas during the summer. The model calculates moisture based solely on precipitation and does not account for any irrigation that may occur.

The higher temperatures seen in some areas like the Great Barrier Island are partially due to large scale climate variations (as can be seen in the WRF model results in the previous section).

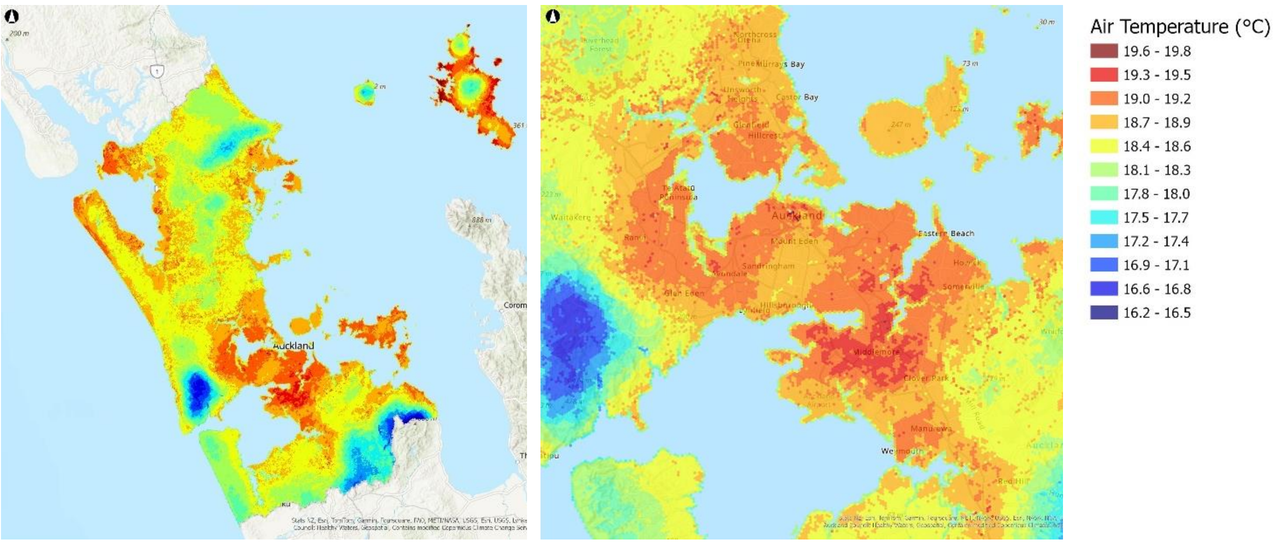


Figure 18: Mean air temperatures averaged over the analysis period. Left – Full AOI. Right – Auckland city centre.

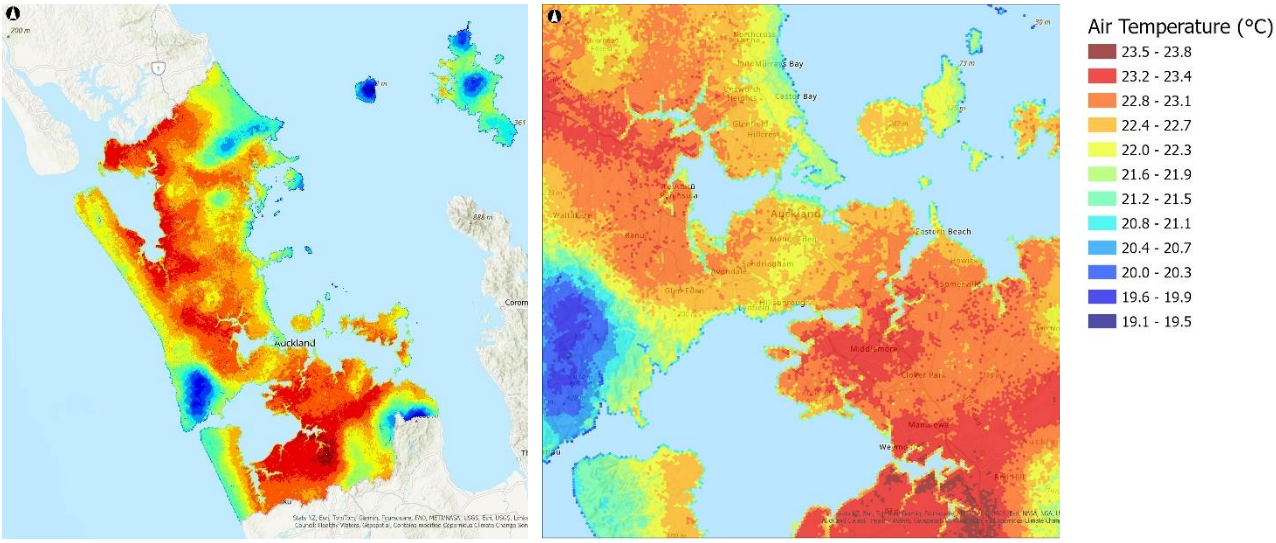


Figure 19: Maximum daily air temperature averaged over the analysis period. Left – Full AOI. Right – Auckland city centre area.

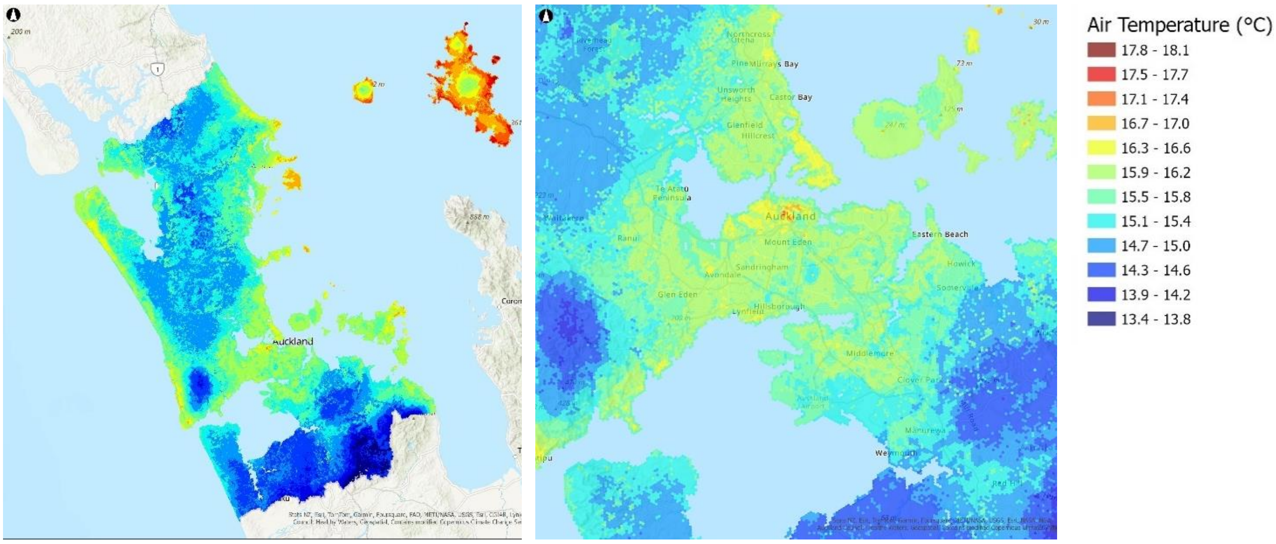
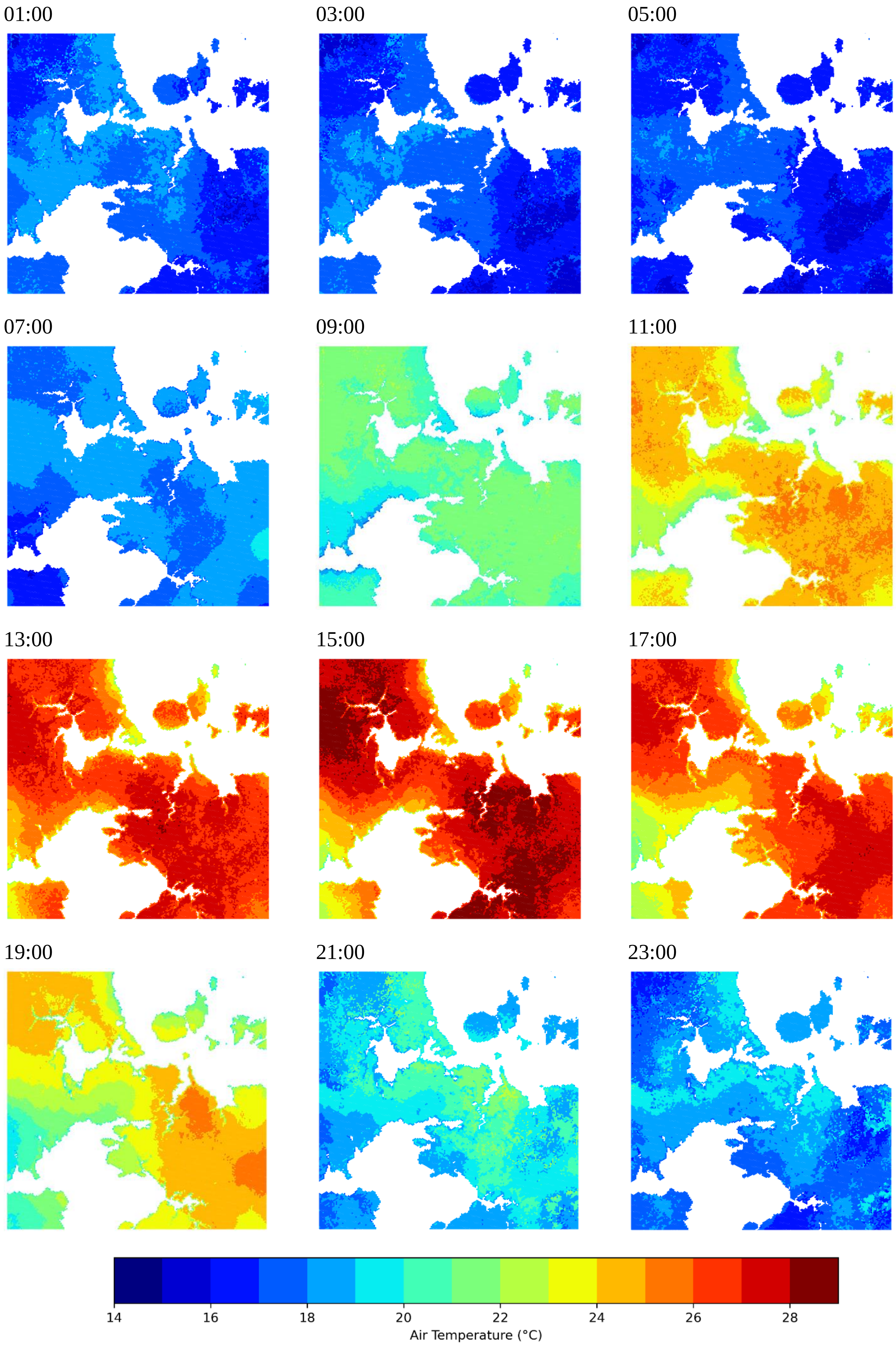


Figure 20: Minimum daily air temperature averaged over the analysis period. Left – Full AOI. Right – Auckland city centre area.

3.2.2 Temporal temperature spatial maps

Figure 21 shows the UHeat predicted air temperatures on the 4th of January 2022 for the urban area, highlighting the differences between the urban zone and surrounding areas and changes through the course of a day. As with the aggregated data maps the UHI is apparent at night-time.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26
28
Air Temperature (°C)

Figure 21: UHeat predicted air temperature at 2m above ground on 4th of January 2022.

Figure 22 shows the UHeat predicted average minimum air temperature over the analysis period highlighting the neighbourhood scale variation and insight provided by the results.

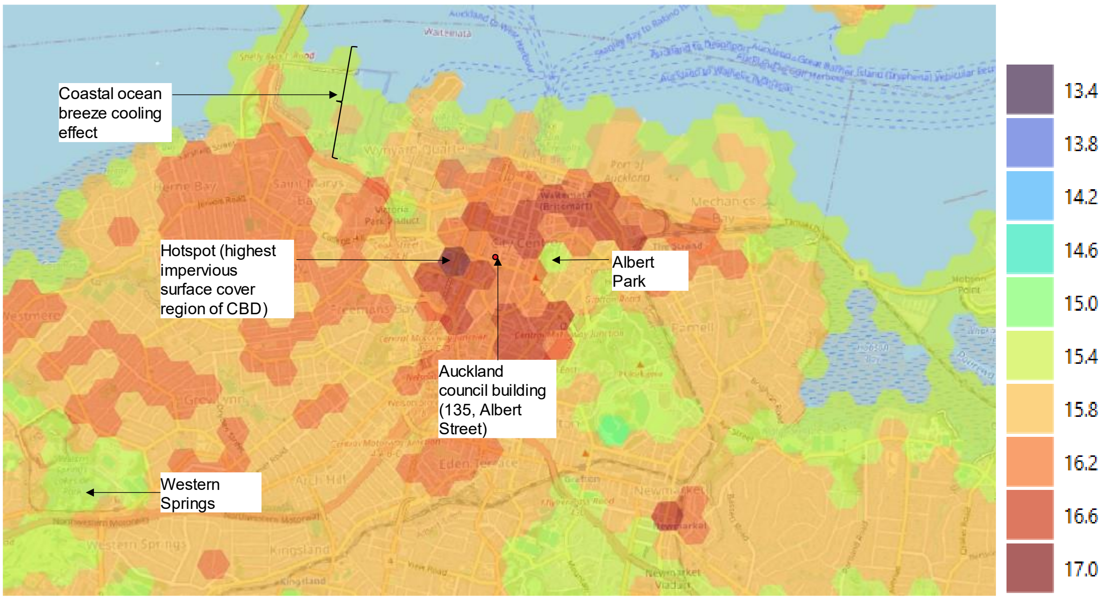

Figure 22:Average minimum air temperature in the city centre .

3.2.3 Temperature time series plots

Figure 23 compares the aggregated daily mean and maximum temperatures at Museum of Transport and Technology (MOTAT) weather station across the full analysis period and Figure 24 compares the hourly temperatures at the same location between 1st and 8th of January 2022. MOTAT weather station was the most representative of all the weather stations of an urban location with the highest percentage of building and paving (46% in total).

In general, UHeat tracks the trends in the measured weather station data well, particularly for the mean temperatures. UHeat predictions show a smaller diurnal temperature fluctuation compared to the weather stations, generally under-predicting the peak temperatures, and over-predicting the minimum temperatures. Figure 19 shows that the differences are approximately between 1 to 1.5°C, which represents a reasonable level of accuracy for the UHeat model. An exact match between the two is not expected, as the weather station represent a single point location whereas UHeat represents a temperature average over an approximately 300m diameter hexagon. Additionally, there may be localised physical effects at the weather stations that are not accounted for in the UHeat analysis.

Similar plots have been reproduced for the other weather stations and are presented in Appendix C.2.

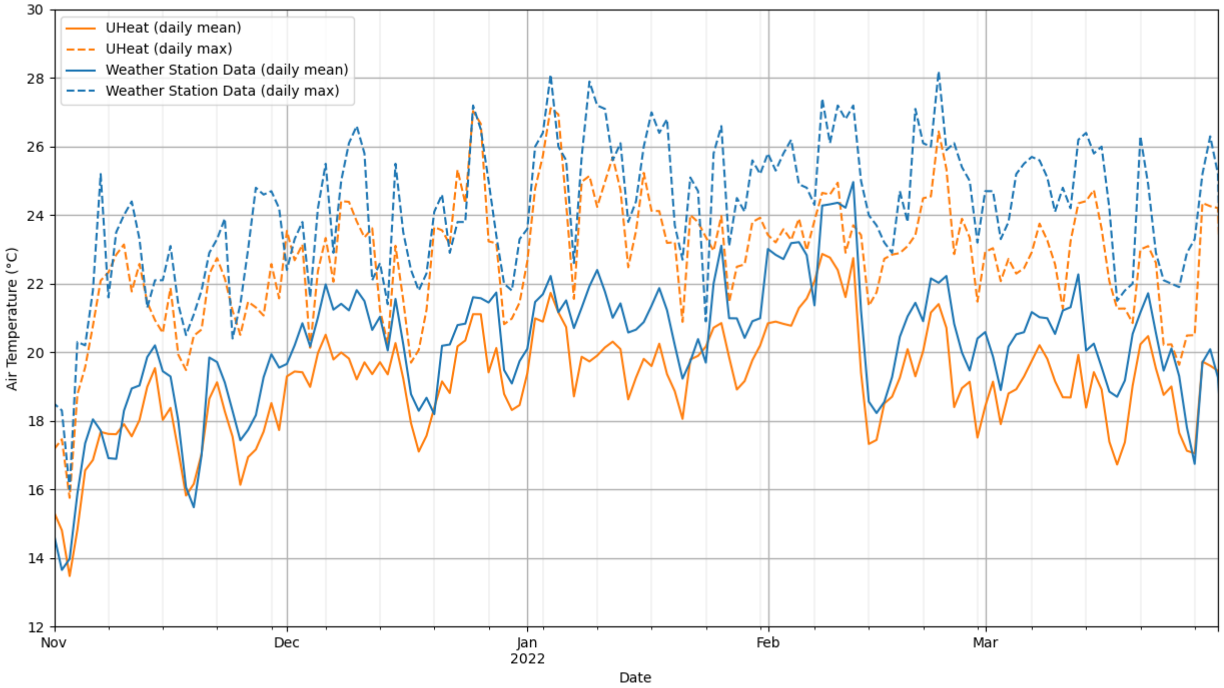

Figure 23: Comparison of the daily mean and maximum temperatures from the UHeat model and measured weather data at MOTAT for the full analysis period.

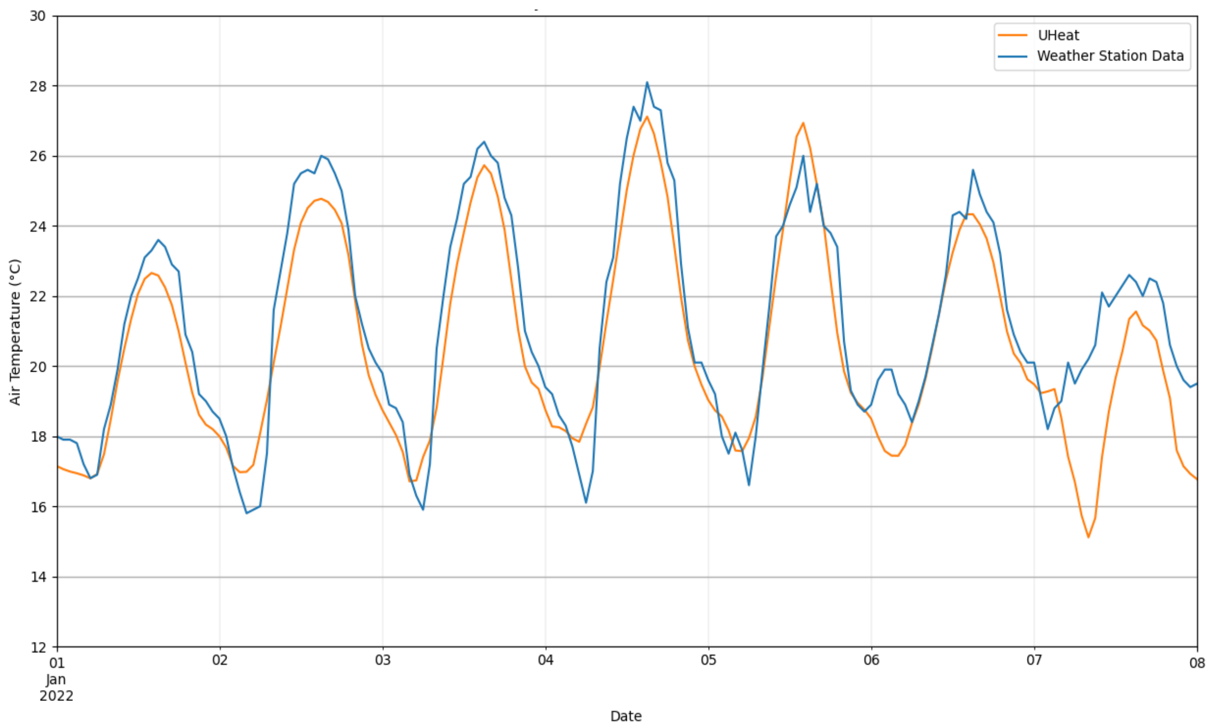

Figure 24: Comparison of the hourly temperatures from the UHeat model and measured weather data at MOTAT between the 1st and 8th of January 2022.

Figure 25 compares the temperature for a representative city centre location to Brookby, which consists of over 90% grass. The city centre location generally has smaller diurnal fluctuation with lower maximums and higher minimums compared to the Brookby location. The difference in nighttime temperatures is due to the UHI effect, whereby urban areas store heat during the day which is then released at night resulting in elevated temperatures. During the day the city centre location shows lower temperatures which is attributed to variation in the local climate, with higher wind speeds observed in the city centre area during the day.

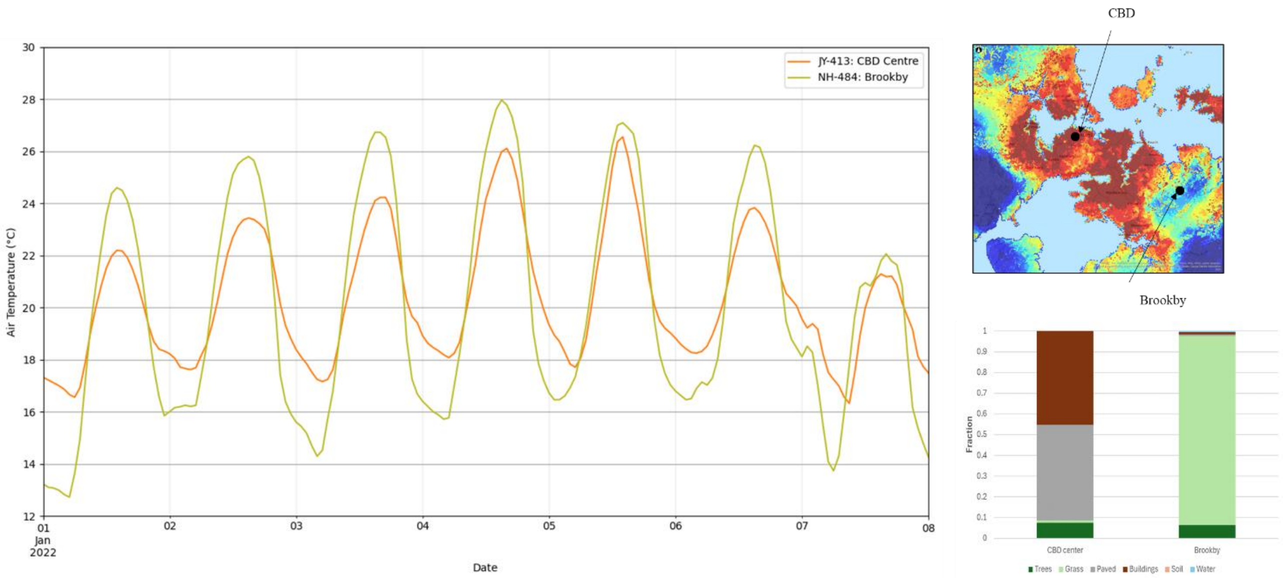

Figure 25: Comparison of the hourly temperatures from the UHeat model for representative city centre location and Brookby between the 1st and 8th of January.

4. Conclusions

In the following sections the main findings from WRF and UHeat are summarised alongside an overview of the limitations associated with the modelling and analysis. Finally, recommendations regarding use of the output data, potential mitigation and adaptation measures and next steps are presented.

4.1 WRF

4.1.1 Summary of key findings

WRF analysis was carried out over the Aukland region to provide high resolution forcing data for the UHeat map and increase the accuracy of the subsequent heat dataset. By downscaling data from the ERA climate input, the WRF model accounted for topographical features and large bodies of water. The WRF results also provided some insights on the climate variation across the Auckland region both spatially and temporally. The model resolution (3km) meant that the UHI effect could also be observed at a lower resolution, as well as in the UHeat modelling. The model showed that in the nighttime temperatures in the urban areas encompassing the city centre were elevated compared to the surrounding rural areas.

The WRF results also showed the influence of the sea surface temperature on the mainland temperatures. When the sea surface temperatures were updated during the simulation, land surface temperatures were higher and more closely aligned to the weather stations.

The WRF results were compared against recorded weather station data observations and generally correlated well with the daily pattern and fluctuations in temperature and wind speed. Temperatures were typically predicted to be lower in WRF than the weather station, but temperatures were within 2°C. Wind speeds showed greater differences from the weather station data, but this is expected. The WRF results also captured the observed variations between the weather stations located across the AOI.

Extensive validation checks were performed on the WRF analysis, with models re-run as necessary to enhance accuracy. The final WRF results presented in this report demonstrate a satisfactory level of accuracy and correlation with observed data, providing reliable input for UHeat.

4.1.2 Limitations

In relation to WRF there are some limitations that are worth noting:

- **Lower resolution land cover data within WRF**. WRF uses a relatively coarse resolution land cover dataset, which is distinct to the datasets provided by Auckland Council. For instance, different land cover classifications are used, and the dataset is associated with a different time period. For this project, the latest land cover dataset available within WRF was used, and a visual comparison was conducted of the WRF land cover dataset and land cover dataset provided by Auckland Council to identify any significant discrepancies. The land cover dataset used in WRF was the modis_landuse_20class_30s_with_lakes from 2001. It was deemed sufficient for the use of WRF modelling as an input to UHeat, and thus not altered.
- **WRF results depend on quality of the ERA5 data**. The accuracy of the WRF model heavily depends on the quality of the input data (e.g., ERA5 climate data). Any inaccuracies in the input data can propagate through the model. In this instance, the ERA5 data was reviewed against the provided weather station data to give confidence of its suitability. However, it should be noted that this can only be checked where accurate observations are available.

4.2 UHeat

4.2.1 Summary of key findings

The UHeat analysis, conducted at a high resolution of 300m by 300m, provides a comprehensive temperature dataset for the Auckland region from November 2021 to March 2022. This high-resolution data allows for detailed visualisation and interrogation of neighbourhood-scale temperature variations. The report includes snapshots from the UHeat output data, highlighting several key insights. Firstly, the UHeat results reveal a UHI effect at nighttime, with urban areas experiencing temperatures up to approximately 3°C higher than surrounding rural areas. During the daytime, temperatures in the Auckland city centre areas are predicted to be cooler than some of the surrounding regions. This daytime cooling effect is likely influenced by localised wind patterns. Additionally, the results indicate that there could be a temperature variation of up to 3°C within the city centre itself.

When compared to weather station data, UHeat replicates the temperature trends well, though it shows a smaller diurnal temperature fluctuation. Peak temperatures in UHeat are lower than weather station measurements by 1 to 1.5°C, which is considered a reasonable level of accuracy for the model. An exact match is not expected, as weather stations represent single point locations, whereas UHeat averages temperatures over an approximately 300m diameter hexagon. Additionally, localised physical effects at weather stations may not be accounted for in the UHeat analysis.

In conclusion, the UHeat model provides a reliable and detailed representation of temperature variations across Auckland, despite some expected discrepancies with weather station data. This analysis underscores the importance of considering localised factors and the inherent limitations of different data sources in urban climate studies.

Direct comparisons between the UHI calculated for Auckland in this study and other cities are challenging. Although UHI values have been calculated for many cities, the assumptions behind these measurements or models can vary significantly. Factors such as the time periods of measurements, definitions of UHI (e.g., what is considered ‘rural’), and locations of measurements (e.g., ground level vs. above the urban canopy) all differ. However, some city comparisons have been selected (based on studies with some similarities) to provide context in the table below:

Table 3 Comparison of UHI across different cities

City	UHI Intensity	Study Context	Link
London	4°C (average summer nightie) 7°C (heatwave nighttime)	‘UrbClim’ simulation, urban climate model by VITO.	https://data.london.gov.uk/dataset/london-s-urban-heat-island---average-summer https://data.london.gov.uk/dataset/london-s-urban-heat-island https://vito.be/en/product/urbclim-urban-climate-modelling
Lagos	~3.6°C (Average uplifts in march, nighttime – midnight to 6am)	Coupled WRF-urban scheme by Obe et al.	https://link.springer.com/article/10.1007/s00484-024-02627-3#Fig5
Delhi	3.63°C (modelled results for a 5-day nightime period in May), 3.53°C (observed for same period)	WRF-UCM (urban canopy model) by Bhati et al., 5-day period in May.	https://geoscienceletters.springeropen.com/articles/10.1186/s40562-018-0126-7#Sec2
Istanbul	1-2.5°C (winter)	Coupled WRF-urban canopy model by Oztaner et al., winter season assessment.	https://presentations.copernicus.org/EMS2015/EMS2015-37_presentation.pdf

4.2.2 Limitations

Given that the temperature dataset is derived from modelling and analysis, it is crucial to acknowledge the key limitations associated with UHeat when using this data. These limitations can impact the accuracy and applicability of the results and understanding them is essential for making informed decisions based on the dataset.

- **UHeat is principally an urban model.** The models are designed for predicting the urban environment and so may be less representative in rural areas. The model accounts for rural land cover such as trees, grass and bare soil but does not account for any distinguishing types and features within each category. For instance, there are no tree variations which may have distinct behaviours when considering heat and water transfer processes. Informed decisions have been made on input parameters to ensure they are as representative as possible, but the model is not inherently created for rural areas. This may impact how the output dataset should be used and noted when utilising the rural data.

- **Validity and accuracy of input information**. The results are highly dependent on the input information, particularly the geospatial data set, which incorporates the land surface cover information and the parameters defining the urban environments (e.g., albedo, building concentration, anthropogenic emissions). Much of this data stems from 2016-2019, and it is noted that Auckland Council are expecting a new land cover dataset in 2024. As such, results may not be valid in areas where there had been considerable change or development since the datasets were created.

- **Model sensitivities**. Whilst the choice of input parameters was based on experience, literature research and expert judgement, there will always be some level of uncertainty regarding their accuracy. This includes:

  - **Irrigation and moisture.** The precise irrigation in the rural areas is unknown, which could impact their latent heat behaviour and predicted temperatures. Due to this uncertainly, the model only uses precipitation as the moisture source.

  - **Heat storage and albedo.** For the urban areas, storage heat and albedo may vary compared to the parameters used in the model. In addition, they may vary across the city if the materiality varies in different areas. This level of detail is not feasible to capture in the model. Where possible these parameters have been determined using sensitivity tests.

  - **Wind.** The cooling or breeze effect of the wind on the urban climate is accounted in UHeat using a combination of the wind information in the forcing data and an equivalent surface roughness across the city derived from the building and tree properties. Detailed information on the wind direction and building orientation are not possible to capture in this type of model.

  - **Anthropogenic heat emission assumptions**. Data on heat emissions from buildings, transport, and people is generally not readily available. As a result, population density is used as a proxy in the model to estimate these variables. While this is a reasonable approach in the absence of detailed data, it should be noted that actual heat emissions across urban areas may differ from those used in the model. Sensitivity tests were conducted to assess the impact of anthropogenic heat emissions, and it was found that this parameter did not significantly affect overall temperatures, as other factors such as solar radiation were more dominant.

- **Model simplifications**. UHeat is a surface-based tool and does not account for detailed 3D features. Furthermore, it cannot replicate the complex wind behaviour and associated advection within cities (e.g., wind flow through a street canyon surrounded by tall buildings. This would impact the UHI effect but require more complex modelling to be carried out and generally cannot be used for large AOIs.

- **Thermal comfort or heat stress considerations.** The temperature output from UHeat does not directly correlate to thermal comfort or heat stress, which is impacted by other climate variables (e.g., humidity, solar radiation). UHeat does include information about these but further work would be required to assess the validity of this information and calculate thermal comfort or heat stress.

4.3 Recommendations

Auckland UHI shown by the dataset combined with increasing urbanisation and the impacts of climate change indicate the need for the region to consider heat planning, adaptation, and mitigation to ensure present and future resilience.

This assessment has produced a heat dataset, which offers valuable insights into how temperatures vary across Auckland, including the urban centre and the surrounding rural areas. The intention of this dataset is to support communication on heat-related hazards and inform decision-making for Auckland Council. Furthermore, the urban heat dataset has the potential to inform climate adaptation planning and contribute to a climate change risk assessment for Auckland. The following sections describe how the dataset can be utilised and identifies some potential next steps.

4.3.1 Using the data

The dataset can be used in multiple ways:

- **Publications and data sharing.** Making the data publicly available could be highly beneficial for various stakeholders across Auckland. Public bodies, such as those responsible for transport, health services, and schools, could use the data to better understand and manage heat risks. The private sector could leverage the information to assess the impact of heat on their assets and interests. Additionally, the community could gain valuable insights into their city, enhancing their understanding and awareness of local heat-related issues. It would be useful to host some of the data maps through an interactive web portal allowing user access across the different stakeholders. Examples include:
  - *London Climate Risks Map* which is hosted on ArcGIS[3] and provides an interactive means of presenting several datasets in an easy and accessible way.
- **Data layering to understand risk.** Integrating the heat dataset with other data, such as socioeconomic or infrastructure vulnerability, can help create detailed heat risk maps for specific areas like the Auckland city centre area. For instance, the GLA's "*Properties Vulnerable to Heat Impacts in London*"[4] project provides a series of heat risk maps that highlight overheating risks in various building types across London. This project offers data at the Lower Super Output Area (LSOA) level, making it accessible to a range of stakeholders, including different local authorities. Presenting information in this way supports decision-making on heat risks, ensuring that the most vulnerable and at-risk populations are prioritised. Examples include:
  - *Keep Bristol Cool mapping tool*[5]. This interactive map layers a number of different heat vulnerabilities including age-related vulnerability and deprivation with both indoor and outdoor exposure (in this instance using land surface temperature rather than air temperature).
- **Community engagement.** The data can be used to inform and support communication on heat-related hazards, resilience, and climate adaptation. It can help raise awareness, for instance, by educating residents about the impacts of heat and ways to stay cool. It would be valuable to involve the community in developing and implementing heat mitigation strategies. Examples of cities that have deployed community engagement strategies include:
  - *Sweltering Cities 2022 Summer Survey* – an extensive survey carried out across Australian cities for rental population to understand and engage with the community on the impacts of extreme heat. The survey helped build an evidence base for policy change.[6]
  - *Buenos Aires Heatwave campaign for elderly* – communication campaign for the vulnerable elderly population via social media and workshops.[7]
  - *Canada Communicating the Health Risks of Extreme Heat Events*[8]. A Toolkit designed to help public health and emergency management officials create or update heat-health communication strategies. It provides guidance for developing targeted campaigns and outreach products for specific audiences.

[3] https://cityhall.maps.arcgis.com/apps/instant/media/index.html?appid=59236d2e842c4a3ba6480d9dac585d1e

[4] https://www.london.gov.uk/sites/default/files/2024-01/24-01-16%20GLA%20Properties%20Vulnerable%20to%20Heat%20Impacts%20in%20London.pdf

[5] https://www.bristol.gov.uk/council/policies-plans-and-strategies/energy-and-environment/the-keep-bristol-cool-mapping-tool

[6] https://swelteringcities.org/wp-content/uploads/2022/04/FINAL-Summer-Survey-2022-Report-v1.2.pdf#page=28

[7] https://buenosaires.gob.ar/adaptacion/programa-de-adaptacion-frente-eventos-climaticos-extremos

[8] https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/climate-change-health/communicating-health-risks-extreme-heat-events-toolkit-public-health-emergency-management-officials-health-canada-2011.html

- *Beating the Heat Hunting Park, Philadelphia*[9]. Hunting Park is a heat-vulnerable neighbourhood with a proactive environmental advocacy community. In 2018, the Office of Sustainability collaborated with local organisations and over 600 residents to develop a neighbourhood heat plan.

- **Gaining insights.** There is a vast amount of data produced for this project which merits further investigation. Useful insights can be gained through carrying out further data processing and analysis. This can include:
  - Investigating the factors that influence the formation of hot and cool spots. This includes examining elements such as land cover, building density, and albedo across Auckland's urban area through layered output and input data.
  - Investigating the potential for heat mitigation. The maps can help identify locations for both short- and long-term mitigation and adaptation measures, such as green infrastructure, water features, cool roofs, and shading.
  - Investigating diurnal and seasonal patterns through probing different time periods. This will help highlight which periods may be the most critical in terms of heat related impacts and which periods are less onerous.
- **Planning and development.** Using the dataset as evidence to inform heat mitigation programmes. A good example:
  - *The New York City Cool Roofs* utilised heat mapping to identify hotspots and prioritise areas where the intervention would be most effective. Temperature mapping helps in targeting areas that experience the highest heat, making the programme more effective by focusing resources where they are needed most.[10]

4.3.2 Next steps

There are several avenues that can be explored to develop data insights for Auckland further. Some of these have already been discussed in the previous section, but there are also additional options that could be considered to build on this work:

- **Incorporate data updates to understanding change.** The development of the UHeat analysis relied on the most current data at the time. Since the inception of the project the land use classification data is due to be updated, and other datasets such as population data may be updated. This step should be considered carefully to ensure that sufficient changes have been made to have influence. It may be beneficial to focus on a few key areas of high development rather than recreating the full dataset.
- **Producing heat stress maps.** Creating detailed maps that highlight areas most affected by heat stress. Going beyond air temperature data, other UHeat model outputs (relative humidity, wind, solar radiation) can be investigated and configured to produce a heat stress dataset. Heat stress is a better indicator of heat related health impacts.
- **Scenario testing.** UHeat can also be used for evaluating the effectiveness of various heat mitigation strategies, such as green roofs, urban greening, and reflective surfaces, in different locations. This can help determine the best approaches for specific areas and provide quantitative evidence which can be used for making implementation decisions.
- **Incorporating climate change projections.** Integrating climate change projections into the assessment and output datasets. For example, using NIWA climate change projections to understand future heat patterns and inform adaptation planning.

These options illustrate the breadth of technical work that can be undertaken to enhance our understanding of heat hazard across Auckland. They can provide valuable insights into which adaptation solutions will be most effective and in which specific areas. By leveraging these technical approaches, we can better identify

[9] https://www.phila.gov/media/20190719092954/HP_R8print-1.pdf

[10] https://climate.cityofnewyork.us/initiatives/nyc-cool-roofs/

targeted strategies for heat mitigation, ensuring that interventions are both efficient and contextually appropriate.

4.3.3 Beyond the data: heat mitigation actions

Although Auckland's climate is relatively mild, high temperatures and urban heat could still pose challenges now and in the future. The city and its surroundings are not necessarily designed for high temperatures, and with climate change, heat events are likely to increase in magnitude and frequency. There is value in considering heat mitigation actions now to avoid future impacts and ensure resilience. This assessment provides spatial data which can help to prioritise areas and vulnerable populations (as discussed above).

Beyond this project, Auckland can look to what adaptation measures and heat mitigation solutions other cities have successfully implemented to establish their own programmes. Some short- to long-term measures are discussed here to provide Auckland Council with direction on potential actions. However, this list is not exhaustive, and further research and assessment are necessary to determine the most effective solutions for Auckland.

Short term:

- *Providing cooling centres and respite areas.* This can be an effective strategy in the short term to provide resilience for the most vulnerable residents and in the hottest areas if the city. A good example of this is *the Ilots de fraîcheur à Parsi*[11] which is an interactive map which shows cooler part of the city, water points and cooling centres – a valuable resource during heat waves.
- *Heat alerts and early warning systems.* Various types of alert systems have been used in cities around the world to communicate with citizens and provide an action plan during heat events. For example, the city of Ahmedabad in India introduced a comprehensive Heat Action Plan, which includes an alert system and coordinated actions for key workers across the city[12]. Although temperatures in Auckland may not be considered high enough to warrant the same level of action as Ahmedabad, there is potential to introduce a more targeted set of actions to address the most at-risk areas. For example, Auckland properties may overheat above a lower heat threshold, and an alert system with advice on how people can stay cool in their homes could be more appropriate.

Long term

- *Building Retrofit measures*. Many properties in Auckland may not be designed for increasing temperature. There may be a need to retrofit buildings to reduce overheating which can occur even at lower summer temperatures. The Climate Change Committee in the UK commissioned Arup to assess overheating in homes and test how retrofit measures can help mitigate the issue. This work is presented in the "*Addressing overheating risk in existing UK homes*" report[13] and can provide some good suggestions which could be considered for Auckland. In addition, the GLA's "*Properties Vulnerable to Heat Impacts in London*"[14] project provides a methodology to identify the most at risk properties for long term retrofit.
- *Green and blue infrastructure.* Nature based solutions can help reduce urban temperatures and can be applied in different ways. This can include increasing tree canopy cover, green and blue surfaces at street level and green roofs and walls on buildings.Soil moisture in vegetation significantly influences its ability to provide cooling. During periods of low precipitation, decreased soil moisture can prevent vegetation from cooling the environment and may even cause it to have the opposite effect. The urban heat assessment for Auckland indicates that there are times when vegetation fails to provide a cooling

[11] https://experience.arcgis.com/experience/97a1ee11f50e4c36afb48b93007b4fb8/page/Version-Fran%C3%A7aise/#data_s=id%3AdataSource_3-188962d6854-layer-5-1889628e6b4-layer-3%3A27446

[12] https://www.nrdc.org/sites/default/files/ahmedabad-heat-action-plan-2018.pdf

[13] https://www.theccc.org.uk/wp-content/uploads/2022/10/Addressing-overheating-risk-in-existing-UK-homes-Arup.pdf

[14] https://www.london.gov.uk/sites/default/files/2024-01/24-01-16%20GLA%20Properties%20Vulnerable%20to%20Heat%20Impacts%20in%20London.pdf

effect during low moisture periods. To mitigate this, an effective irrigation and maintenance strategy should be designed. The analysis does not differentiate between vegetation species and relies on general assumptions about plant behaviour. However, there may be localised plant species that perform better in dry conditions, such as those adapted to drier environments. Careful selection of these species could enhance cooling effectiveness.

Examples where vegetation has been implemented effectively:

- Green Corridors (Medellin, Colombia). Medellín has successfully reduced urban temperatures by an average of 2°C through its “green corridors” initiative, which involves planting extensive greenery along roads, parks, and public spaces[15]. This project not only mitigates heat but also improves air quality, improve carbon sequestration potential of the city and enhances urban biodiversity.
- Green Axes (Barcelona, Spain). Barcelona’s “Superblocks” initiative aims to transform the city by merging nine existing blocks into larger, pedestrian-friendly areas, reducing car traffic, noise, and pollution. This urban renewal project enhances public spaces, promotes sustainability, and improves the quality of life for residents[16].

- *Cool surfaces.* This can include both cool streets cool roofs where reflective coating or materials are used to reduce the amount of heat absorbed into the urban fabric. Examples where this has been implemented:
  - CoolStreets LA (Los Angeles, USA). To help lower temperatures and provide shade in L.A.'s hottest and most vulnerable communities, the “CoolStreets LA”[17] program employs multiple cooling strategies. These include planting new street trees, constructing bus benches with shade structures, expanding cool roofs, providing hydration stations, and installing cool pavements city-wide. The cool pavements use reflective coatings to reduce the absorption of solar radiation and reflect it back out.
  - NYC CoolRoofs (New York, USA). The NYC CoolRoofs programme has been going for over a decade now and has resulted in large scale implementation of cool roofs across the city. The programme is a partnership between both public and private sector and has results in a number of co-benefits such as paid training and work experience for citizens.

The mitigation solutions discussed here provide an overview of some of the popular strategies deployed globally to mitigate urban heat. Auckland is in an advantageous position to learn from cities in hotter climates that have already made significant progress in addressing heat. The challenge will be to identify which strategies will be most effective for Auckland, both from a heat mitigation and a holistic perspective (e.g. co-benefits, feasibility). This includes determining where these strategies should be focused and establishing the mechanisms to unlock funding and investment. The heat map produced in this project is a crucial component in this effort and can provide the data and evidence base to prioritise efforts, communicate to stakeholders and help drive action on heat.

[15] https://www.bbc.com/future/article/20230922-how-medellin-is-beating-the-heat-with-green-corridors

[16] https://www.gabarcelona.com/blog/superblocks/

[17] https://streetsla.lacity.org/cool-la-neighborhoods

References

SUEWS dev team. (n.d.). *Typical values*. Retrieved from SUEWS: https://suews.readthedocs.io/en/latest/input_files/SUEWS_SiteInfo/Typical_Values.html#typical-values

Aqualinc. (2020, September 8). *National Irrigated Land Spatial Dataset.* Retrieved from Ministry for the Environment: https://environment.govt.nz/assets/Publications/national-irrigated-land-spacial-dataset.pdf

Arup. (2023). *London's most extreme urban heat island "hot spot" revealed*. Retrieved from Arup: https://www.arup.com/news/londons-most-extreme-urban-heat-island-hot-spot-compared-to-five-other-global-cities-in-new-survey/

Auckland Council. (2013). *Temperature as a Contaminant in Streams in the Auckland Region, Stormwater Issues and Management Options.* Auckland: Auckland Council.

Auckland Council. (2023, June 1). *10 things you need to know about Auckland's Future Development Strategy*. Retrieved 2024, from https://ourauckland.aucklandcouncil.govt.nz/news/2023/06/10-things-you-need-to-know-about-auckland-s-future-development-strategy/#:~:text=Over%20the%20next%2030%20years%2C%20Auckland%20will%20continue%20to%20grow,grow%20in%20many%20different%20ways.

Auckland Council. (n.d.). Auckland landcover dataset. Retrieved March 26, 2024

Auckland Council. (n.d.). Auckland open water dataset. Retrieved April 09, 2024

Auckland Council. (n.d.). Auckland weather data for Arup. Retrieved April 05, 2024

Auckland Council. (n.d.). Hexagon grid shape file. Retrieved March 22, 2024

Auckland Council. (n.d.). Urban canopy dataset. Retrieved March 26, 2024

Betti, G. T. (2024). CBE Clima Tool: A free and open-source web application for climate analysis tailored to sustainable building design. *Building Simulation, 17*, 493-508.

Brody-Heine, S., Katurji, M., Stewart, C., Wilson, T., Smid, E. R., & Trancoso, R. (2024). Modeling SO2 dispersion from future eruptions in the Auckland Volcanic Field, New Zealand. *Journal of Applied Volcanology, 13*.

Climate Central. (2024, July 10). *Urban Heat Hot Spots in 65 Cities*. Retrieved from Climate Central: Daytime UHI Intensity: In summer, Toronto's daytime UHI intensity can reach up to 4.5°C higher than surrounding rural areas1.

Cohen, A. E., Cavallo, S. M., Coniglio, M. C., & Brooks, H. E. (2015). A Review of Planetary Boundary Layer Parameterization Schemes and Their Sensitivity in Simulating Southeastern U.S. Cold Season Severe Weather Environments. *Weather and Forecasting, 30*.

Dayal, K. K., Cater, J. E., Kingan, M. J., Bellon, G. D., & Sharma, R. N. (2020). Evaluation of the WRF model for simulating surface winds and the diurnal cycle of wind speed for the small island state of Fiji. *Journal of Physics: Conference Series, 1618*.

Duan, Y. a.-A. (2024). Urban Heat Island Effect in Canada: Insights from Five Major Cities. *SSRN*. Retrieved from http://dx.doi.org/10.2139/ssrn.4965331

Eagle Technology; LINZ; StatsNZ; NIWA; Natural Earth; OpenStreetMap . (n.d.). *Auckland Council Open Data*. Retrieved from Auckland Council: https://data-aucklandcouncil.opendata.arcgis.com/datasets/aucklandcouncil::ecosystem-current-extent/explore

ESA. (2021). WorldCover Version 2. Retrieved from https://esa-worldcover.org/en

Golubiewski, J. L. (2019). *Development of the Auckland Heat Vulnerability Index.* Auckland. Retrieved from https://knowledgeauckland.org.nz/media/h2ti3nl4/tr2019-012-development-of-the-auckland-heat-vulnerability-index-final.pdf

Järvi, L., Grimmond, C., & Christen, A. (2011). The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver . *Journal of Hydrology, 411*(3-4), 219-237.

Jennifer L R Joynt, N. E. (2019). *Development of the Auckland Heat Vulnerability Index: Technical Report 2019/012.* Auckland: Auckland Council.

Kate Newton. (n.d.). *The Green Divide, How Wealth Buys Shade in a Warming World*. (Stuff) Retrieved 2024, from https://interactives.stuff.co.nz/2022/03/urban-heat-island-tree-cover/

Khan, B. A. (2010). Sea Breeze Circulation in the Auckland Region: Observational Data Analysis and Numerical Modelling. *University of Canterbury*.

Kleczek, M. A., Steeneveld, G.-J., & Holtslag, A. A. (2014). Evaluation of the Weather Research and Forecasting Mesoscale Model for GABLS3: Impact of Boundary-Layer Schemes, Boundary Conditions and Spin-Up. *Boundary-Layer Meteorol, 152*, 213-243.

Kropač, E., Mölg, T., & Cullen, N. J. (2023, 04 19). NZ-WRF. *OSFHOME*.

Kropač, E., Mölg, T., Cullen, N. J., Collier, E., Pickler, C., & Turton, J. V. (2021). A Detailed, Multi-Scale Assessment of an Atmospheric River Event and Its Impact on Extreme Glacier Melt in the Southern Alps of New Zealand. *JGR Atmospheres, 126*(9).

LINZ Data Service. (2016, December 16). *Auckland North LiDAR 1m DSM (2016-2018)*. Retrieved from Land Information New Zealand: https://data.linz.govt.nz/layer/105089-auckland-north-lidar-1m-dsm-2016-2018/

LINZ Data Service. (2019, December 16). *Auckland South LiDAR 1m DEM (2016-2017)*. Retrieved from Land Information New Zealand: https://data.linz.govt.nz/layer/104318-auckland-south-lidar-1m-dem-2016-2017/

LINZ Data Service. (2019, December 18). *Auckland South LiDAR 1m DSM (2016-2017)*. Retrieved from Land Information New Zealand: https://data.linz.govt.nz/layer/104382-auckland-south-lidar-1m-dsm-2016-2017/

LINZ Data Service. (2021, November 7). *Auckland North LiDAR 1m DEM (2016-2018)*. Retrieved from Land Information New Zealand: https://data.linz.govt.nz/layer/106410-auckland-north-lidar-1m-dem-2016-2018/

LINZ Data Service. (2024, August 14). *NZ Building Outlines*. Retrieved from Land Information New Zealand: https://data.linz.govt.nz/layer/101290-nz-building-outlines/

MIT. (2021, April 16). *Urban Heat Islands*. Retrieved from Climate Portal: https://climate.mit.edu/explainers/urban-heat-islands

NASA. (n.d.). *GLDAS Forcing Data*. Retrieved from https://ldas.gsfc.nasa.gov/gldas/forcing-data

NOAA. (2021, September 22). *Climate Forcing*. Retrieved 2024, from https://www.climate.gov/maps-data/climate-data-primer/predicting-climate/climate-forcing

Pirooz, A. A., Moore, S., Turner, R., & Flay, R. G. (2021). Coupling High-Resolution Numerical Weather Prediction and Computational Fluid Dynamics: Auckland Harbour Case Study. *Applied Sciences, 11*(9).

Stats NZ Geographic Data Service. (2020, May 26). *2018 Census Individual (part 1) total New Zealand by Statistical Area 1*. Retrieved from Stats NZ: https://datafinder.stats.govt.nz/layer/104612-2018-census-individual-part-1-total-new-zealand-by-statistical-area-1/

SUEWS dev team. (n.d.). *SUEWS: Surface Urban Energy and Water Balance Scheme*. Retrieved from SUEWS: https://suews.readthedocs.io/en/latest/

Sun, T. (2024, August 24). SUEWS model: supy 2024.8.2.dev0. Retrieved from https://pypi.org/project/supy/2024.8.2.dev0/

U.S. Environmental Protection Agency. (2024, August 20). *Learn About Heat Islands*. Retrieved from EPA: https://www.epa.gov/heatislands/learn-about-heat-islands

United States Environmental Protection Agency. (2024, August 20). *Heat Island Impacts*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/heatislands/heat-island-impacts

United States Environmental Protection Agency. (n.d.). *Heat Island Effect*. Retrieved from EPA United States Environmental Protection Agency: https://www.epa.gov/heatislands

University of Calgary. (n.d.). *Climate Forcing*. Retrieved from https://energyeducation.ca/encyclopedia/Climate_forcing

Webster, S., Uddstrom, M. J., Oliver, H., & Vosper, S. (2008). A high-resolution modelling case study of a severe weather event over New Zealand. *Atmospheric Science Letters*, *9*(3), 119-128.

Appendix A | Detailed methodology

Appendix A provides a detailed description of the methodology adopted for this project, including the geo-spatial data processing, the selection of WRF input parameters and the coupling of WRF to UHeat. An overview of the SUEWS model, which is a core component of UHeat is also provided in this Appendix.

A.1 Data collection and processing

This section presents the steps followed to process, combine, and update the geo-spatial data underpinning the heat dataset produced as an output from UHeat.

A.1.1 Hex grid and AOI

Figure 26 compares the extent of the hex grid to the Auckland Council boundary (the AOI), provided in the form of the shapefile. The hex grid extends further than the AOI boundary in some places, and only hexes contained fully within the AOI were used in the subsequent modelling (i.e. the hex grid was clipped by the AOI boundary).

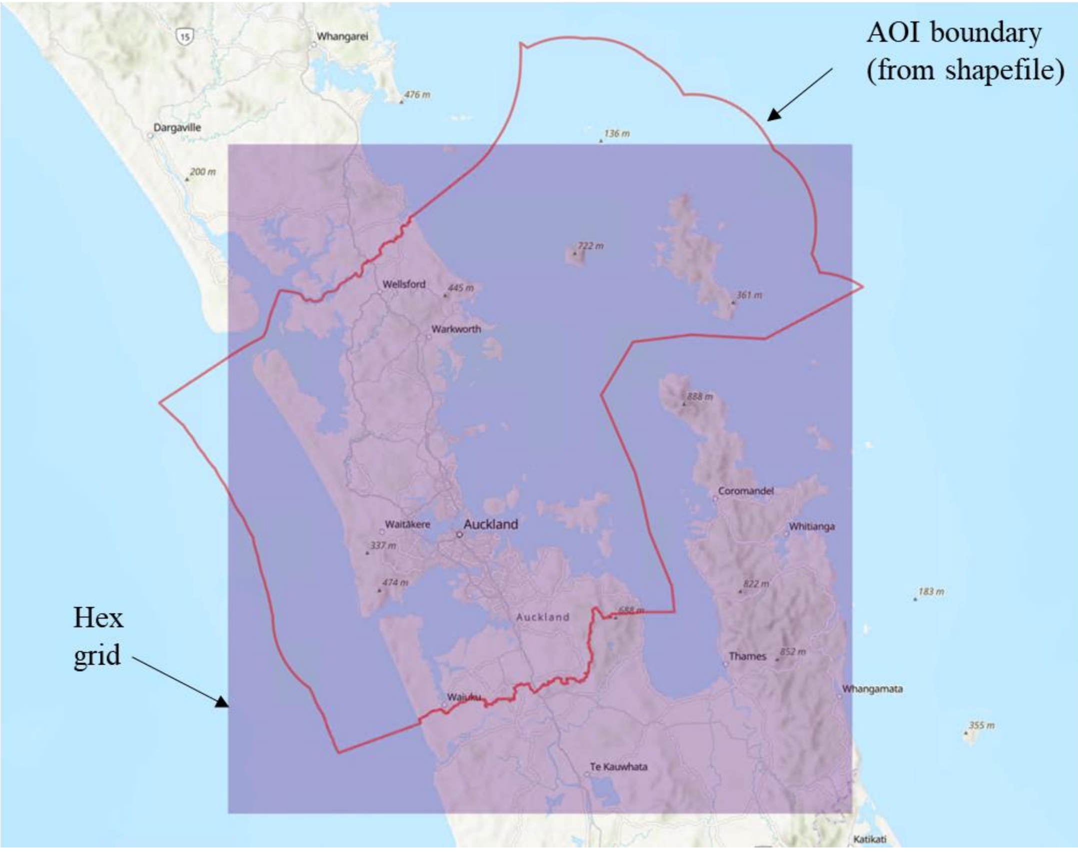

Figure 26: Comparison of the hex grid to the Auckland Council boundary.

A.1.2 Combination of datasets to produce land cover dataset

The next aspect of the processing was to combine the land cover, canopy height and inland water bodies datasets (referenced in Table 1). Figure 27 provides an overview of the workflow used to do this.

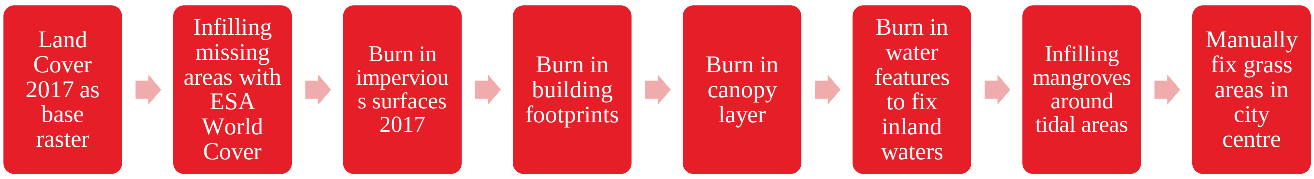

Figure 27: Overview of the steps followed to combine the different geospatial datasets into a single geospatial land cover dataset.

A.1.3 Updates to land cover dataset

The combined land cover dataset was reviewed, and the following data quality aspects were identified. They were discussed with Auckland Council on the 18th of April 2024, and mitigation was agreed as outlined below:

- Land cover information was missing for the Birds Beach Reserve, as highlighted in Figure 28. Auckland Council noted that this area was likely missing from the 2010-2011 aerial imagery. Consequently, the ESA World Cover dataset (ESA, 2021) was used to fill this missing area. ESA World Cover is of lower resolution to the land cover dataset; however, it was considered acceptable for this location as it away from urban areas.

- In the land cover data provided by Auckland Council the buildings were not classified completely, as shown in Figure 29. To resolve this, the building footprints dataset from the Land Information New Zealand portal (LINZ Data Service, 2024) was used to define the building, as shown in Figure 29.

- The land cover dataset is generally constrained to mean high-water springs and so there is limited coverage beyond the shoreline, for example mangroves were not captured in the land cover dataset as highlighted in Figure 30. Auckland Council provided an additional ecosystem dataset (Eagle Technology; LINZ; StatsNZ; NIWA; Natural Earth; OpenStreetMap , n.d.) to help identify mangrove locations and other similar terrain types (e.g. salt marshes, estuaries). This dataset agreed well with the ESA World Cover dataset, and so the ESA World Cover dataset was used to update the land cover dataset. Additionally, to include these types of terrain in UHeat they were classified as follows:
  - Mangroves: trees
  - Salt/marshes or estuaries: grass
  - Inter-tidal mudflats: water
- The land cover dataset did not include some of the inland water bodies as highlighted in Figure 31. The specific water bodies dataset provided by Aukland Council was used to fill these missing regions.
- Within the urban areas, shadows from the building were misclassified as grass in the land cover dataset. An example of the misclassification within the city centre is shown in Figure 32, with the shadows highlighted in green. Auckland Council noted that misrepresentation of vegetation classes was a known issue with the land cover dataset, which prioritised the classification of impervious surfaces. Table 4 lists the different options considered for resolving this misclassification and option C was chosen.

Table 4: Options for resolving misclassification of shadows in city centre.

Option	Description
A) Use of land cover 2024 (if available and suitable)	Auckland Council confirmed that the latest land cover dataset would not be ready until the second half of 2024.
B) Use of ESA World Cover dataset	ESA World Cover dataset is lower resolution than the land cover dataset and would lose important detail in the urban areas, for example gardens. The loss in resolution in these urban areas was considered unacceptable for this project.
C) Manual fixing of misclassification	Using a combination of satellite imagery, Google imagery the land cover dataset would be manually updated hex by hex. This was the most manual of the interventions considered.

Figure 28: Missing information in land cover dataset (Birds Beach Reserve).

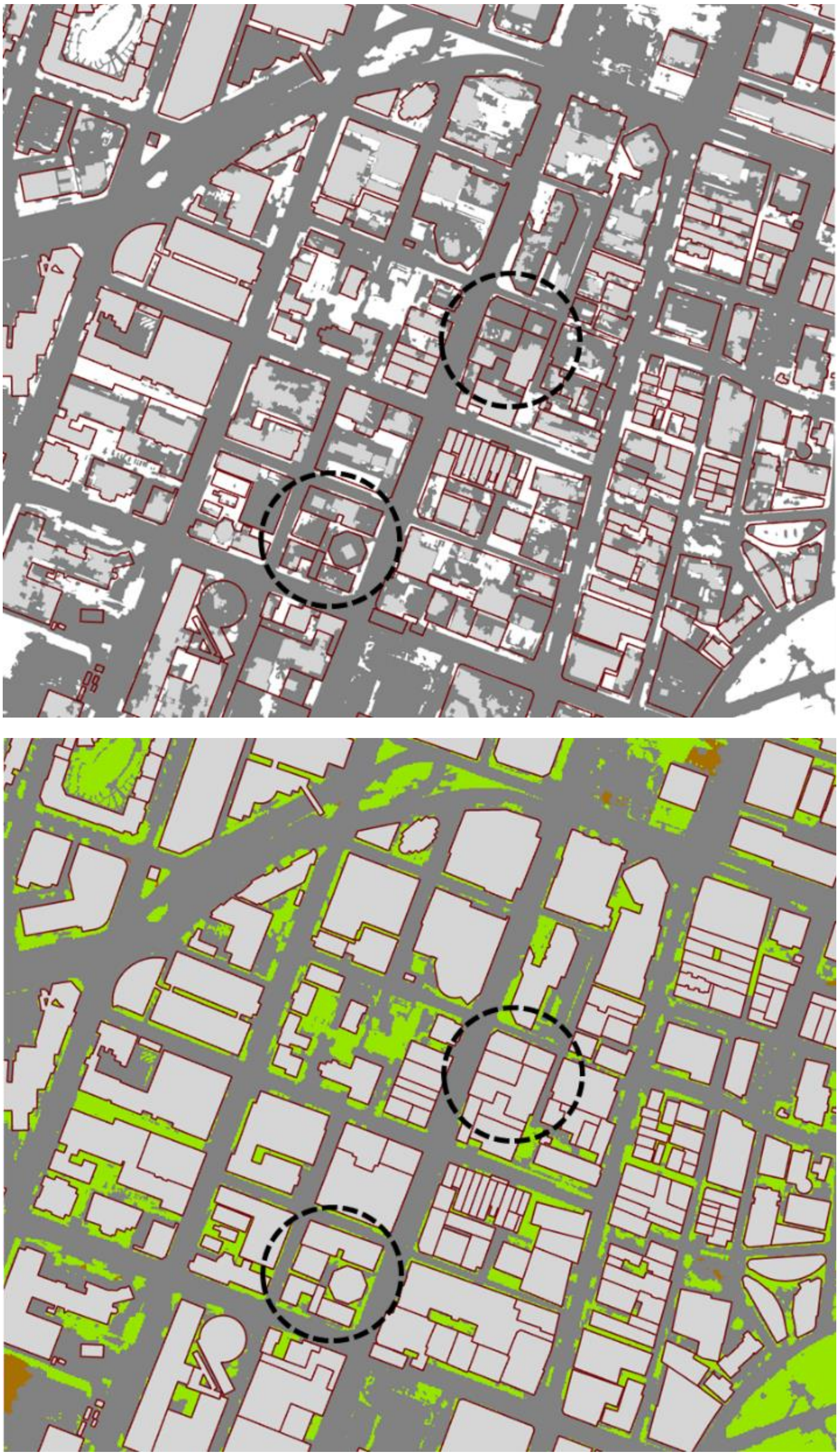

Figure 29: Top – buildings not fully captured in the land cover dataset. Bottom – information in the buildings outline dataset used in classify buildings.

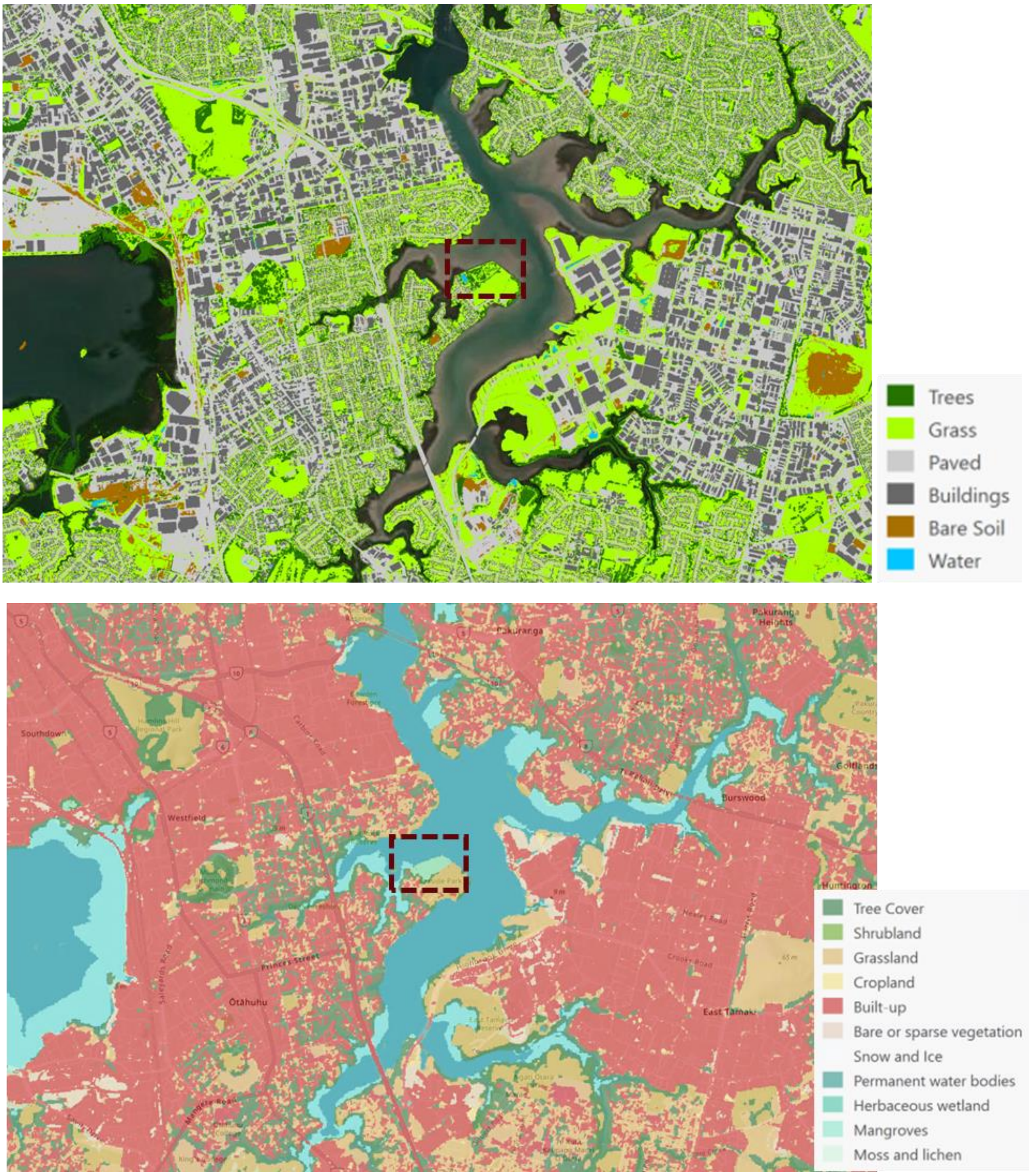

Figure 30: Top– land cover dataset with mangroves not identified. Bottom – ESA world cover dataset highlighting mangrove location.

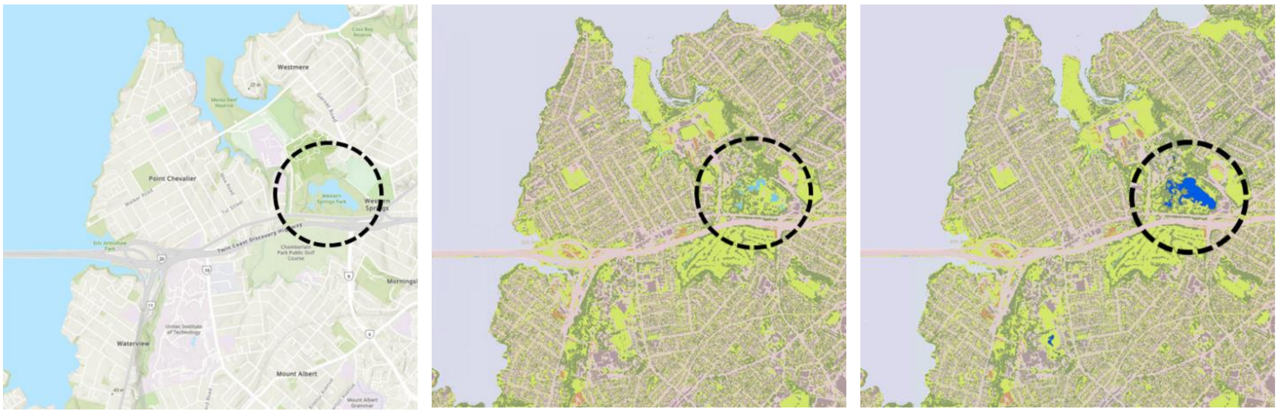

Figure 31: Left – Map highlighting location of inland water (Data source: ESRI). Middle – missing water body in land cover dataset (Data source: Auckland Council) Right – combined land cover and inland water body dataset.

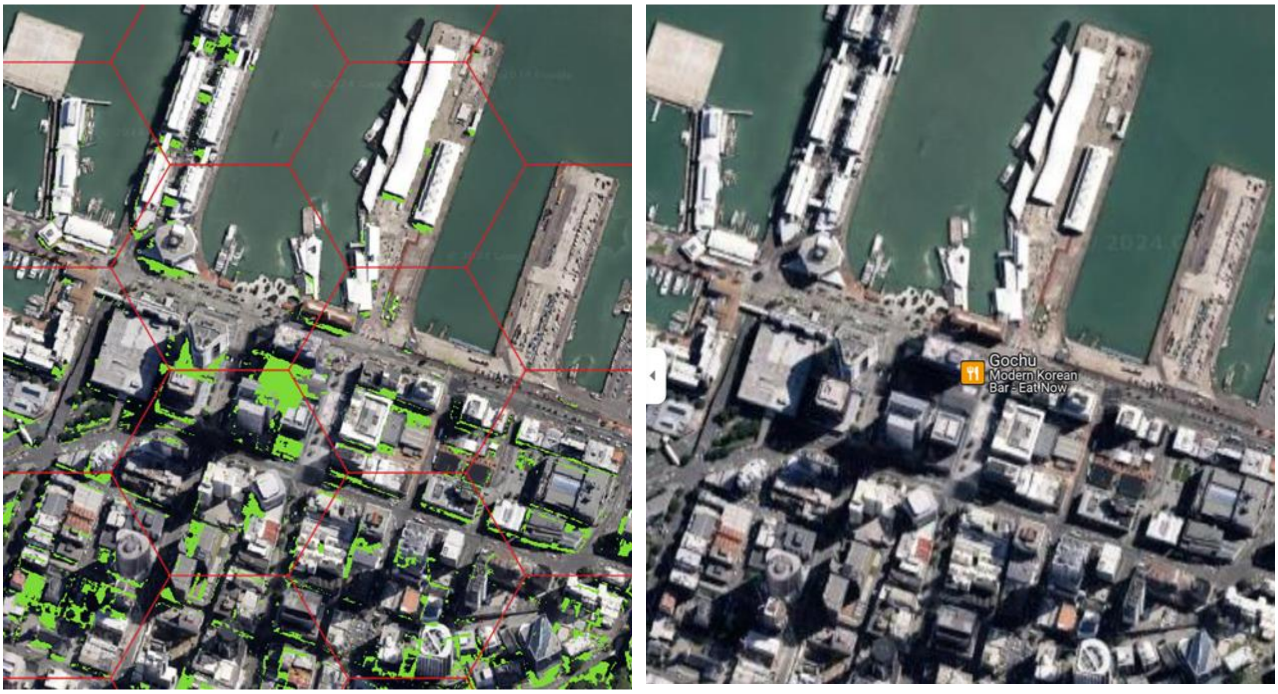

Figure 32: Left- misclassification of shadows as green in the land cover dataset highlighted in green. Right – Google image of city centre region.

A.2 WRF input parameters and sensitivity studies

A critical aspect of successfully using WRF is the appropriate choice of the model inputs. Inputs need to be chosen carefully and vary on the specific application of WRF. In this project the inputs had to suitable for the climate in Auckland, and ultimately for providing forcing input data to UHeat.

A literature review was conducted to understand previous WRF modelling in the Auckland region. The review included:

- *A Detailed, Multi-Scale Assessment of an Atmospheric River Event and Its Impact on Extreme Glacier Melt in the Southern Alps of New Zealand* by Kropač, et al., 2021
- *NZ-WRF*, Kropač, by Mölg, & Cullen, 2023
- *Coupling High-Resolution Numerical Weather Prediction and Computational Fluid Dynamics: Auckland Harbour Case Study, Pirooz,* by Moore, Turner, & Flay, 2021
- *A high‐resolution modelling case study of a severe weather event over New Zealand*, by Webster, Uddstrom, Oliver, & Vosper, 2008
- *Sea Breeze Circulation in the Auckland Region: Observational Data Analysis and Numerical Modelling*, by Khan, 2010
- *Modeling SO2 dispersion from future eruptions in the Auckland Volcanic Field, New Zealand*, by Brody-Heine, et al., 2024
- *Evaluation of the WRF model for simulating surface winds and the diurnal cycle of wind speed for the small island state of Fiji,* by Dayal, Cater, Kingan, Bellon, & Sharma, 2020
- *A Review of Planetary Boundary Layer Parameterization Schemes and Their Sensitivity in Simulating Southeastern U.S. Cold Season Severe Weather Environments,* by Cohen, Cavallo, Coniglio, & Brooks, 2015
- *Evaluation of the Weather Research and Forecasting Mesoscale Model for GABLS3: Impact of Boundary-Layer Schemes, Boundary Conditions and Spin-Up*, by Kleczek, Steeneveld, & Holtslag, 2014

Studies specific to Auckland were limited, thus the review expanded to other islands and areas with a similar climate such as Europe. The findings from the literature review were combined with previous experience and engagement with Dr Ting Sun (UCL) to determine appropriate settings for several of the inputs.

Some inputs required further investigation and for these sensitivity studies were conducted to determine the most appropriate settings.

Table 5 summarises the WRF inputs and identifies the ones that were chosen for sensitivity studies based on the literature review and guidance from Dr Ting Sun.

Table 5: WRF inputs summary.

<table>
<tr><th>Input Type</th><th>Input</th><th>Sensitivity Study</th><th colspan="3">Values</th><th>Comments</th></tr>
<tr><td rowspan="2">Forcing data</td><td>Time resolution</td><td>No</td><td colspan="3">Hourly</td><td>Hourly resolution computationally appropriate</td></tr>
<tr><td>Input data</td><td>No</td><td colspan="3">ERA5</td><td>Academic and industry recognised</td></tr>
<tr><td>Simulation time</td><td>Spin-up</td><td>No</td><td colspan="3">1 week</td><td>Academic advice from Dr Ting</td></tr>
<tr><td rowspan="2">Domain</td><td>Resolution around AOI</td><td>Yes</td><td>~8km</td><td>~3km</td><td>~1km</td><td>Precision vs computational requirements</td></tr>
<tr><td>Vertical resolution</td><td>No</td><td colspan="3">35 levels</td><td>Literature (Kleczek et al, 2014) indicates not much impact.</td></tr>
</table>

Input Type	Input	Sensitivity Study	Values		Comments
Physics	Microphysics	No	WRF Single-Moment 6-Class Scheme		Literature, confirmed with Dr Ting.
	Shortwave radiation	No	Dudhia		Dudhia is widely used in literature, confirmed with Dr Ting.
	Longwave radiation	No	RRTMG		RRTMG is widely used in literature, confirmed with Dr Ting.
	Atmospheric Surface Layer	No	Monin Obukhov (Revised MM5) MM5 Similarity		This will vary accordingly to the PBL scheme below.
	Land Surface Model	No	Noah		Academic advice from Dr Ting. Latest version used.
	PBL scheme (Planetary Boundary Layer)	**Yes**	**YSU**	**MYJ**	**YSU was the main PBL scheme used for New Zealand across literature, but MYJ was also used.**
	Ocean model	No			Academic advice from Dr Ting.
	Urban Canopy Model	No	Single Layer		Academic advice from Dr Ting.

A.2.1 Sensitivity studies

As noted in Table 5 sensitivity studies were conducted for the following two inputs:

- **Horizontal spatial resolution -** A finer spatial resolution can better capture the climate variations over the AOI, however requires more computational effort. This sensitivity study intended to find a balance between modelling precision and computational requirements.
- **Planetary boundary layer (PBL) -** The PBL is used to capture the interaction between the land and atmosphere. There are a range of PBL schemes which can be selected in WRF depending on the application.

The impact of different choices for these inputs was investigated by comparing the WRF predictions both qualitatively via spatial maps and quantitatively via comparison to weather station data provided by Auckland Council.

Three different horizontal spatial resolutions were investigated: coarse (8.1km), medium (2.7km), and fine (0.9km). These resolutions were used in the literature findings and follow WRF best practice. Some of the literature used resolutions up to 300m, however using such a resolution was not possible with the computational resources available and timescales of this project.

Figure 33 compares the spatial distribution of the temperature at 2m above ground on a hot day (18th February 2022) for the different resolutions. The 8.1km resolution does not capture the topographical and coastline variations across Auckland. Whilst the 0.9km has a finer resolution, there is not a significant difference to the 2.7km resolution results, with the latter still resolving the hot and cold areas sufficiently.

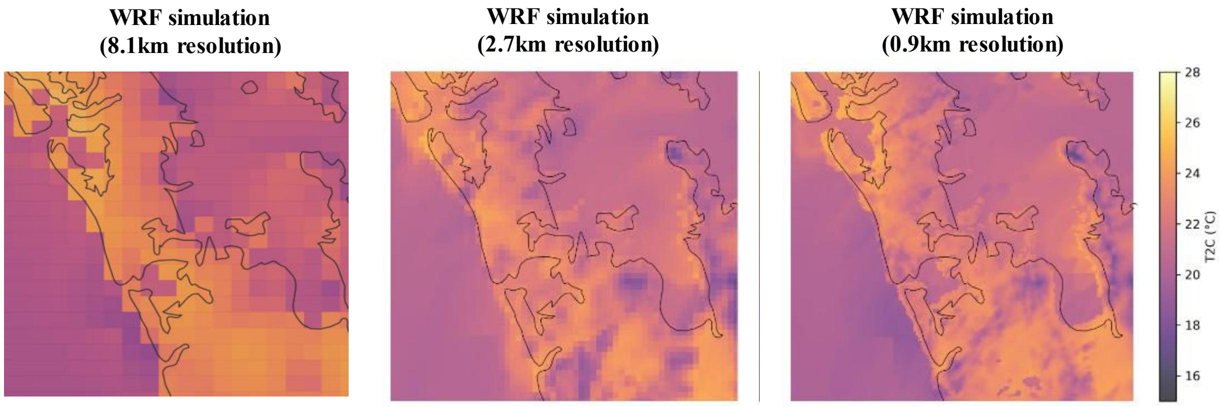

Figure 33: Sensitivity study results for horizontal resolution showing 2m temperature on 18th February 2022.

Figure 34 compares the WRF air temperature prediction for the different grids (8.1km, 2.7km and 0.9km) to the Warkworth weather station for a hot week in February 2022. The coarse grid does not sufficiently reproduce the temperature maximums and minimums of the temperature profile. The medium and fine grid simulations replicate the weather station measurements better and are relatively similar. Similar observations were made for other weather station locations.

Difference between the weather station data and the WRF model predictions are expected. WRF gives a temperature over an area corresponding to the grid size, whereas weather stations are a discrete single location. For example, greater variation is expected in the weather station measurements, which will capture local microclimate effects. Other causes for the differences are due to the inherent limitations with modelling the real world, with assumptions such as land cover classifications and geographical features.

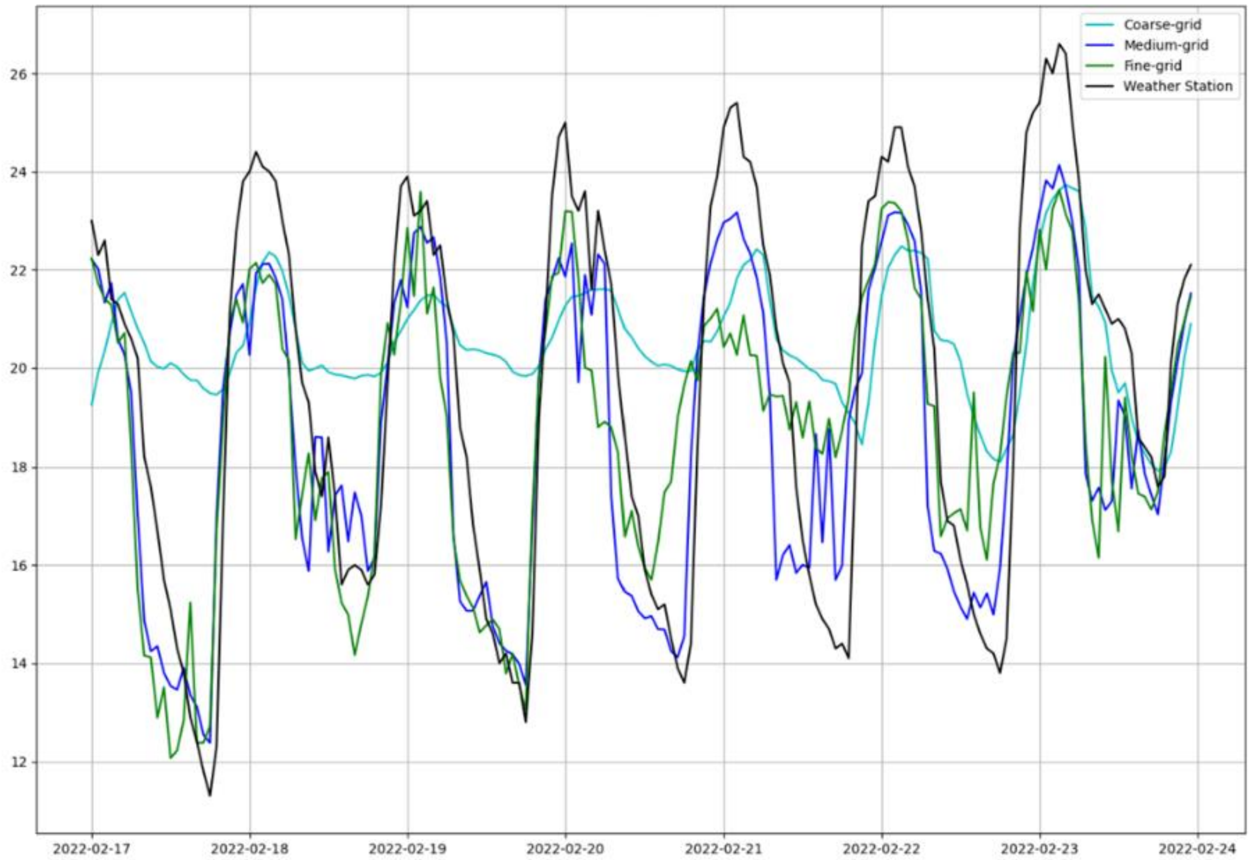

Figure 34: Comparison of the temperature at Warkworth weather station location for the coarse (8.1km), medium (2.7km) and fine (0.9km) grids and the weather station data.

Figure 35 compares the WRF wind speed prediction for the different grids (8.1km, 2.7km and 0.9km) to the Warkworth weather station for a hot week in February 2022. Both the coarse and medium grids replicate the magnitude and temporal variations well, whereas the fine grid (0.9km) shows the most discrepancies from the weather station recordings. The wind prediction within WRF is influenced greatly by the representation of turbulent flow structures (e.g. eddies or gusts). With finer resolution there is a more chaotic nature to the turbulent flow structures, which results in more fluctuations in the wind speed predictions.

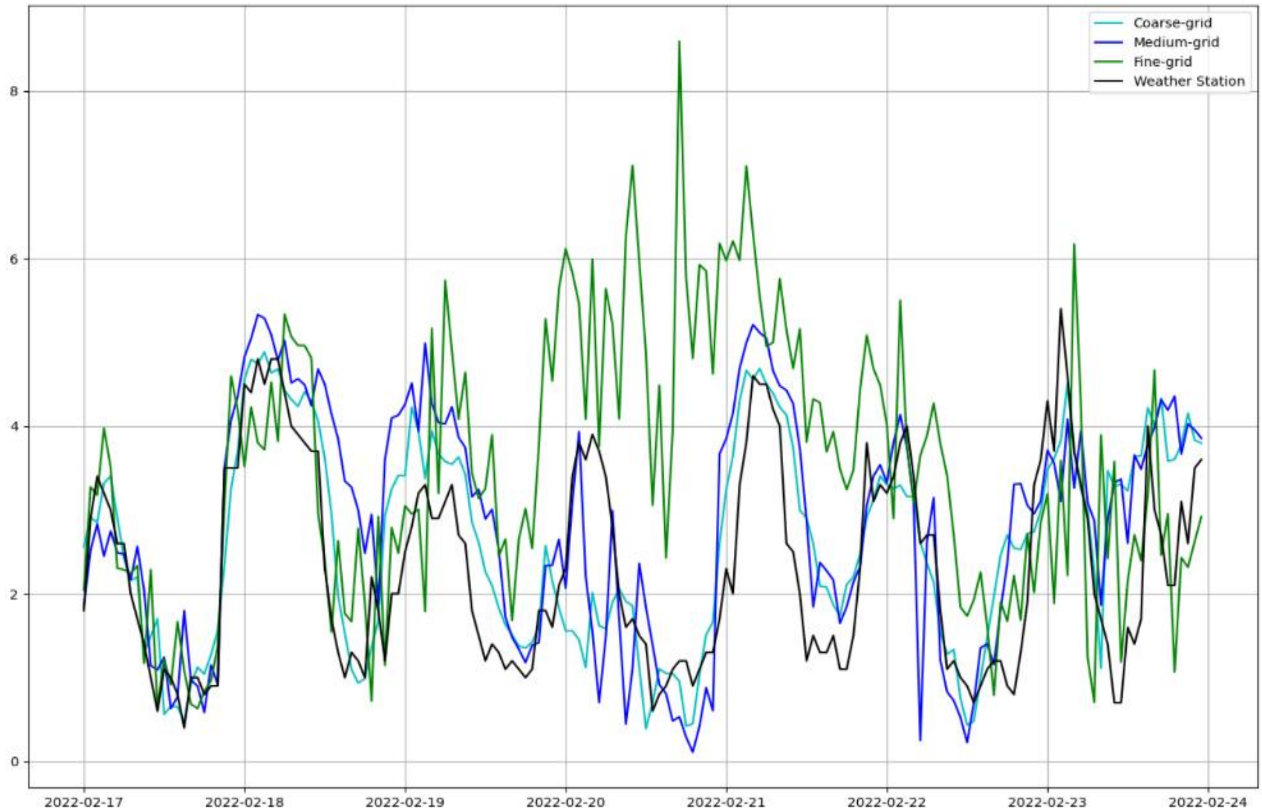

Figure 35: Comparison of the wind speed in m/s at Māngere weather station location for the coarse (8.1km), medium (2.7km) and fine (0.9km) grids and the weather station data.

Table 6 summarises the computational time required for the different resolutions to run the full analysis period (November 2021 to March 2022.)

Table 6: Comparison of the computational time required for WRF simulations with different grid resolution.

Grid Resolution	Computational Time (CPU Hours)	Time (using 30 CPUs)
Coarse (8.1km)	770	< 1 day
Medium (2.7km)	1386	1.5 days
Fine (0.9km)	7392	1 week

The medium resolution of 2.7km was chosen for the final WRF simulation as it sufficiently captured spatial variations in climate, and more manageable within the timescales of this project.

To assess the impact of planetary boundary layer (PBL) scheme, two PBL schemes were compared: the Yonsei University (YSU) and Mellor-Yamada-Janic (MYJ) models. This choice was based on the literature review, The YSU scheme represents the vertical mixing near the boundary to a greater depth than the MYJ scheme, where the resolution at the boundary is more localised.

Figure 36 compares the spatial temperature predictions between the two PBL schemes at daytime and nighttime. Both show largely similar spatial variations, however the YSU model better picks out the cooler locations, as seen previously in the weather station in Warkworth in Figure 36.

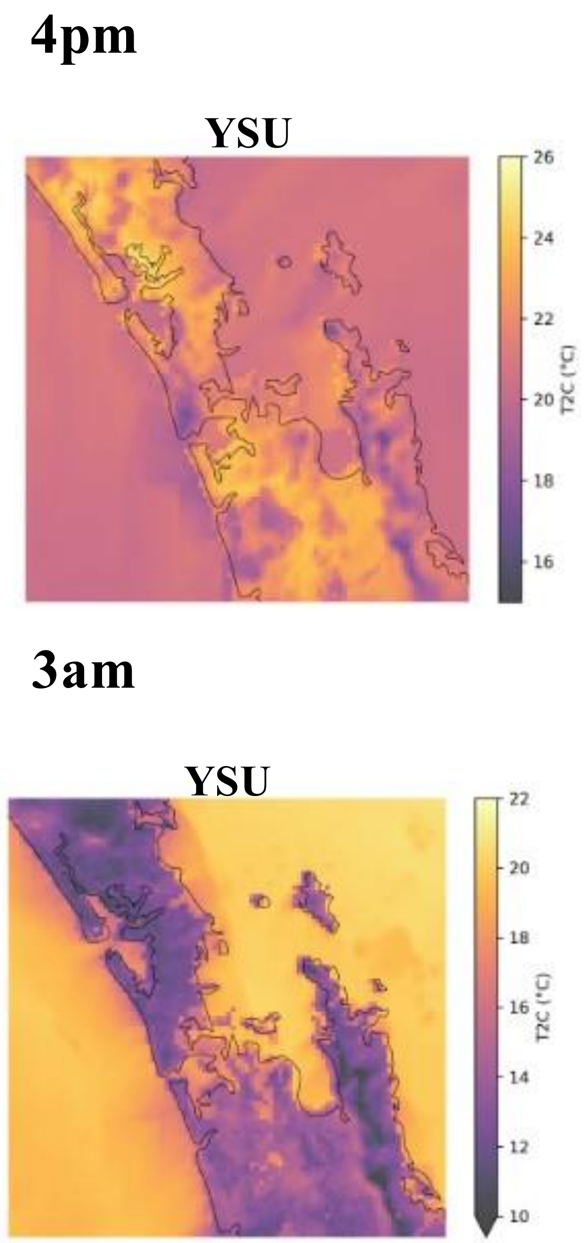

Figure 36: Sensitivity study results for horizontal resolution showing temperature at 2m on 18th of February at 4pm (top) and 3am (bottom).

Figure 37 shows the YSU scheme replicates the temperature peaks and troughs better than the MYJ model, when compared to the weather station data. However, Figure 38 shows the MYJ model is better at picking up the higher wind speeds. The YSU PBL scheme was chosen due to better simulating temperature peaks and troughs. This is required for the UHeat model to be able to simulate the hotspots and cold spots around Auckland.

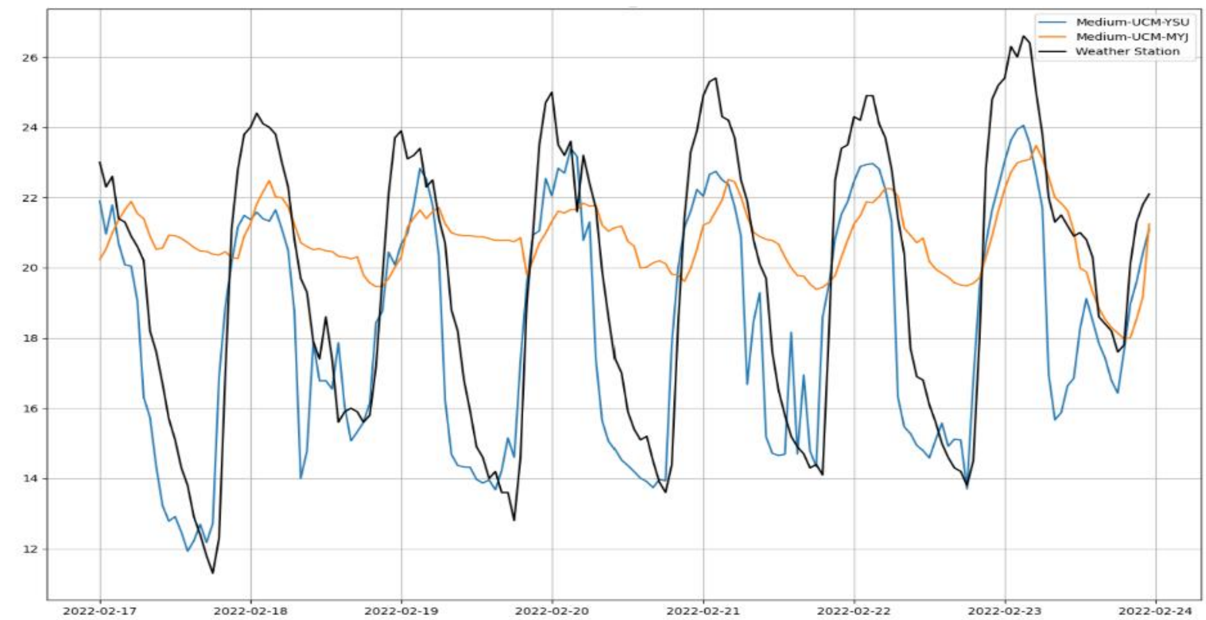

Figure 37: Comparison of the temperature at Warkworth weather station location for the different PBL schemes and the weather station data.

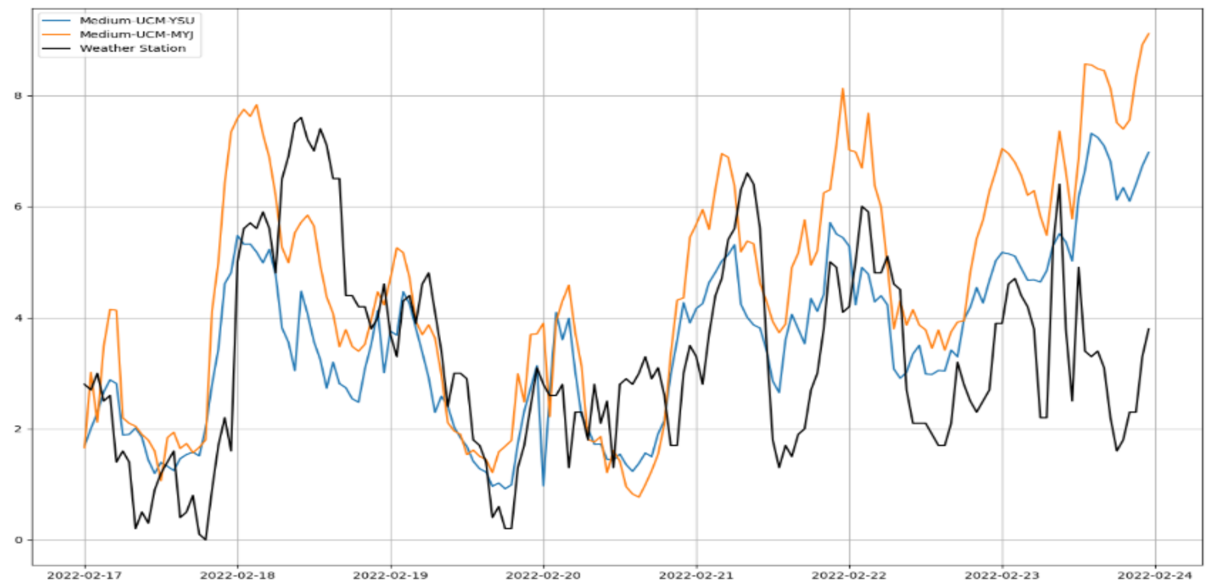

Figure 38: Comparison of the wind speed at Warkworth weather station location for the different PBL schemes and the weather station data.

A.2.2 Computational domain

WRF best practice was used to define the computational domain. A nest in WRF is a finer resolution domain contained within a coarser domain. They are used to capture detail around an AOI, without significantly increasing the computational cost. A two-nest model was applied in the analysis consisting of a coarse outer domain of 8.1km resolution and an inner nest of 2.7km resolution, which covered the Auckland AOI.

The computational domain used in WRF is shown in Figure 39. The extent of the domain is much larger than the AOI as WRF requires a buffer zone around the AOI for the wind patterns to develop sufficiently away from the edges of the domain.

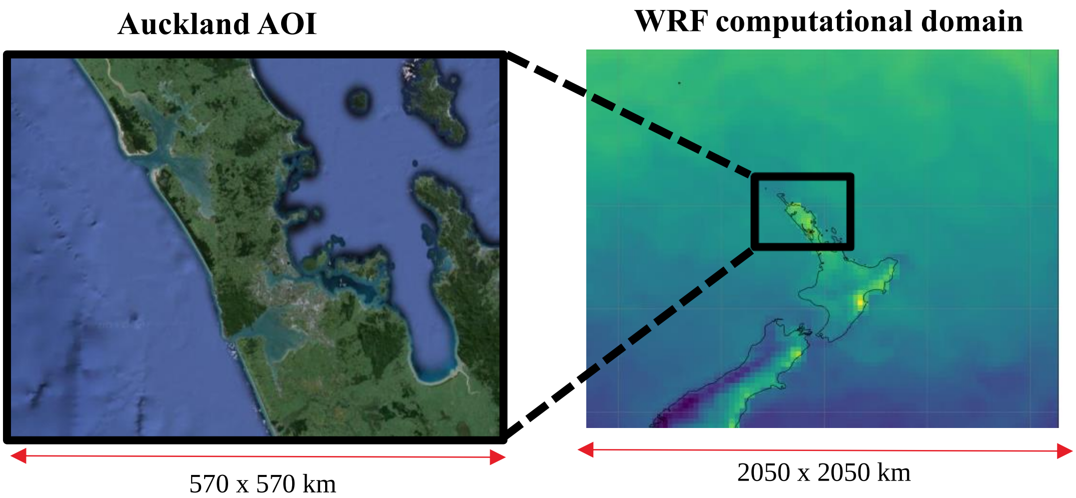

Figure 39: AOI used in SUEWS model (left), WRF computational domain (right)

A.2.3 Sea surface temperature

Sea surface temperature (SST) is a key meteorological input required for WRF modelling. Initial WRF simulations were performed with a constant SST. However, using a constant SST assumption is not appropriate for long analysis periods where temperature variations can be significant. Figure 40 illustrates the temperature variation across the simulation period.

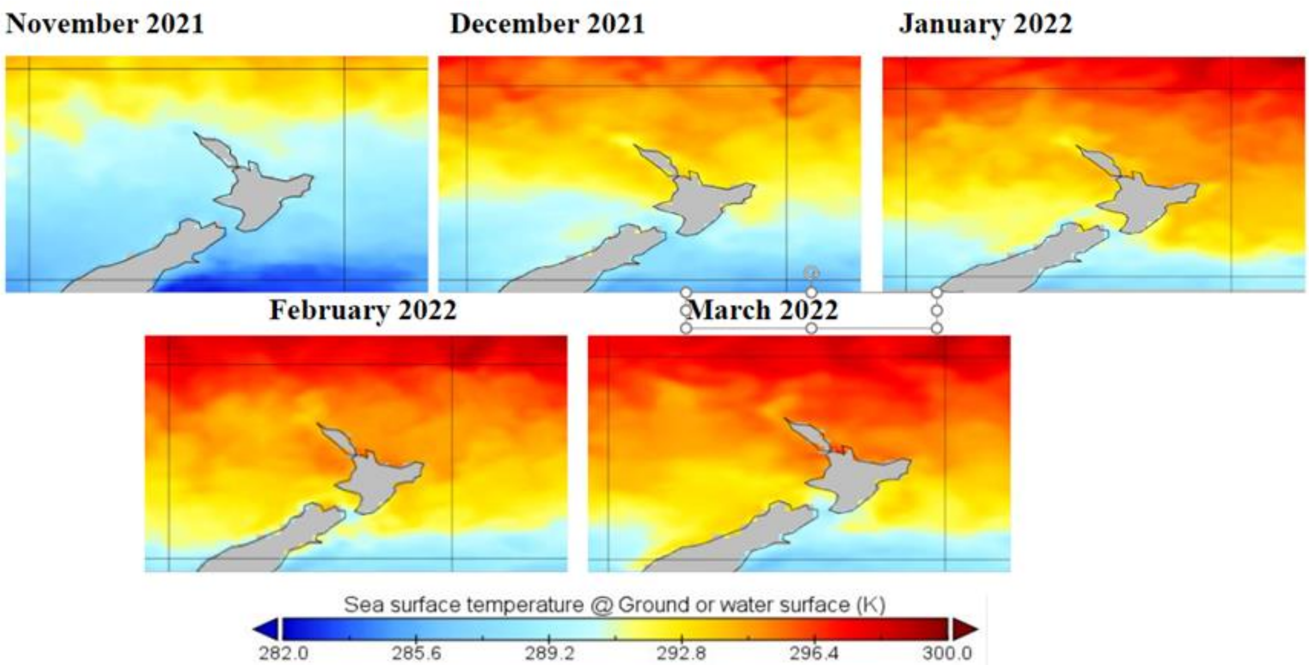

Figure 40: Variation of sea surface temperature (in Kelvin) around Auckland from November 2021 and March 2022 obtained from Panoply software.

The model was adjusted so that the SST input from ERA5 was updated daily in the WRF simulation. Figure 41 compares the SST temperature for the two simulations for a location in the Tasman Sea, showing the variation in temperature in February. The SST is around 5-6°C warmer with varying SST, which would impact the inland temperatures. The final WRF simulation also incorporated SST updates for the different bodies of water surrounding Auckland as they exhibit different variations as shown in Figure 42.

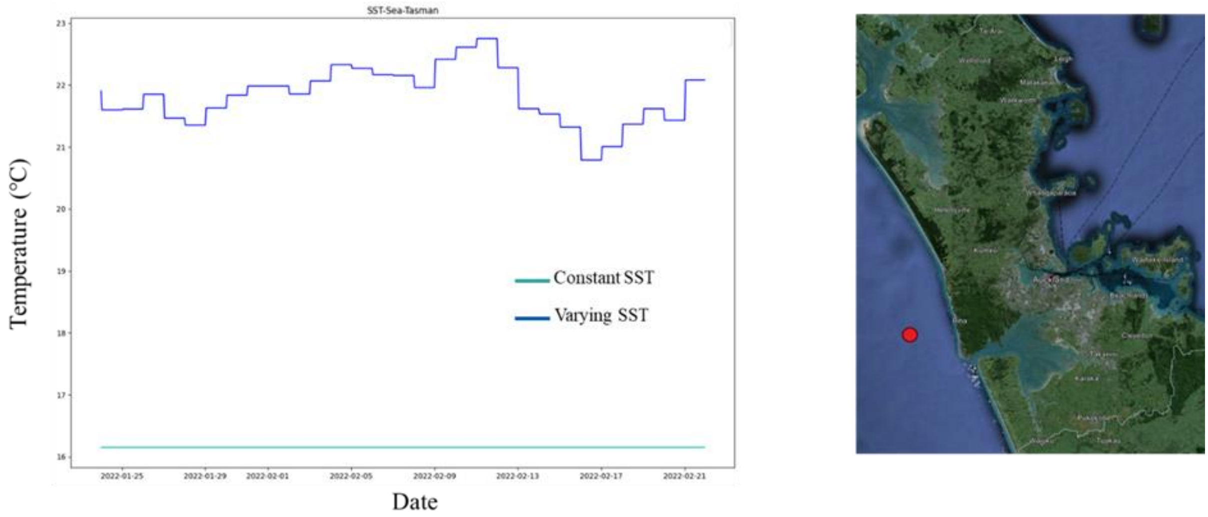

Figure 41: Sea surface temperature (in Kelvin) in February 2022 extracted with constant SST and varying SST.

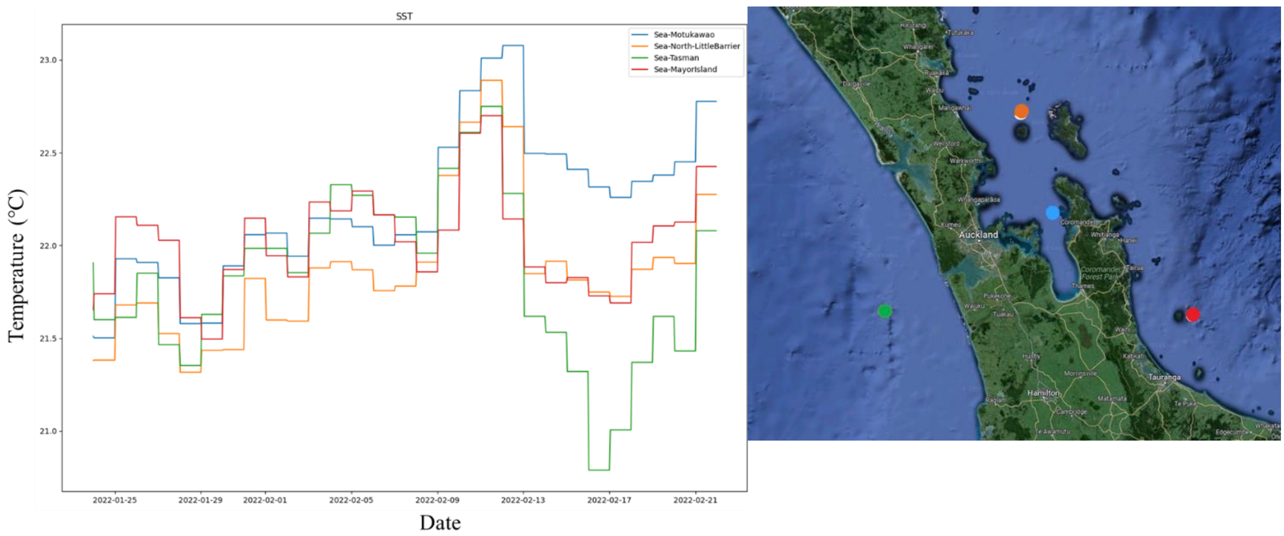

Figure 42: Variation of the sea surface temperature for the different seas surrounding Auckland.

Figure 43 compares the temperatures from both WRF simulations to the weather station data at Māngere and Warkworth. The WRF simulations with constant SST underpredicted the temperature by between 1 to 4°C, however the WRF simulations with varying SST predicted temperature within 0.5-1°C generally.

Figure 44 compares the wind speed from both WRF simulations at Warkworth and Māngere. There is a less noticeable difference in the wind speed predictions with the SST updating during the simulation, however the daily wind speed variation is replicated better in the WRF simulation with SST updates.

The WRF simulations with the SST updates were considered the final results for this assessment and are presented in Section 3.1.

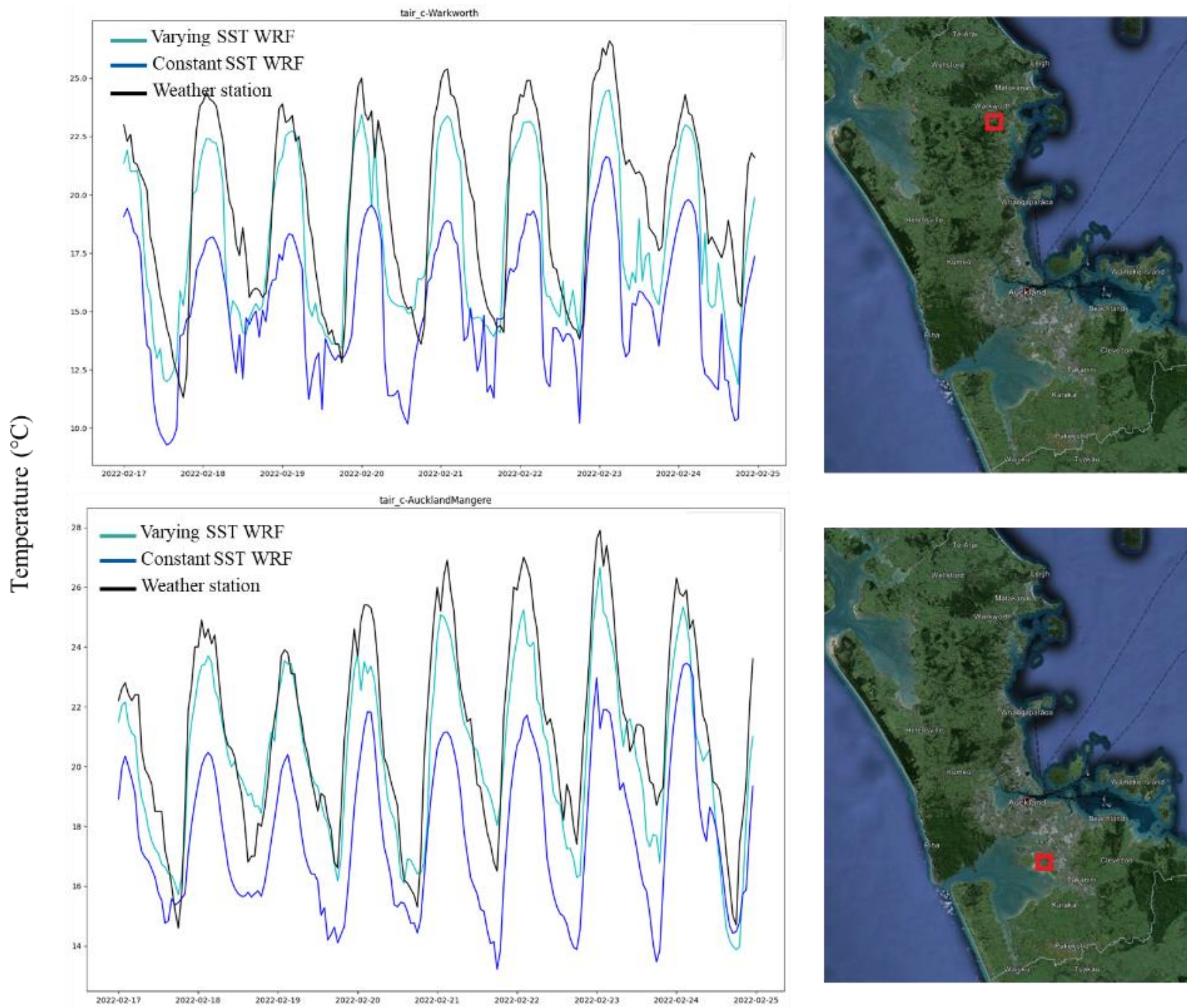

Figure 43: Comparison of the air temperature predicted by WRF (with constant and varying SST) and weather station data.

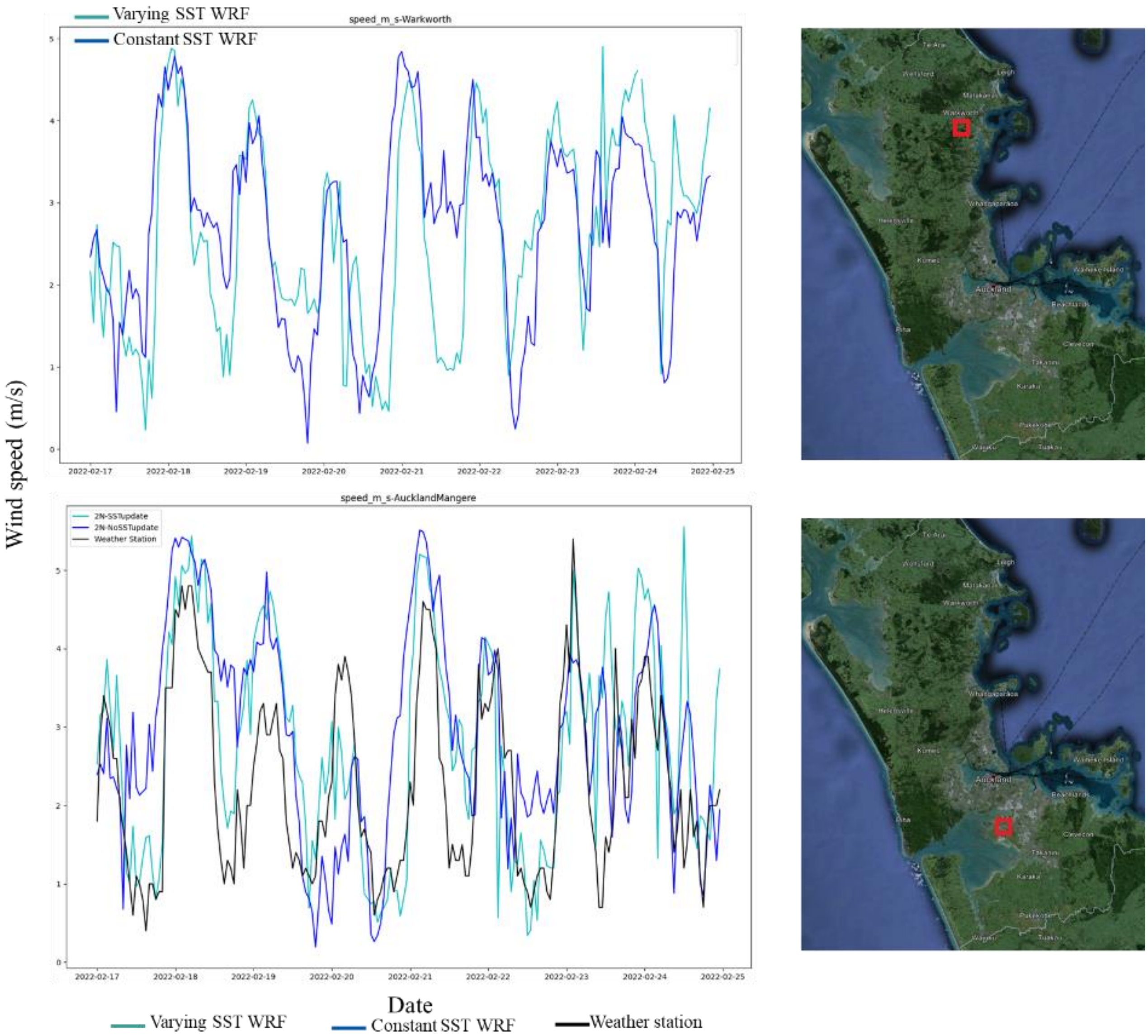

Figure 44: Comparison of the wind speed predicted by WRF (with constant and varying SST) and weather station data. Note Warkworth did not have wind data.

A.3 SUEWS model

The SUEWS model contains a number of sub-models, the most significant being the calculation of an energy balance and an urban water balance, as illustrated in Figure 45. A brief description of the energy and water balance sub-models are included in the following sections.

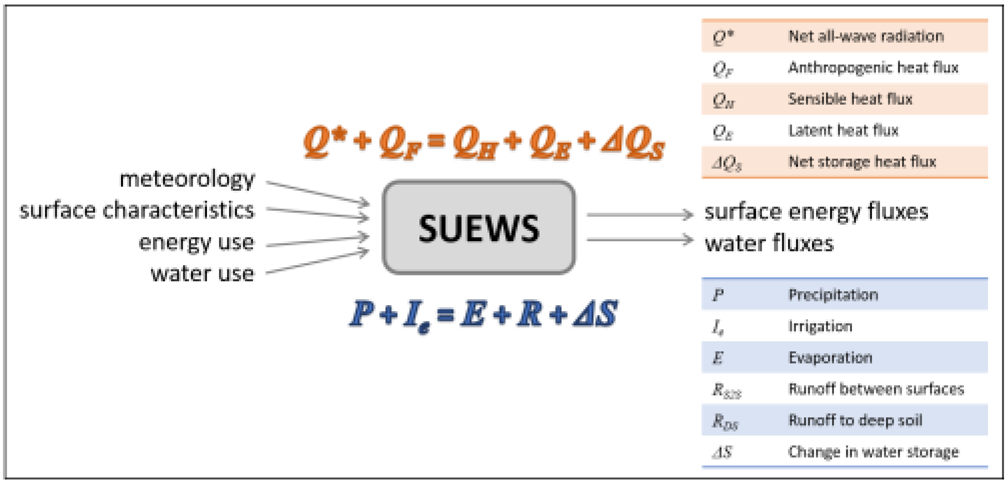

Figure 45: Overview of SUEWS energy and water balance. Diagram from (SUEWS dev team, n.d.).

A.3.1 Energy balance

The energy balance is:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S, \quad [1]$$

where Q^* is net all-wave radiation, Q_F is anthropogenic heat flux, Q_H is latent heat flux, Q_E is sensible heat flux, and ΔQ_S is sensible heat flux (Järvi, Grimmond, & Christen, 2011). Table 7 describes how these fluxes are defined and calculated.

Table 7: Description of the fluxes in the energy balance sub-model for SUEWS.

Fluxes	Description
Net all-wave radiation	The difference between incoming radiation, determined by the weather conditions, and outgoing radiation, determined by the weather conditions and the properties of the landcover such as albedo. Higher net all-wave radiation results in higher air temperatures.
Anthropogenic heat flux	Heat emissions due to human activity (e.g. cooling/heating of homes and buildings, travelling into urban areas). Accurate calculations of this are difficult with limited real-world data available. Consequently, the anthropogenic heat emissions are defined to be proportional to the population density and have a diurnal variation to replicate typical pattern of human activity. Higher anthropogenic heat flux results in higher air temperatures.
Storage heat flux	This is the energy absorbed by land and is therefore dependent on landcover properties such as thermal mass. Urban areas have greater thermal mass, resulting in increased storage of heat during daytime, which is released at night. Storage heat flux is also dependent on the ambient air temperature. An empirical model is used to predict the storage heat flux. Higher storage heat flux results in lower air temperatures
Latent heat flux	This is the energy used in the evaporation of water present in bodies of water, soil, grass, trees, and other vegetation. Higher latent heat flux results in lower air temperatures.
Sensible heat flux	This is calculated from the other heat fluxes (Q^*, Q_F, Q_H, and ΔQ_S) using Equation 1 and in turn is used to calculate air temperature.

A.3.2 Water balance

The water balance is:

$$P + I_e = E + R + \Delta S, \quad [2]$$

where P is precipitation, I_e is water from irrigation, E is evaporation, R is runoff, and S is the change in water stored within the landcover (Järvi, Grimmond, & Christen, 2011). Table 8 describes how these variables are defined and calculated.

Table 8: Description of the variables in the water balance sub-model for SUEWS.

Water variable	Description
Precipitation	Volume of water incoming to the land surface from rain, snow, or other precipitation.
Irrigation	Volume of water incoming to the land surface by artificial means, such as watering farmland and parks.
Evaporation	Volume of water evaporated from the land surface.
Runoff	Volume of water flowing away from the land surface. Water can runoff to drain, to a deep soil layer, or between different landcover types.
Change in water storage	Change in the volume of water held within the land surface.

A.4 WRF to UHeat coupling

The heat dataset created for this project is derived from a one-way coupling of WRF and UHeat, where the WRF outputs are input as forcing data into the UHeat. The coupling between the models requires a couple of steps to ensure compatibility:

- Extraction and processing of weather variables from WRF.
- Mapping of data from WRF squares to UHeat hexes.

A.4.1 Extraction and processing of weather variables from WRF

The forcing data includes several climate variables: wind speed, relative humidity, air temperature, barometric pressure, rainfall, and incoming radiation (both shortwave and longwave). This information is required at hourly intervals and typically corresponds to a specific vertical height in the atmosphere above the urban canopy. For some variables, adjustments were made to ensure they are at the correct height for input to UHeat.

Rainfall, incoming shortwave radiation, and incoming longwave radiation are not dependent on height above ground level. These are output from WRF for a single vertical level, therefore one value for these variables exists at each hourly timestep, taken directly as a time series for each WRF square.

In contrast, wind speed, relative humidity, air temperature, and barometric pressure vary with height above ground level and can be output from WRF at various vertical levels corresponding to a corresponding to atmospheric pressure levels. Values for these variables are extracted at the lowest WRF pressure level above the urban canopy. More detail about the processing of the different climate variation is provided in Table 9.

Table 9: Climate variable processing for WRF to UHeat coupling.

Weather Input	Unit	Description	Coupling
Air temperature	°C	Air temperature at forcing height z above ground level, averaged over one hour.	Output is extracted from WRF at height z. A mean is taken over each hour to give average hourly values.
Wind speed	$m\ s^{-1}$	Wind speed at forcing height z above ground level, averaged over one hour.	Wind velocity is extracted from WRF at height z, from which the wind speed magnitude is calculated. A mean is taken over each hour to give average hourly values.
Relative humidity	%	Relative humidity at forcing height z above ground level, averaged over one hour.	Output is extracted from WRF at height z. A mean is taken over each hour to give average hourly values.
Rainfall	$mm\ h^{-1}$	Rainfall over one hour.	Cumulative rainfall is extracted from WRF. To get rainfall over one hour for SUEWS, the value at a given hour is subtracted from the value at the preceding hour.
Pressure	kPa	Barometric pressure at forcing height z above ground level, averaged over one hour.	Output is extracted from WRF at height z. A mean is taken over each hour to give average hourly values.
Incoming shortwave radiation	$W\ m^{-2}$	Shortwave radiation arriving at ground level, averaged over one hour.	Output is extracted from WRF. A mean is taken over each hour to give average hourly values.
Incoming longwave radiation	$W\ m^{-2}$	Longwave radiation arriving at ground level, averaged over one hour.	Output is extracted from WRF. A mean is taken over each hour to give average hourly values.

A.4.2 Mapping of data from WRF squares to UHeat hexes

The grid resolution differed between WRF and UHeat, necessitating a conversion to map WRF results onto the UHeat grid. The WRF model used square grids with a resolution of 2.7 km x 2.7 km, while UHeat used hexagonal grids with a resolution of 300 m x 300 m (as provided by Auckland Council). An overlay of the WRF and SUEWS grids is shown in Figure 46.

Consequently, the WRF time series output had to be spatially resampled for use in the UHeat model. Bilinear interpolation was used, where for a given UHeat hex, the values from the nearest four WRF squares were proportionally mapped. This approach for resampling meant unique climate forcing data for each UHeat hexagon and ensured smooth spatial variations in the UHeat outputs.

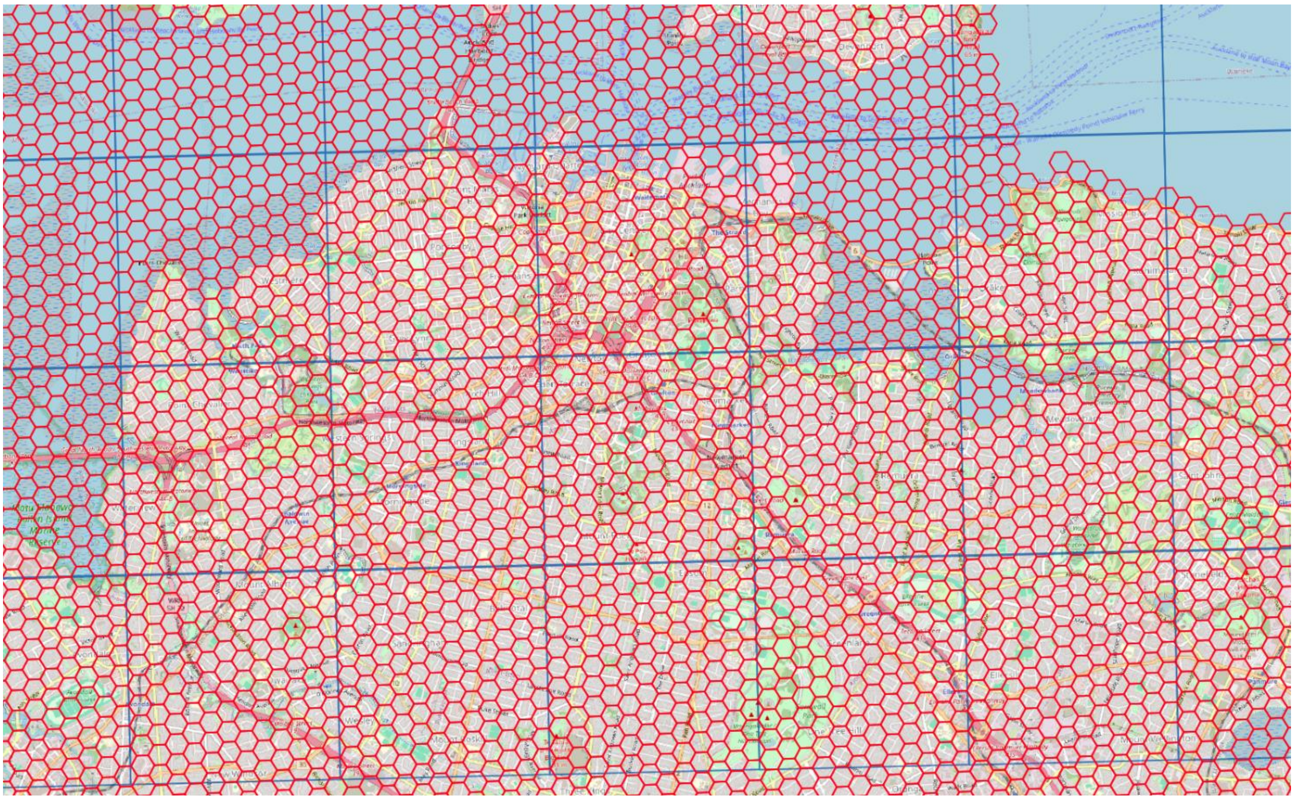

Figure 46: Overlay showing a sample of the WRF square grid (blue) and UHeat hex grid (red).

Appendix B | UHeat sensitivity tests and model log

B.1 Sensitivity Tests

The table below described the sensitivity tests that were performed as part of this project to refine the choice of UHeat model parameters.

Table 10: Details of sensitivity test and outcomes for UHeat analysis.

Parameter	Details	Outcomes
Soil moisture	A range of soil saturation options were tested to understand their impact on air temperature.	Initial tests indicated minimal sensitivity to soil saturation, suggesting that setting a specific parameter was unnecessary. Although irrigation observed values can be provided there was not sufficient data to include this in the model. *The final analysis calculates soil moisture values using climate parameters.*
Soil water capacity	Soil water capacity indicates how much moisture the ground can hold before surface run-off.	Initial tests indicated minimal sensitivity to soil water capacity. *Final analysis therefore used the default values within SUEWS.*
Analysis period	A simulation for one week in February conducted in isolation was compared to the same week in February extracted from the 5-month run to assess sensitivity to length of analysis.	In most cases, a small difference (<1°C) was observed between the two cases. For a grassy hex, the discrepancy was larger, up to 4°C. This is likely due to the impact of the initial soil moisture chosen for the 1-week simulation. For the full 5-month simulation, the soil moisture value s adjusted according to climate conditions and is less influenced by the starting value, which is deemed a more accurate methodology. *The final simulation was run from November 2021 to March 2022, with the key periods of interest being the hottest months of January and February.*
Roughness sub layer (RSL)	Two models exist within SUEWS for calculating the temperature profile within the urban canopy (RSL): - (Default) Parameterizations based on empirical or observational data - Monin-Obukhov Similarity Theory (MOST) Both options were tested.	The default method, while more sophisticated, exhibited instability and produced unphysical results during sensitivity testing. Conversely, the MOST model demonstrated greater reliability and yielded consistent results throughout testing. *Consequently, the MOST model was employed in the final analysis.*
Storage heat flux	The Objective Hysteresis Model (OHM) coefficients are parameters used to model the relationship between the net storage heat flux and the net all-wave radiation. There are three key OHM coefficients. The first OHM coefficient, a1, broadly controls daytime thermal energy storage; a range of values of a1 were tested for each landcover type.	Tests indicated moderate sensitivity to the first OHM coefficient, with peak daytime temperatures varying by approximately 2°C for the range of values tested. *In final analysis, the default OHM coefficient values were used, which follow the literature (* SUEWS dev team, n.d.).

Parameter	Details	Outcomes
Anthropogenic heat emissions	As a default anthropogenic heat emissions are correlated to population density (which is deemed appropriate where other data is not available). As a proxy for anthropogenic emissions, a range of population density values were evaluated.	Tests indicated minimal sensitivity to population density. This suggests that air temperature in Auckland is primarily influenced by other factors, such as climate and the thermal energy storage of the land cover. Consequently, it was deemed unnecessary to explore alternative methods for calculating population density in Auckland. This may be due to a relatively low population density compared to other cities. In final analysis, population density was taken from census data (Stats NZ Geographic Data Service, 2020).
Forcing height	This is the height at which the forcing variables (e.g., temperature, pressure) are evaluated. A range of forcing heights were tested,	Tests indicated moderate sensitivity to forcing height, with the lowest forcing height of 26m most closely fitting weather station observed data. *In final analysis, a forcing height of 26m was used.*

B.2 Analysis Log

The table below summarises the different UHeat simulation performed during this project, with the last row representing the parameters for the final analysis.

Table 11: Analysis log detailing tests conducted for UHeat analysis.

Date	Supy Version	Input parameters	Notes
23-05-2023	2023.7.3. dev0	Forcing height 100m Forcing data from WRF	Air temperatures in regions with bare soil and grass were observed to be higher than anticipated. This discrepancy was attributed to a known bug in supy 2023.7.3.dev0. The issue was resolved in supy 2024.7.5.dev0, which was subsequently employed for further model simulations. Conversely, in areas with alternative land cover types, the predicted air temperatures were lower compared to the data recorded by weather stations. To address this, tests were conducted on the forcing height, resulting in the selection of a reduced height of 26 meters for subsequent simulations.
15-07-2024	2024.7.5. dev0	Forcing height 26m Forcing data from WRF	Air temperatures in regions with bare soil and grass no longer appear unphysically high, and the results were considered satisfactory. However, in areas with other types of land cover, the predicted air temperatures remain cooler despite the adjusted forcing height. An error was identified in the processing of forcing data at the new forcing height, which was corrected for subsequent simulations.
16-07-2024	2024.7.5. dev0	Forcing height 26m Forcing data from WRF	Air temperatures and aligned better with weather station data. However, land surface temperatures could not be output due to an error in supy. This error was resolved in supy version 2024.8.2.dev0, which was used for the final run.
17-07-2024	2024.7.5. dev0	Forcing height 26m Forcing data from ERA5	A run was conducted using ERA5 as the forcing data for comparison with the previous run that used WRF forcing data. The average air temperatures were comparable to the previous run, but the resolution was lower, and the diurnal range was less pronounced, as expected due to the lower resolution of the forcing data.

Date	Supy Version	Input parameters	Notes
05-08-2024	2024.8.2.dev0	Forcing height 26m Forcing data from WRF	The final run incorporated all the changes and final parameters identified through sensitivity tests and previous models.

Appendix C | Results comparison to weather station data

C.1 WRF results comparison

The final WRF run for input into UHeat was compared against the weather station data to give confidence in using WRF outputs as inputs in UHeat. Figure 47 to Figure 57 presents a comparison of the temperatures and wind speed magnitude at each of the weather station locations between the 1st and 8th January, a hot week in the analysis period.

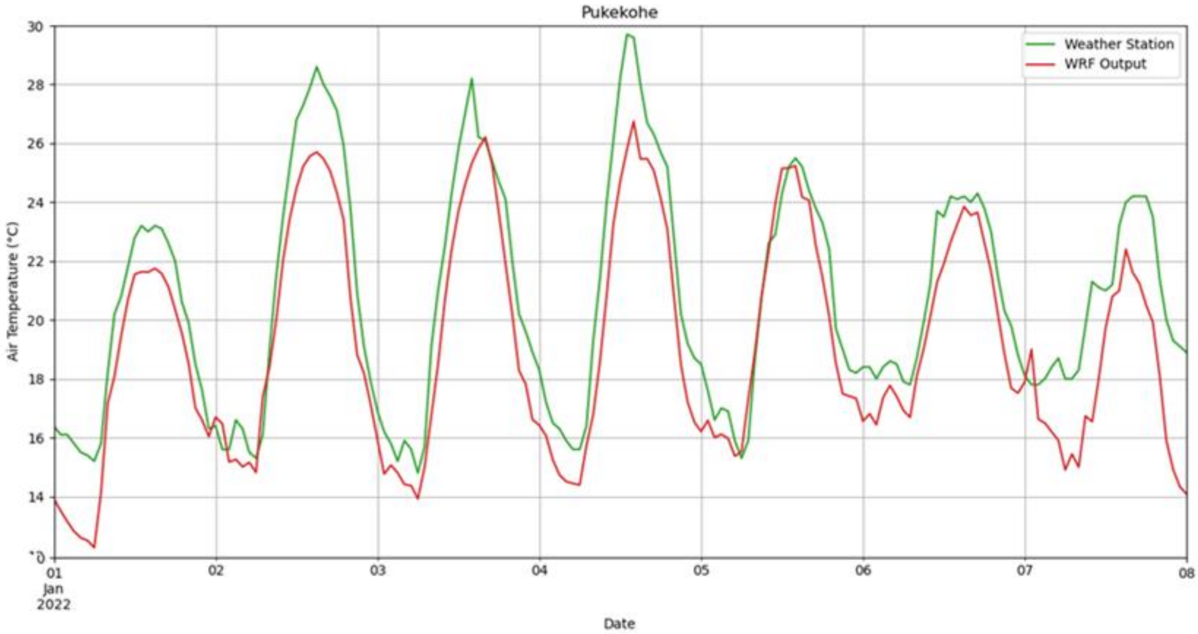

Figure 47: Comparison of WRF predicted temperature to weather station data at Pukekohe.

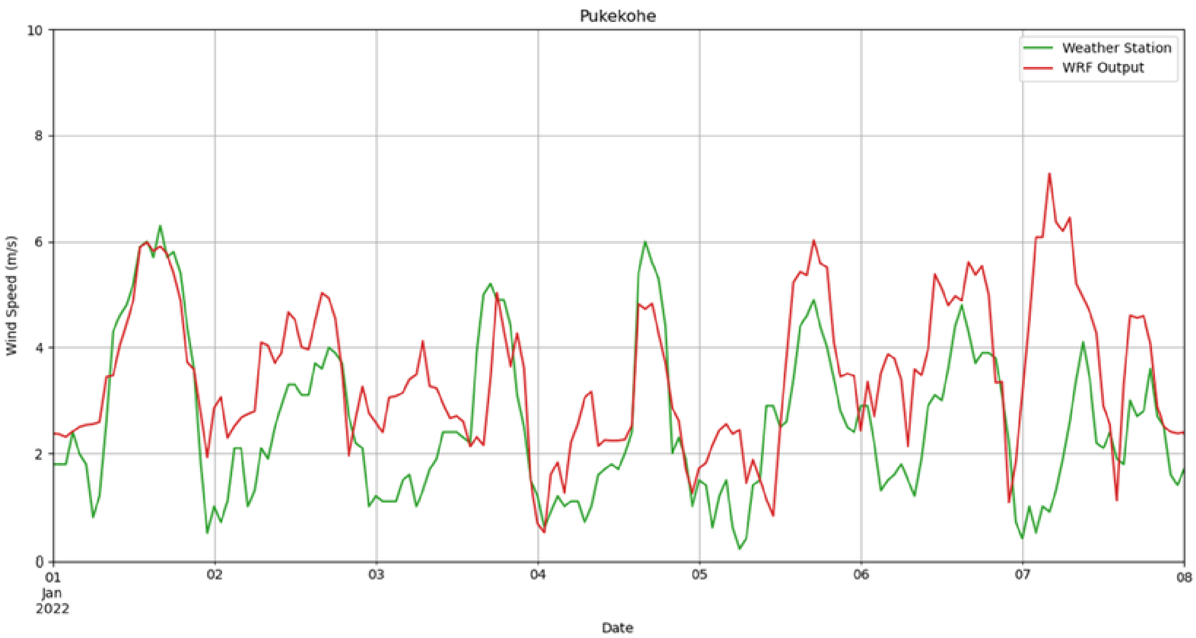

Figure 48: Comparison of WRF predicted wind speed magnitude to weather station data at Pukekohe.

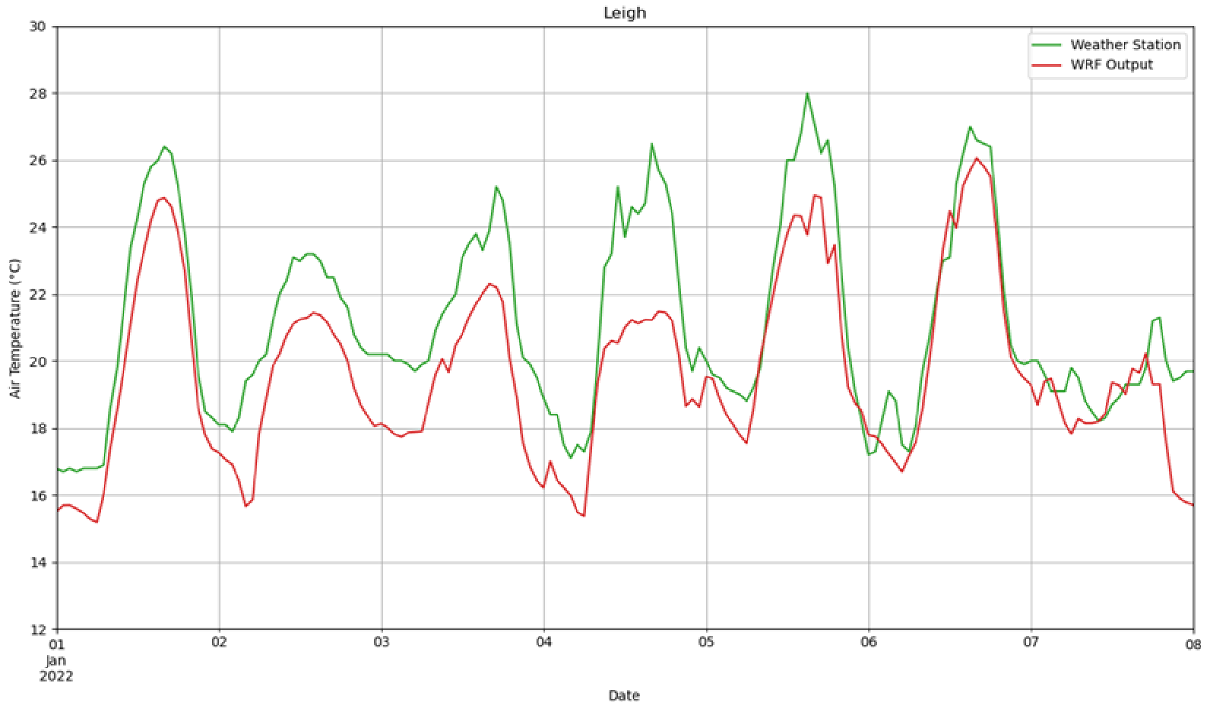

Figure 49: Comparison of WRF predicted temperature to weather station data at Leigh.

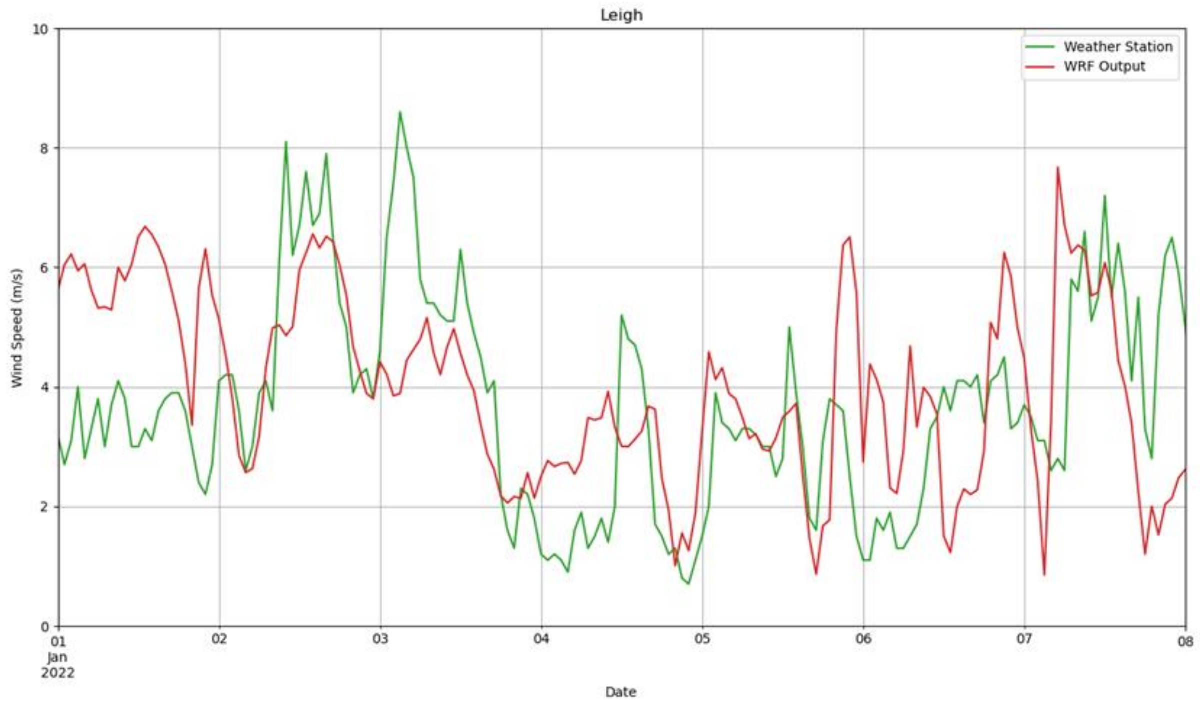

Figure 50: Comparison of WRF predicted wind speed magnitude to weather station data at Leigh.

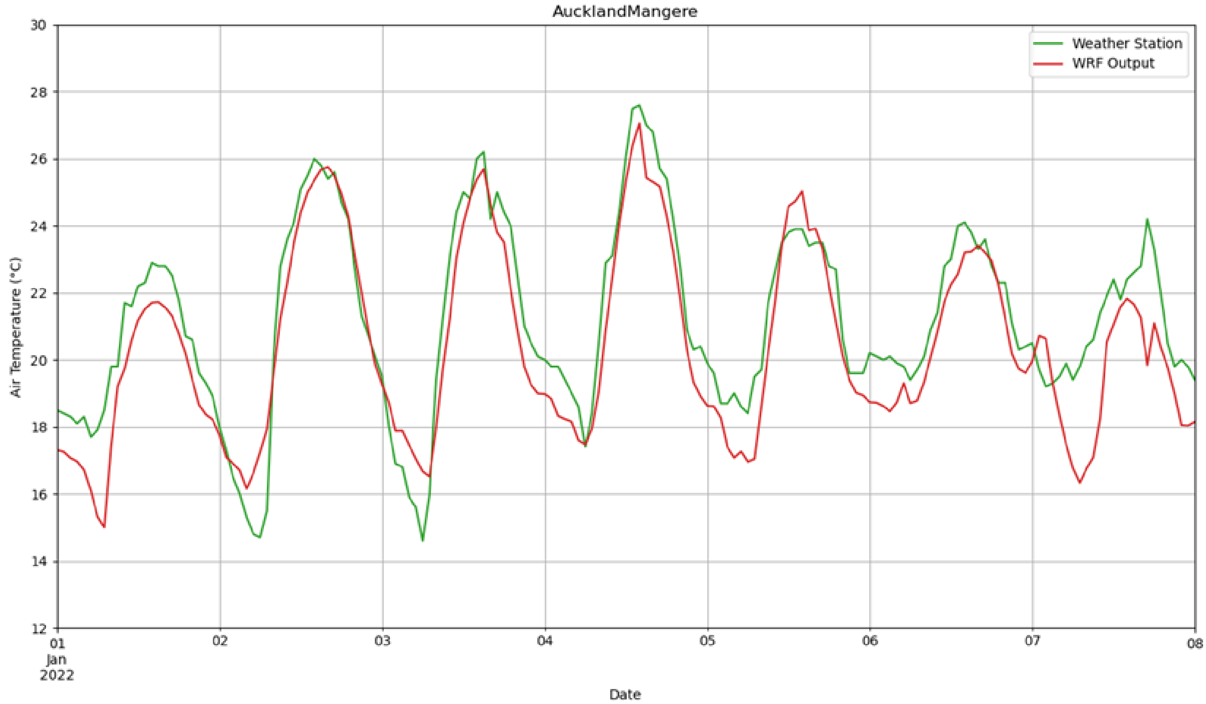

Figure 51: Comparison of WRF predicted temperature to weather station data at Māngere.

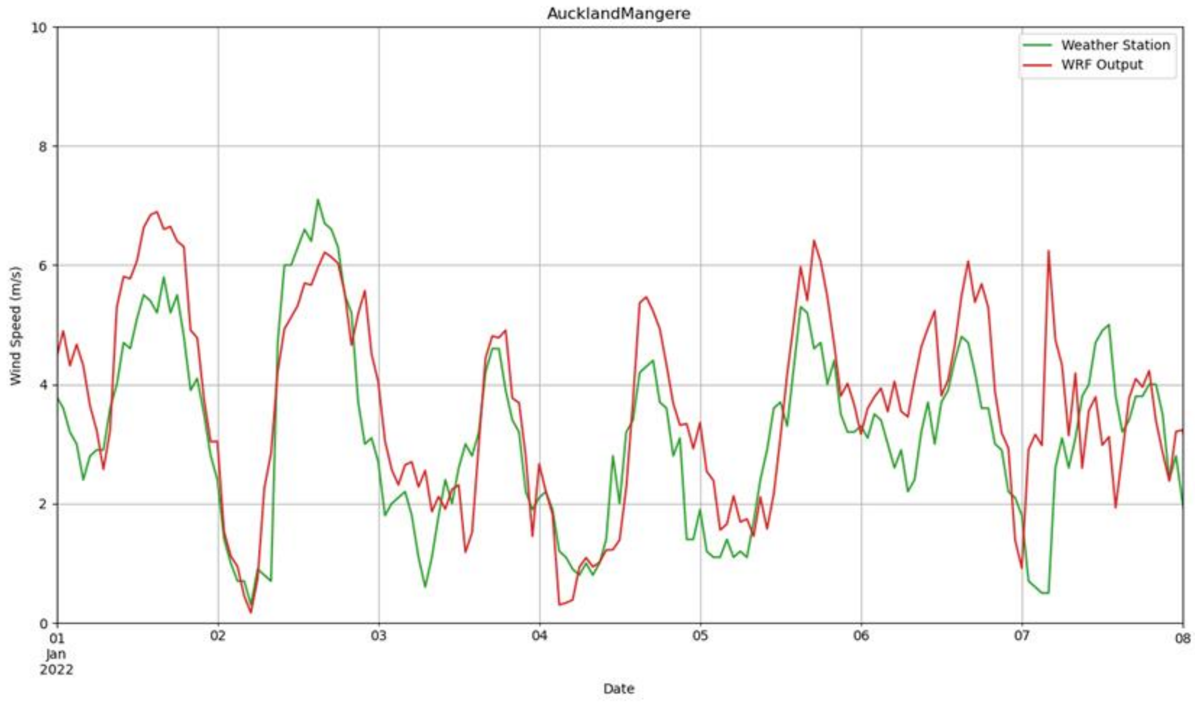

Figure 52: Comparison of WRF predicted wind speed magnitude to weather station data at Māngere.

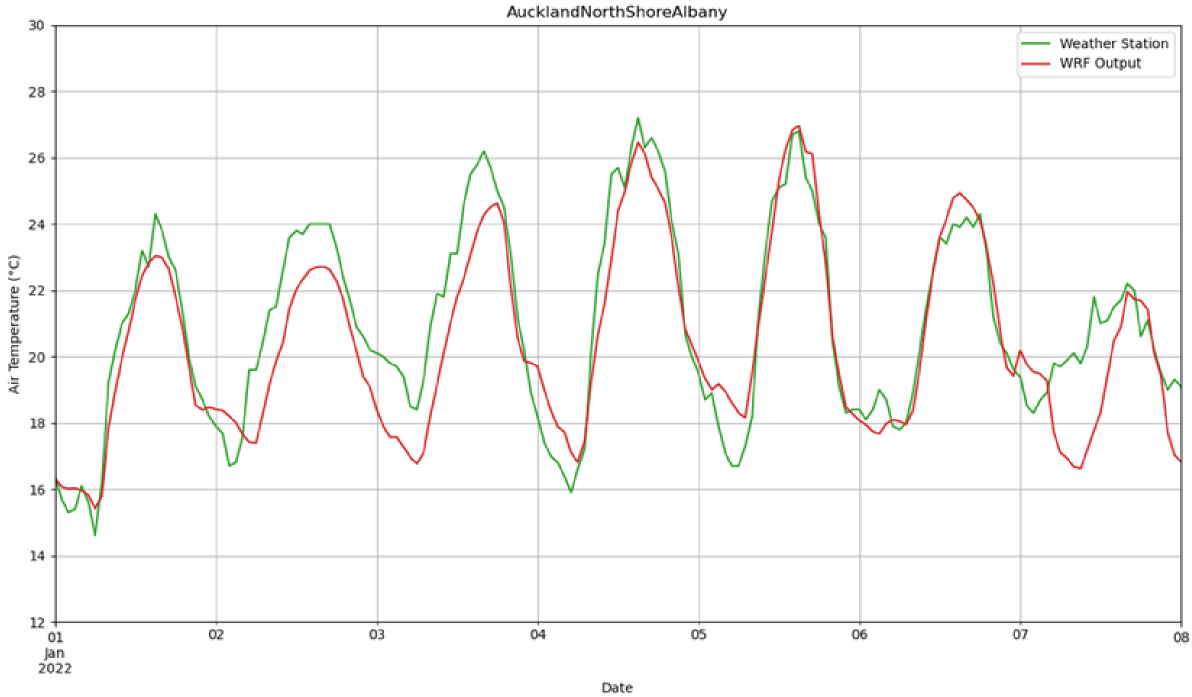

Figure 53: Comparison of WRF predicted temperature to weather station data at North Shore Albany.

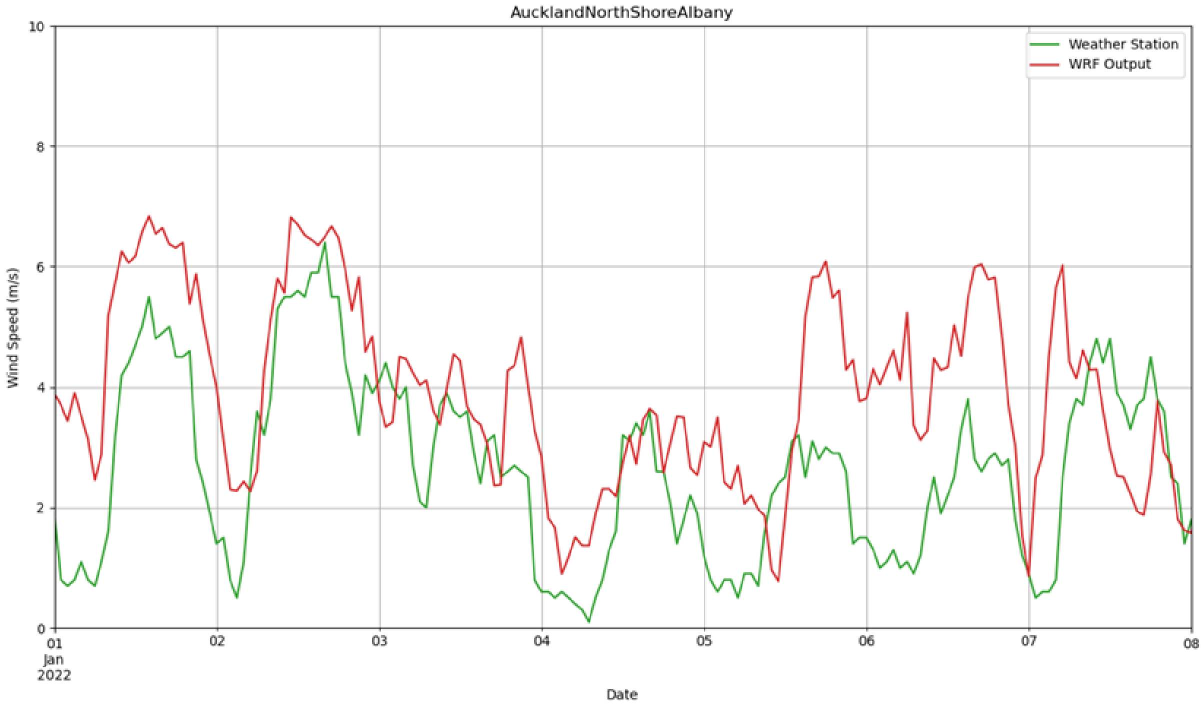

Figure 54: Comparison of WRF predicted wind speed to weather station data at North Shore Albany.

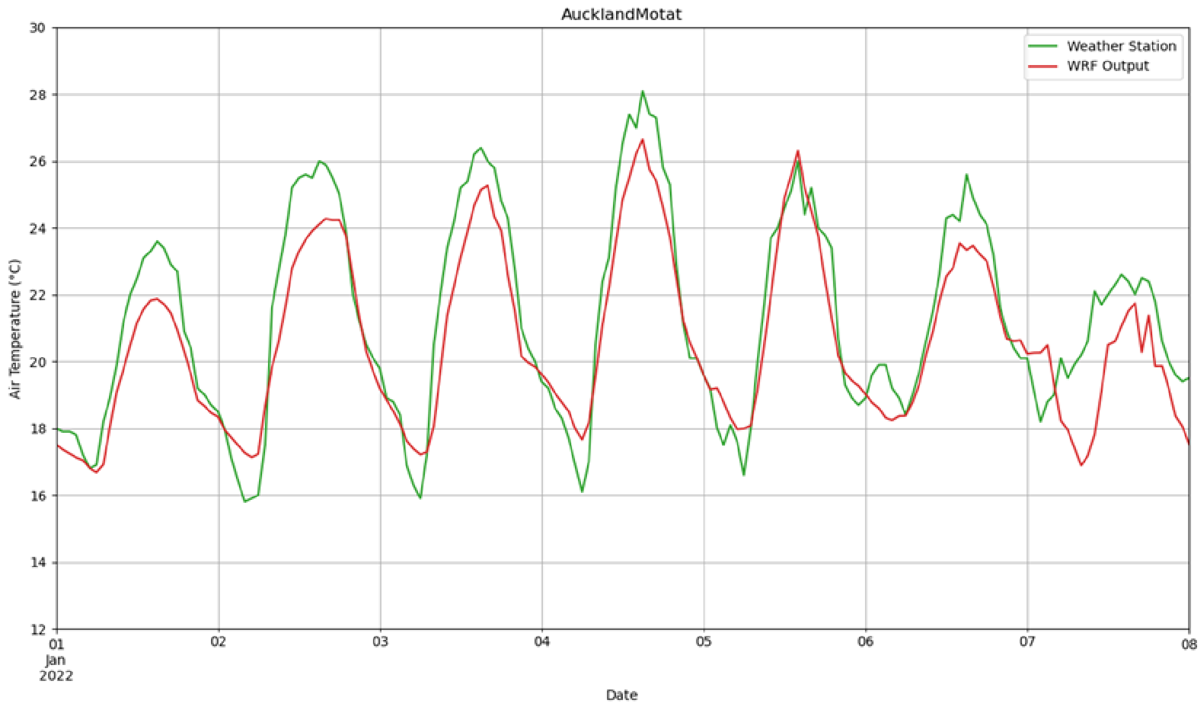

Figure 55: Comparison of WRF predicted temperature to weather station data at MOTAT.

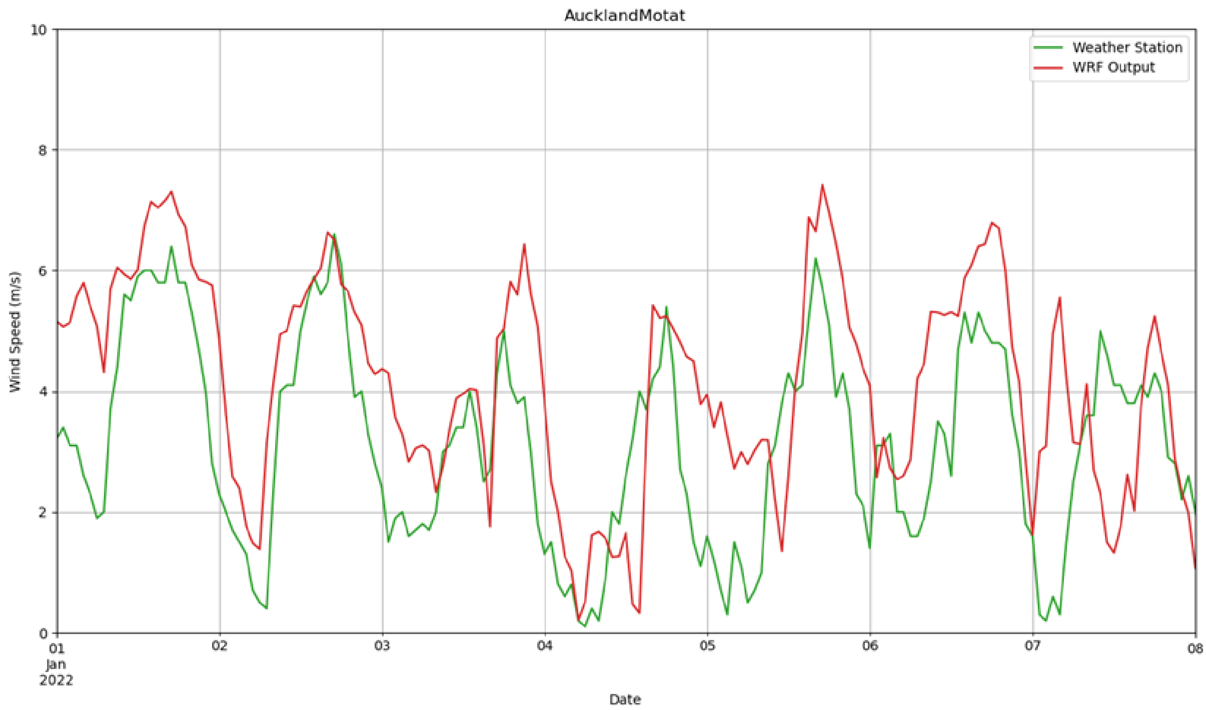

Figure 56: Comparison of WRF predicted wind speed to weather station data at MOTAT.

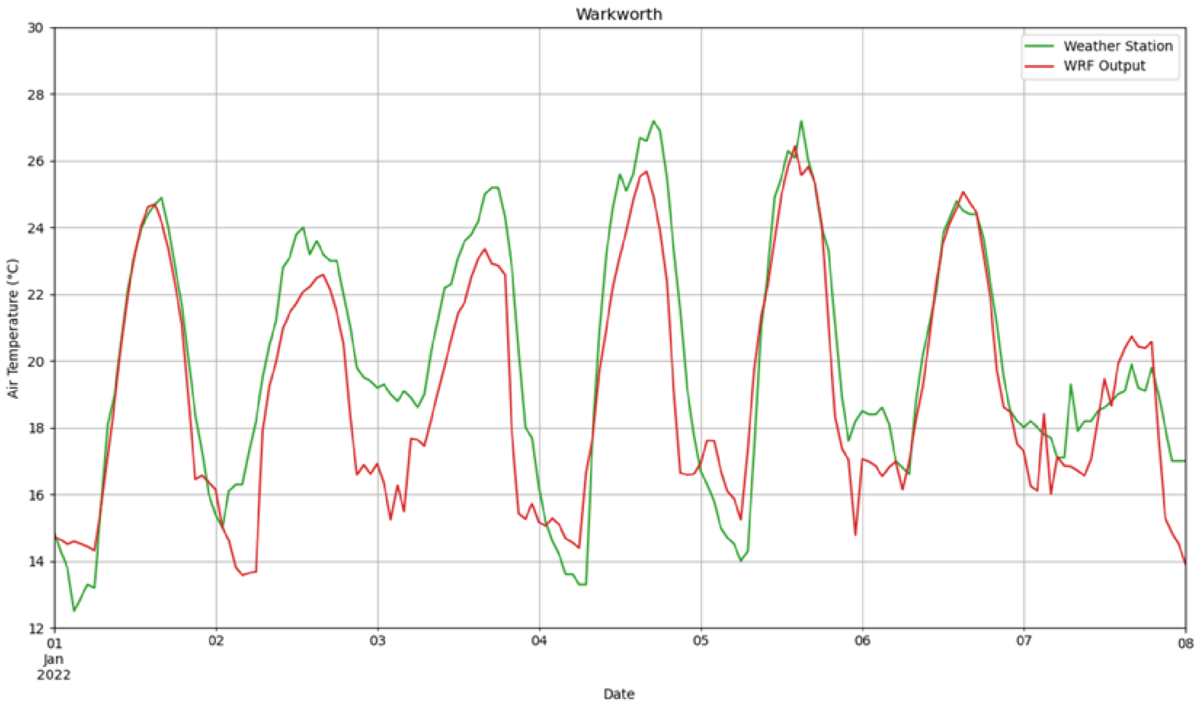

Figure 57: Comparison of WRF predicted temperature to weather station data at Warkworth.

There was no wind speed data available from Warkworth.

C.2 UHeat results comparison

The UHeat output temperatures were compared weather station data as verification. Figure 58 to Figure 67 presents a comparison of the temperatures at each of the weather station locations. Two types of comparison were made:

- The daily mean and maximum temperatures through the whole analysis period.
- The hourly temperatures between the 1st and 8th January, a hot week in the analysis period.

The comparisons of the MOTAT weather station have been included in the main body of the report (see Figure 23 and Figure 24).

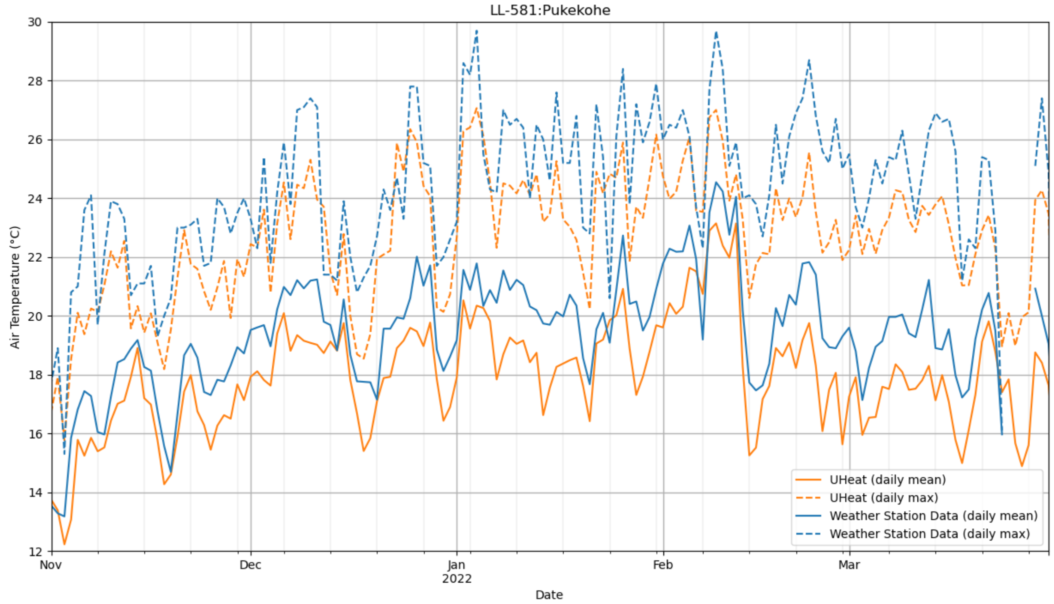

Figure 58: Comparison of the daily mean and maximum temperatures from UHeat to weather station data at Pukekohe for the full analysis period.

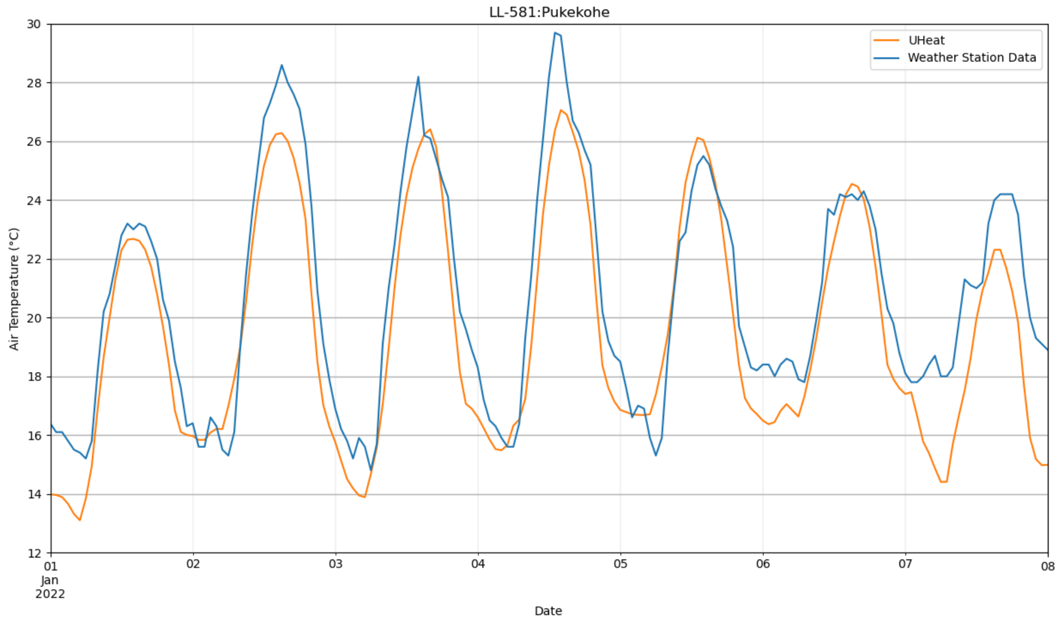

Figure 59: Comparison of the temperatures from UHeat to weather station data at Pukekohe between the 1st and 8th of January 2022.

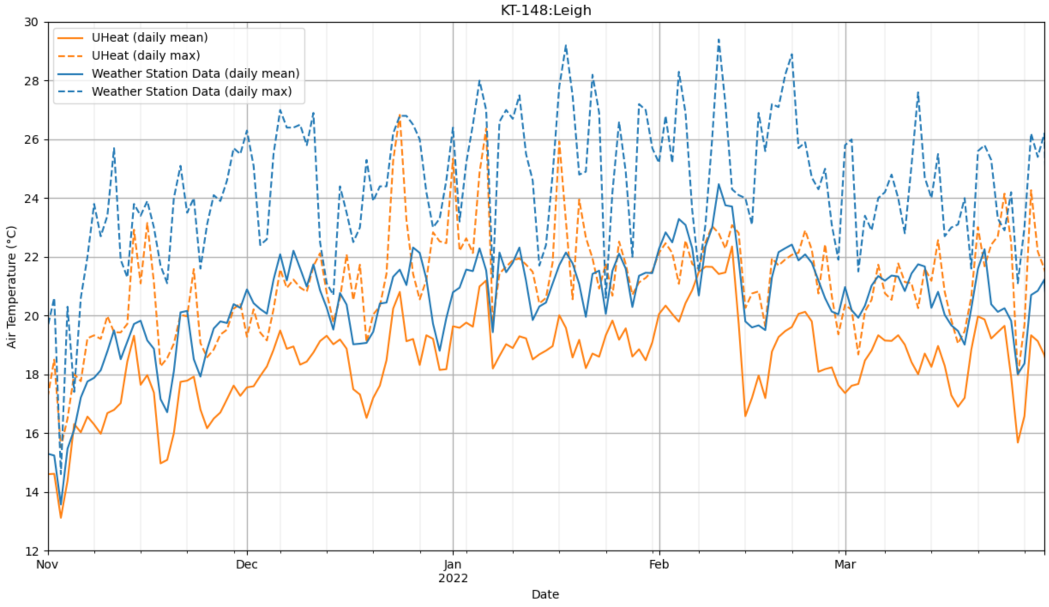

Figure 60: Comparison of the daily mean and maximum temperatures from UHeat to weather station data at Leigh for the full analysis period.

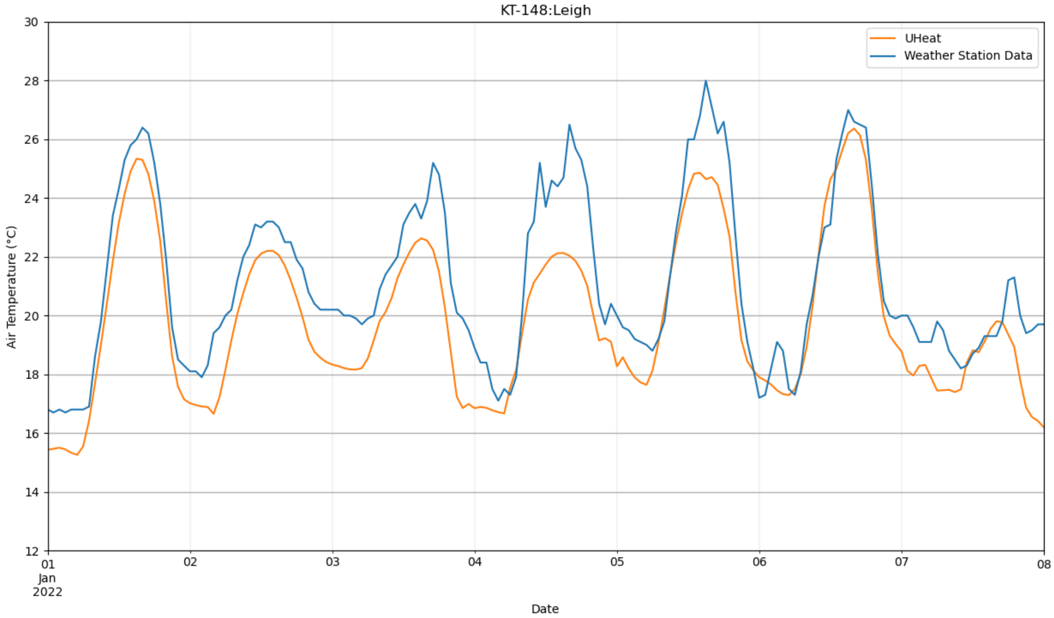

Figure 61: Comparison of the temperatures from UHeat to weather station data at Leigh between the 1st and 8th of January 2022.

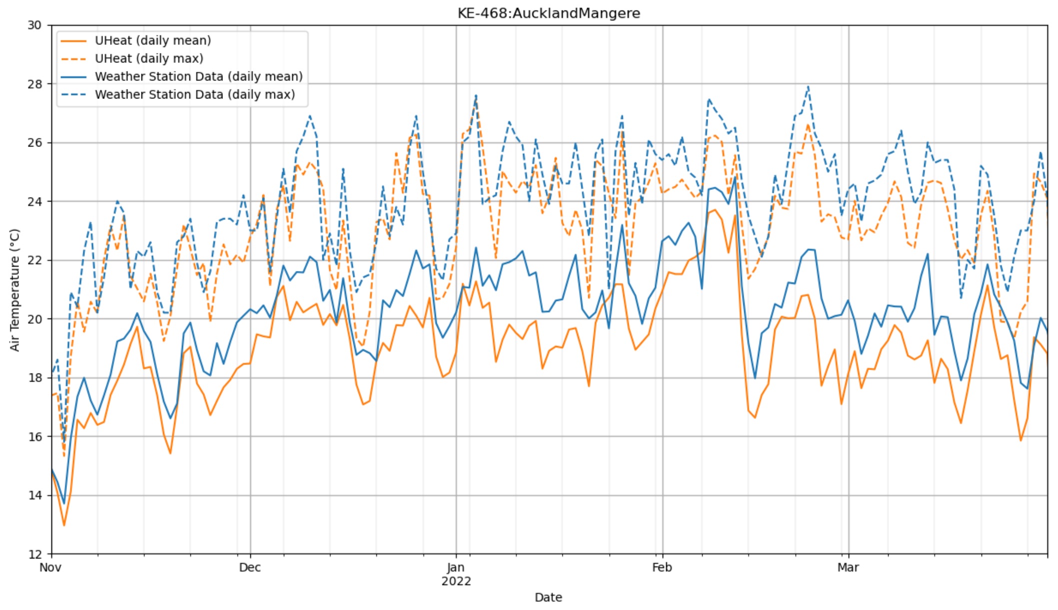

Figure 62: Comparison of the daily mean and maximum temperatures from UHeat to weather station data at Māngere for the full analysis period.

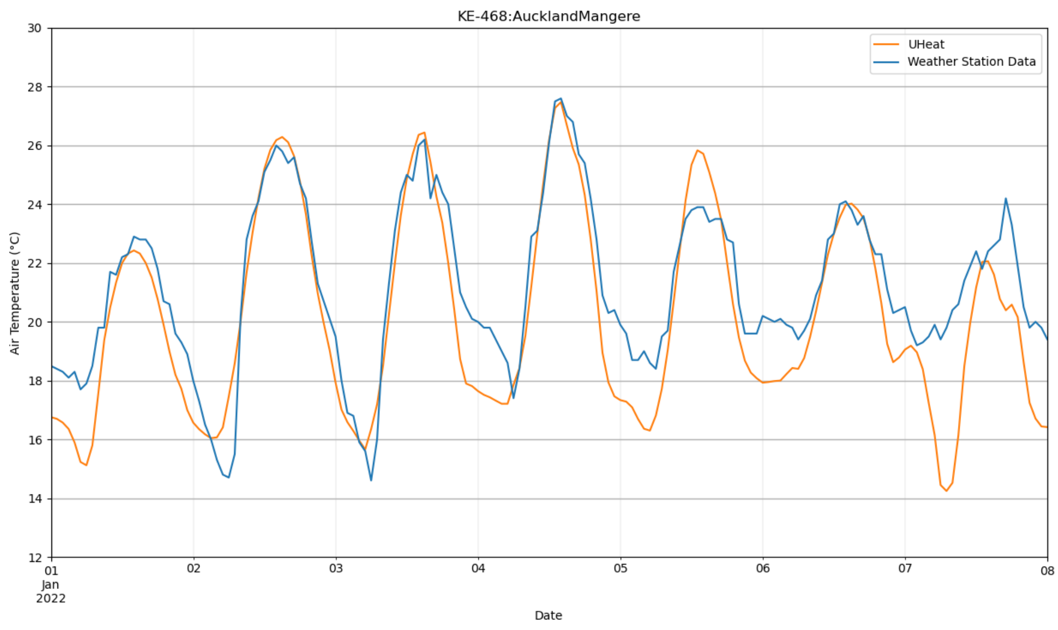

Figure 63: Comparison of the temperatures from UHeat to weather station data at Māngere between the 1st and 8th of January 2022.

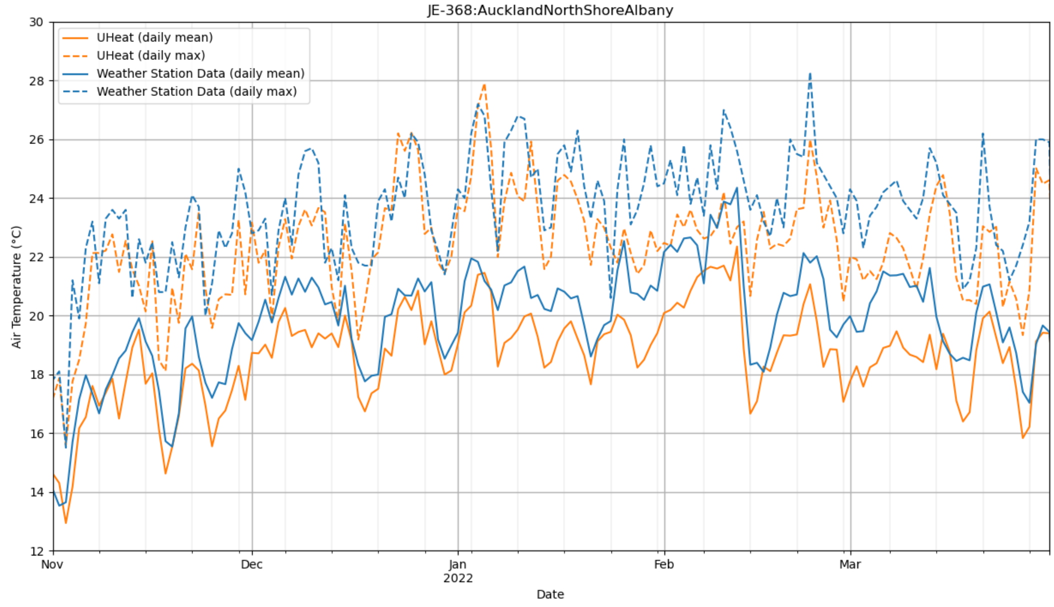

Figure 64: Comparison of the daily mean and maximum temperatures from UHeat to weather station data at North Shore Albany for the full analysis period.

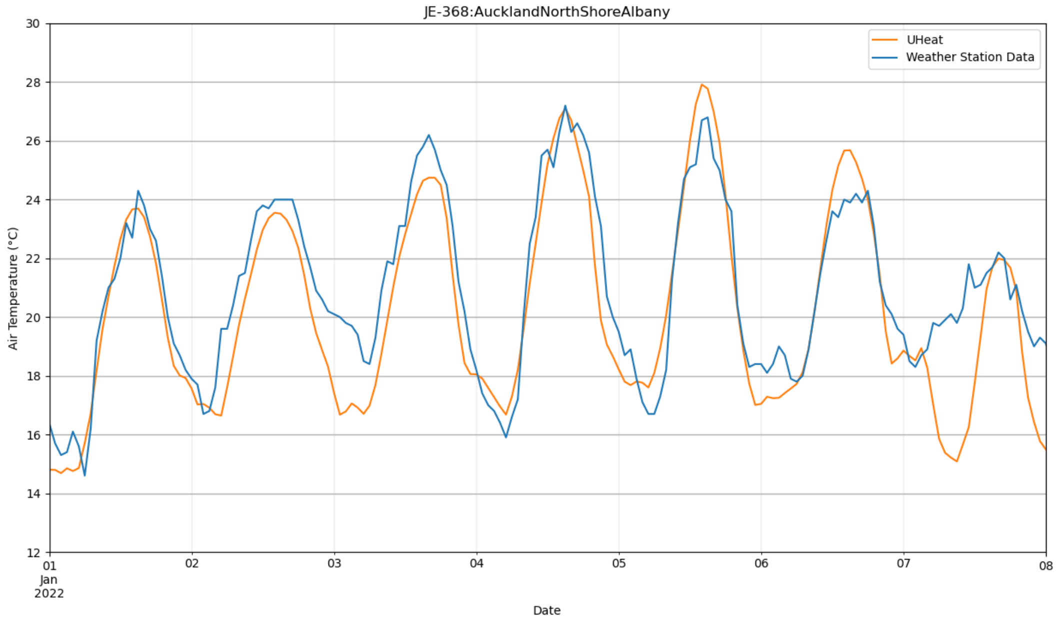

Figure 65: Comparison of the temperatures from UHeat to weather station data at North Shore Albany between the 1st and 8th of January 2022.

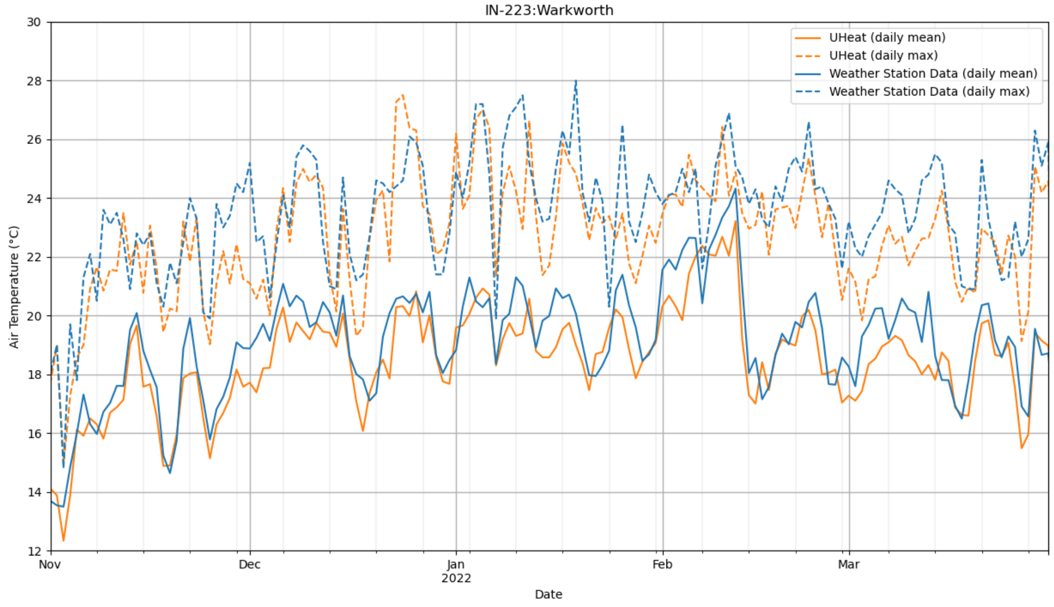

Figure 66: Comparison of the daily mean and maximum temperatures from UHeat to weather station data at Warkworth for the full analysis period.

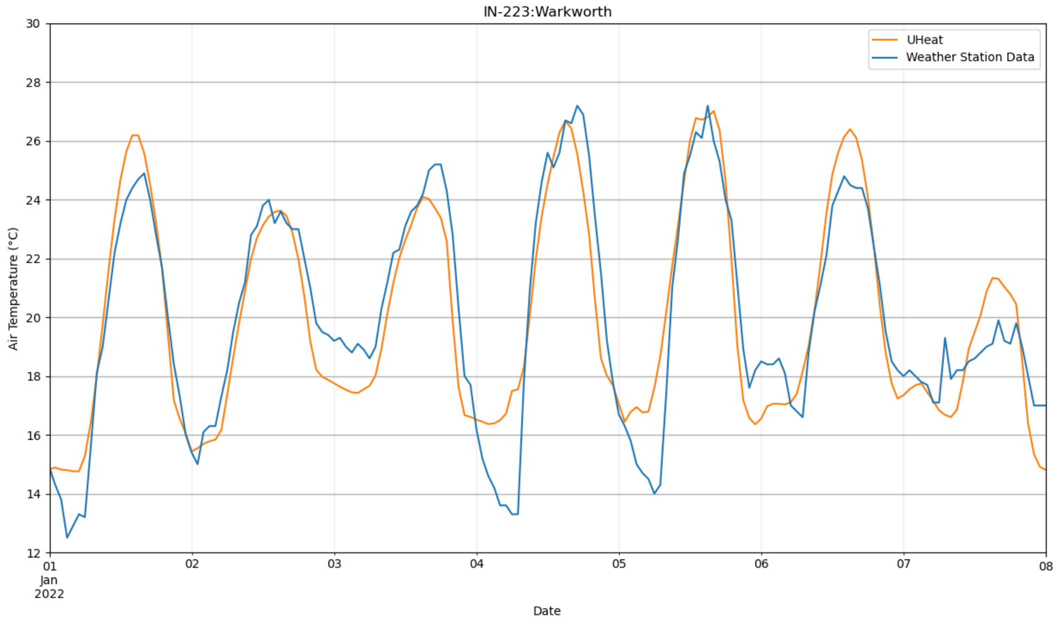

Figure 67: Comparison of the temperatures from UHeat to weather station data at Warkworth between the 1st and 8th of January 2022.