Heatwaves and Mortality:

Comparing the Excess Heat Factor (EHF) and the NZ MetService heat alert approach in Canterbury and Auckland, 2000–2021

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List of abbreviations

CCRI	Climate Change Research Institute
DHB	District Health Board
DMT	daily mean temperature
DMT_{95}	95^{th} percentile of daily mean temperature
EHF	Excess Heat Factor (Australian method for defining heatwaves)
EHINZ	Environmental Health Intelligence New Zealand
EHI_{accl}	Acclimatisation index (part of EHF)
EHI_{sig}	Significance index (part of EHF)
ESR	Institute of Environmental Science and Research (changed to PHF Science on 1 July 2025)
HHAP	Heat-Health Action Plan
HHWS	Heat-Health Warning System
IPCC	The Intergovernmental Panel on Climate Change
MfE	Ministry for the Environment
MoH	Ministry of Health
NIWA	National Institute of Water and Atmospheric Research (changed to Earth Sciences New Zealand on 1 July 2025)
TA	Territorial authority
T_{max}	daily maximum temperature
T_{mean}	daily mean temperature
T_{min}	daily minimum temperature
WHO	World Health Organization
WMO	World Meteorological Organization

Executive summary

Introduction

Heatwaves can negatively impact people's health, with outcomes ranging from dehydration to death. Climate change projections for New Zealand indicate that extreme temperatures are expected to occur more frequently and persist for longer, increasing the risk of heatwaves and, potentially, associated health impacts. It is not clearly understood what impact hot days and heatwaves are currently having in New Zealand, and there is no consensus on the best methods for defining heatwaves or measuring this health impact. This report assesses and compares the performance of two approaches for identifying heatwaves – the Excess Heat Factor, and the NZ MetService heat alert scheme – and then estimates and compares associated excess mortality in Canterbury and Auckland, New Zealand, using these two different approaches.

Methods

In this project, two different approaches were tested to identify heatwaves / hot days: (i) the Excess Heat Factor (EHF), developed in Australia and currently used as the basis for the Australian heat-health warning system, and (ii) the New Zealand MetService's Heat Alerting scheme. We identified heatwaves (or, for the MetService approach, 'heat alert days') retrospectively in the summer seasons from 2000/01 to 2020/21 in the Auckland and Canterbury regions.

The Excess Heat Factor (EHF) identifies periods of three or more consecutive days where the three-day daily mean temperature is unusually high at a location, compared with the long-term daily mean temperature at that location (and taking into account an acclimatisation period of the previous 30 days). Severity thresholds were applied to determine if a heatwave was low-intensity (the most common type of heatwave), severe (less common, and challenging for vulnerable people) or extreme (rare, and likely to affect everyone if they do not take precautions). By contrast, the New Zealand MetService's Heat Alerting scheme uses two distinct thresholds to identify unusually hot conditions: a single-day daily maximum temperature threshold, as well as a two-day daily mean temperature threshold (applied if the daily maximum temperature also reached 27°C on both days). Temperature thresholds are specific to locations and are revised each year, and thresholds are set very high in order to identify 'top end heat'.

For each of these two approaches, we estimated the excess mortality during heatwaves, then compared excess mortality and other parameters.

Key findings

Both the EHF and MetService approaches identified a number of heatwave episodes in Canterbury and Auckland from 2000/01 to 2020/21. The two approaches had reasonable agreement in terms of identifying periods of hot weather, as well as the summer seasons with the highest number of heatwave episodes and excess heat. Some of the hottest summers included 2015/16, 2017/18, and 2019/20, in line with Earth Sciences New Zealand reporting.

The EHF approach identified the highest number of heatwave episodes and heatwave days in both Canterbury and Auckland. The MetService heat alert approach identified much fewer heat alert days than the main EHF approach; the MetService heat alert episodes also tended to be much hotter and shorter in duration than EHF main heatwaves, and often lasted only one day in duration. More intense EHF heatwaves, categorised as 'EHF severe heatwaves', were less common in both regions, but were generally hotter and shorter in duration.

Our study found that heatwaves have had a substantial impact on excess mortality in two of New Zealand's major cities, over the past 20 years, according to both the EHF and MetService approaches. In Canterbury, heatwaves identified using the EHF were associated with 114.2 excess deaths overall (95% confidence interval: 0.3 to 231). In comparison, heatwaves identified using MetService heat alert days were associated with 55.7 excess deaths overall (95% CI: 2.7 to 111.7). For Auckland, heatwaves identified using the EHF heatwave approach were associated with 379 excess deaths (95% CI: 193.3 to 567.6), while heatwaves identified using MetService heat alert days (using their recent operational thresholds used during the 2022/23 and 2023/24 summer seasons) found 59.3 excess deaths (95% CI: 14.9 to 106.7). The EHF 'severe heatwave' approach was also associated with excess mortality in Canterbury (70.3 excess deaths; 95% CI: 21.0 to 122.6) and, to a lesser extent, in Auckland, where the result was not statistically significant (67 excess deaths; 95% CI: -6.8 to 143.9).

In general, the EHF identified heatwaves that were relatively long in duration, while MetService heat alert days identified episodes that were much hotter, but much shorter in duration (often only a single hot day). Both methods use historical local weather data rather than national data to determine thresholds, which has the benefit of taking into account 'normal weather' for that location. The EHF approach also included a severity threshold, with the EHF 'severe heatwaves' aligning somewhat with the MetService heat alert days in terms of duration and frequency. Both the EHF and MetService approaches also include both daily maximum (T_{max}) and minimum (T_{min}) temperatures in the same index, which can help to account for higher nighttime temperatures (which can have health risks). These two approaches appear to have been much better at identifying heatwave periods with associated excess mortality, compared with methods based only on daily maximum temperatures from our previous Canterbury pilot study.

Implications

Deciding which heatwave definition to use depends considerably on the intended purpose and desired outcomes. One potential use of this study is to inform the development of a heat-health warning system in New Zealand. For a heat-health warning system, a preferred heatwave definition would ideally align conceptually with heatwave definitions from the health literature (of being unusually hot weather of at least 2–3 days duration), would identify periods of higher-than-normal temperatures (both daytime and overnight), would be strongly associated with health impacts, and would have the potential for different severity thresholds linked to different public health actions. It is important that a heat-health warning system can detect heatwaves that are likely to negatively impact health, including at lower thresholds where more susceptible populations may be more likely to be impacted.

From this perspective, the EHF heatwave definition warrants further investigation for implementation in New Zealand, as it meets these criteria better than the current MetService heat alert approach, has been investigated and validated more widely around the world, and has been shown to be significantly associated with a range of health outcomes. The EHF approach also has several severity/intensity thresholds, which are used as part of heat-health warning systems in Australia. Nonetheless, the MetService approach has been developed specifically for the New Zealand situation, and still appears to be associated with excess mortality.

Implementing an effective heat-health warning system has been shown to be a cost-effective way to reduce the health impacts of heatwaves. Additionally, heatwaves are more likely to negatively impact the health of susceptible populations, including young children, older adults, people with chronic health conditions, and people taking certain medications. In New Zealand, some population groups already experience substantial health inequities, including Māori and Pacific peoples, and therefore a heat-health warning system is likely to have population health benefits, help prevent health impacts during heatwaves, and contribute to reducing further health inequities.

Additionally, these study results could be used to inform the retrospective monitoring and surveillance of heatwaves and associated impacts on health in New Zealand. For surveillance purposes, the EHF would make more sense to use as it is strongly aligned with heatwave definitions and allows for different severity thresholds, and can be used across New Zealand.

Conclusions

Both the EHF and MetService approaches identified periods of hot weather associated with significant excess mortality in Auckland and Canterbury, although the EHF approach was associated with higher excess mortality. These study results suggest that the EHF warrants further investigation as a heat-health warning system in New Zealand, given its better alignment with heatwave definitions, strong link with health outcomes, and the potential to link different heatwave intensity thresholds with public health action. Nonetheless, the MetService heat alert definition appears to be currently identifying periods of hot weather associated with excess mortality, and has already being implemented operationally.

Introduction

Project aims

This project investigated two different approaches to identifying heatwaves/hot days: (i) the Excess Heat Factor (EHF), which was developed in Australia and used as the basis for their heat-health warning system, and (ii) the New Zealand MetService's Heat Alerting scheme.

For each of these approaches, we estimated the excess mortality during the heatwaves, then compared excess mortality and other parameters across the two approaches. The study regions were Canterbury and Auckland, over the summer seasons from 2000/01 to 2020/21.

The main objectives of this project were:

- to compare heatwave periods identified by the EHF and MetService heat alert approaches in the Canterbury and Auckland regions
- to estimate the excess mortality associated with heatwaves using these two approaches
- to investigate which heatwave definition has the greatest applicability in the New Zealand context when considering impacts on mortality.

By investigating the link between historical climate data and mortality data, this study may help to inform the development of a heatwave definition and alert thresholds applicable and relevant for New Zealand.

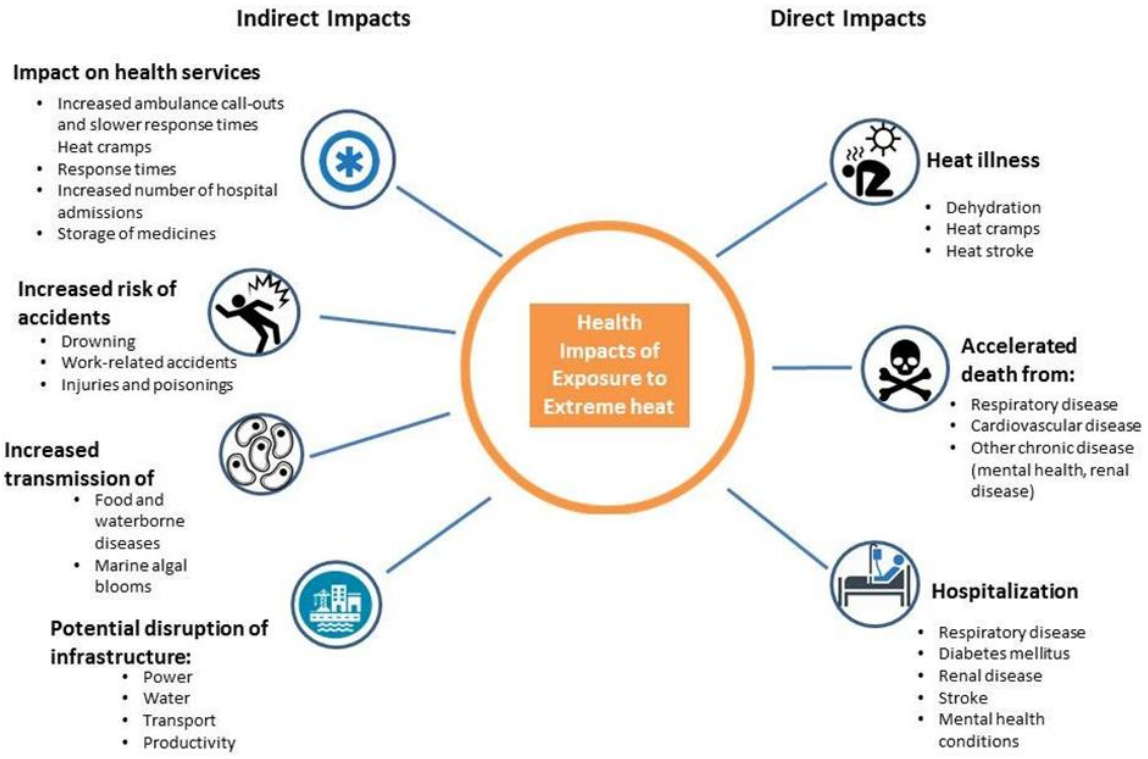
This project builds on a previous Environmental Health Intelligence NZ (EHINZ) pilot study, which investigated the relationship between heatwaves and excess mortality in the Canterbury region (Haenfling et al 2023). The pilot study tested three heatwave definitions (Excess Heat Factor (EHF), as well as the Stats NZ/Ministry for the Environment approach and the UK approach, both based only on daily maximum temperatures), and found the EHF performed best at identifying hot days associated with excess mortality. The EHF was the only heatwave definition that included daily mean temperatures (ie taking into account warm overnight temperatures, which are associated with health impacts as the body does not get a chance to recover).

Heatwaves and health

Heatwaves are associated with negative impacts on public health, with outcomes ranging from dehydration to death (Figure 1) (Ebi et al 2021, Ministry of Health 2018, WMO and WHO 2015). Key population groups who are more vulnerable to the health impacts of heatwaves include: older adults (65+ years), young children under 5 years old, pregnant women and nursing mothers, people with disabilities, people with pre-existing health conditions, people taking certain medications, migrants and refugees, people who do not understand English, homeless people, outdoor workers, overweight and obese people, people living alone, and people living in areas of higher socioeconomic deprivation (Department of Human Services 2009, Mayrhuber et al 2018, RCCC 2019, WMO and WHO 2015). Additionally, in New Zealand, some population groups already experience substantial health

inequities, including Māori and Pacific peoples (Gurney et al 2020), and these groups may therefore have a higher risk of experiencing negative health impacts of heatwaves.

Figure 1: Summary of health impacts of exposure to extreme heat



Source: WHO, URL: https://www.who.int/globalchange/publications/heat-and-health/en/

Climate change will likely increase the risk of heatwaves in the future. Climate change projections for New Zealand indicate there will be increasing intensity and frequency of hot days across the country (Bodeker et al 2022). By 2040, mean temperatures are projected to increase between +0.7° and +1.0°C (Ministry for the Environment 2018). Additionally, maximum temperatures are estimated to be higher, and the number of hot days (maximum temperature above 25°C) is projected to increase between 40% and 100% by 2040. Extreme temperatures are expected to occur more frequently and persist for longer, increasing the risk of heatwaves. Consequently, health impacts are also predicted to increase.

Defining heatwaves

Despite the intuitive understanding of the term ‘heatwave’, there is no single, universal definition of a heatwave. The World Meteorological Organization (WMO) and World Health Organization (WHO) guidance on heat-health warning systems (HHWS) describes a heatwave as “*periods of unusually hot and dry or hot and humid weather that have a subtle onset and cessation, a duration of at least two to three days and a discernible impact on human activities*” (WMO and WHO 2015, p1).

Most heatwave definitions mention average temperatures, either directly or indirectly. Average temperatures are relative to a specific location as well as the time of year. In other words, a

temperature value (or other particular meteorological elements) may be experienced as extreme in one location but could be normal in another location. The most effective heatwave definitions, therefore, do not specify absolute temperature thresholds but instead are normalised to the specific region and climatology.

In New Zealand, the MetService (MetService 2017) refers to the UK Met Office definition, where a heatwave occurs when "*the daily maximum temperature exceeds the average maximum temperature by five degrees or more for five consecutive days*" (Met Office UK). The MetService also notes that one day does not make a heatwave (MetService 2017). In 2020, the Ministry for the Environment and Stats NZ (2020) provided the following definition: "*…heatwaves are defined as three or more consecutive days with a maximum temperature or more than 5 degrees Celsius above the monthly average for 1981–2010."*

Heat-Health Warning Systems (HHWS)

In general, heat-health warning systems (HHWS) are the weather-based alert component of a wider heat-health action plan (HHAP) (WMO and WHO 2015). Development of most HHWS starts with the selection of an appropriate heatwave definition. A heatwave definition helps to identify the level of heat stress in a region. However, because there is no universal heatwave definition, there is no standard methodology for deriving this definition. Methods can include indices based on single or combined temperature measures, humidity, wind speed or results from more complex heat-budget models. Data availability is a key driver behind the choice of method. Therefore, selecting a methodology based on temperature might be more reliable (Nairn and Fawcett 2015, WMO and WHO 2015) as it is the most well-observed and documented climate variable.

Once selected, a heatwave definition can be used to identify threshold values for heat alerts. However, there is also no standard methodology to calculate alert threshold values (Hajat et al 2010). Some methodologies are response-specific, where the alert threshold is set to a level associated with negative health effects. Other systems rely solely on historical climate data and set thresholds at various percentile levels (WMO and WHO 2015). Weather forecasts are then used to predict exceedances of the pre-defined alert thresholds, triggering warnings that will notify the general population and decision-makers (WMO and WHO 2015). Implementing an HHWS should also include an evaluation to test whether the chosen methodology is effective for that specific location (WMO and WHO 2015).

Even though there are different methodologies in setting up an HHWS, the goal should be to *"identify those days associated with the largest health effects attributable to adverse weather conditions"* (Hajat et al 2010). Increasing evidence points to the effectiveness of an HHWS in reducing heat-related mortality and morbidity (de Perez et al 2018, Mayrhuber et al 2018, WMO and WHO 2015). The WHO states that the negative impacts of heat on human health are well understood, predictable, and largely preventable with public health actions (WHO 2026). Heat-health warning systems help save lives, have economic benefits (Toloo et al 2013, Chiabai et al 2018, Williams et al 2022), and can be a 'no-regret public health response to heatwaves' (Williams et al 2022).

Some key considerations in setting up an HHWS include the following.

- There is a stronger association of increased mortality with heatwaves occurring early in the summer season than with heatwaves occurring later in the season. Acclimatisation is key to this association (WMO and WHO 2015).
- Research has shown that a lag time of 0–3 days produces the most significant effect on mortality following extreme temperatures. Quick warning systems are therefore key to preventing excess mortality and morbidity (Basu and Samet 2002, Nairn and Fawcett 2015).

Setting HHWS alert thresholds based on mortality

A wide range of methods exist to calculate alert thresholds, but WMO and WHO (2015) have advised that alert thresholds in a HHWS should be determined by using actual heat-health relationships. These methods generally use epidemiological analysis of historical mortality and/or morbidity data to model the heat-health relationship. Even though extreme temperatures have wide-ranging health effects, total all-cause mortality is most widely used in these calculations. The main reason is these records' availability and straightforward use (Basu and Samet 2002). All-cause mortality is also used to avoid misclassification and underreporting of heat-related deaths (WMO and WHO 2015).

Long-term mortality data is used to derive a daily baseline value, which can be used to calculate excess mortality (difference between baseline and observed deaths) and correlated with weather conditions (WMO and WHO 2015). Again, various methodologies are used to analyse this relationship (Gosling et al 2009). J- or U-shaped relationships are most often observed in the epidemiological models, with increases in mortality at the low and high extremes (Basu and Samet 2002, Gosling et al 2009). Additionally, studies may need to analyse data over longer pooled time periods than specific heatwave events, to provide sufficient data to detect statistically significant differences in excess mortality (Zhao et al 2021, Guo et al 2017).

Excess Heat Factor (EHF) heatwave definition

The Excess Heat Factor (EHF) was developed in Australia as an indicator of health-relevant heat events (Nairn et al 2009; Nairn and Fawcett 2013, 2015), and has been shown to be associated with higher levels of attributable mortality due to heatwaves compared with other heatwave definitions (Kanti et al 2022). The EHF has been used in a number of different countries to measure the health impacts of heatwaves (Nairn et al 2018), including mid-latitude countries and jurisdictions where humidity tends not to be too high (Oliveira et al 2022), European countries (Oliveira et al 2022), South Australia (Borg et al 2019, Wondmagegn et al 2021), Greece (Tolika 2019) and France (Kanti et al 2022).

The EHF has also been used and/or trialled as a heat alert system in a number of countries (Nairn et al 2018), including as the basis of the National Heatwave Warning Framework and heat-health action plans in Australia (Bureau of Meteorology 2023). The EHF has been shown to predict higher levels of mortality (Kanti et al 2022), health service utilisation (Scalley et al 2015), ED presentations and associated costs (Wondmagegn et al 2021), work-related injuries and illnesses (Varghese et al 2019), ambulance callouts (Hatvani-Kovacs et al 2016) and heatwave-related urinary disease (Borg et al 2019).

Since 2014, the Australian Bureau of Meteorology has publicly released national 7-day heatwave severity maps based on the EHF (Nairn et al 2018). The intensity of EHF heatwaves can be categorised (through the EHF severity metric) into low-intensity, severe, and extreme heatwaves (Nairn et al 2018, Hatvani-Kovacs et al 2016). In Australian heatwave hazard plans, EHF severity thresholds are used to identify trigger levels for emergency management and public health actions (Department of Health, Western Australia, 2025).

MetService heat alerts

In 2021, the New Zealand MetService introduced the Heat Alerting scheme for public warnings about unusually hot weather in specific locations (Griffiths and Nabi 2023). During the summer months, when a substantial heat event for a region is forecast, the MetService publishes heat alert banners on their website advising people to stay hydrated, seek shade and check on the vulnerable.

MetService's heat alerting scheme used two distinct thresholds to identify unusually hot conditions: a one-day maximum temperature threshold, and a two-day mean temperature threshold. A heat alert is triggered when temperatures on one day (for the daily maximum temperature threshold) or two consecutive days (for the daily mean temperature threshold) are forecast to be above certain location-specific thresholds. Temperature thresholds are decided each summer for each location. The MetService notes that the thresholds were selected to be high (ie conservative) in part to allow flexibility in the system for future warming (Morton 2022). The MetService aims for 1–3 heat alerts on average each summer season for each location.

The heat alert system was developed together with the Climate Change Research Institute at Te Herenga Waka – Victoria University of Wellington and the then Institute of Environmental Science and Research (ESR) (now Public Health and Forensic Science, PHF Science) (Victoria University of Wellington 2021). This heat alert system was piloted over the 2021/22 summer season in 22 locations in New Zealand. It was then revised and run over the 2022/23 summer season in 44 locations, and further revised for the 2023/24 summer for 46 locations, and has run every summer since then (Griffiths and Nabi 2024; Griffiths 2024).

Monitoring heatwaves over time

Currently, there is no national surveillance of heatwaves in New Zealand or their health impacts. Monitoring heatwaves retrospectively would allow comparison of heatwave episodes across different seasons, climates, and populations. It would also allow assessment of the performance of heatwave definitions, highlight geographic inequities, and show how often, where, and how intense, heatwaves have been in New Zealand, to detect meaningful patterns. Additionally, overlaying nation-wide heatwave patterns with population vulnerability information would help highlight the geographic areas most at risk of heat-related health outcomes during the summer months, to guide preparedness and adaptation measures.

About this project

In this project, we used a three-stage process to analyse the association between daily values of air temperature and mortality counts across the Canterbury and Auckland regions during the study period (November to March (summer months), 2000 to 2021). This process was to:

1. identify heatwaves retrospectively, using two different approaches:
   a) the Excess Heat Factor (EHF) used in Australia (Nairn and Fawcett 2015)
   b) MetService's heat system alert (Griffiths and Nabi 2023)
2. estimate the excess mortality during the identified heatwaves
3. compare the excess mortality and other parameters across the two approaches.

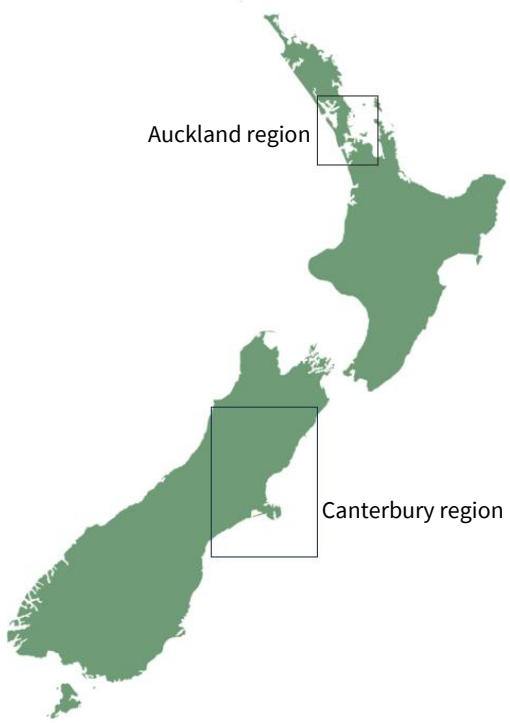
Data and methods

The study used daily temperature and mortality data for the period 2000 to 2021. The main analysis was restricted to the summer months (1 November to 31 March) between 2000 and 2021 (ie, summer seasons 2000/01 to 2020/21).

Mortality and temperature data for the Canterbury and Auckland regions were sourced from the New Zealand Mortality Collection and NIWA's (now Earth Sciences New Zealand[1]) DataHub database, respectively. Daily mortality data were available for the period 2000 to 2021 (the most recent data available at the time of this study), whereas daily temperature data for the selected climate stations were available for the period 1965 to the present.

Two regions were selected to test the heatwave definitions: Canterbury and Auckland (Figure 2). Canterbury was the focus of our previous pilot study (Haenfling et al 2023), while Auckland provided a further opportunity to test heatwave definitions in a different meterological context and with a larger population.

Figure 2: Map of New Zealand, with Canterbury and Auckland regions shown

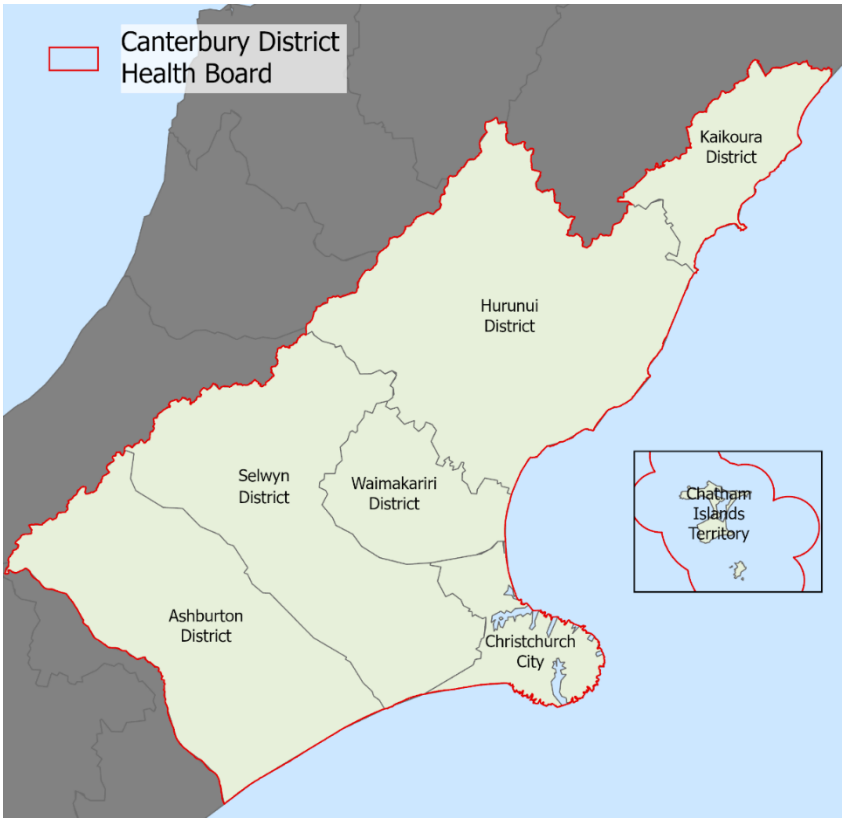


Canterbury study area

For this report, the Canterbury study area covers the Canterbury district, which is the second largest health district (formerly known as a district health board) in New Zealand, both by geographical area and population size. It covers approximately 26,881 km^2 over seven territorial authorities (TAs) (Figure 3) and provided health services to 539,631 people in 2018, according to the 2018 Census.

[1] Earth Sciences New Zealand was formed on 1 Jul 2025 by the merger of NIWA and GNS Science.

Figure 3: Map of Canterbury district (formerly known as Canterbury District Health Board) and seven Territorial Authorities, 2018



The climate and weather in the Canterbury region are subject to the influence of the Southern Alps on the prevailing westerly winds over New Zealand (Macara 2016). New Zealand's highest recorded air temperature was measured in Canterbury, 42.4°C, at Rangiora in February 1973. Days with maximum air temperatures above 25°C occur relatively frequently across the region, especially on the Canterbury Plains. These hot days are generally due to foehn episodes (the Canterbury nor-wester), a strong, hot and dry wind that brings heavy rain to the mountains of the West Coast and subsequently warm and dry conditions on the lee of the Southern Alps.

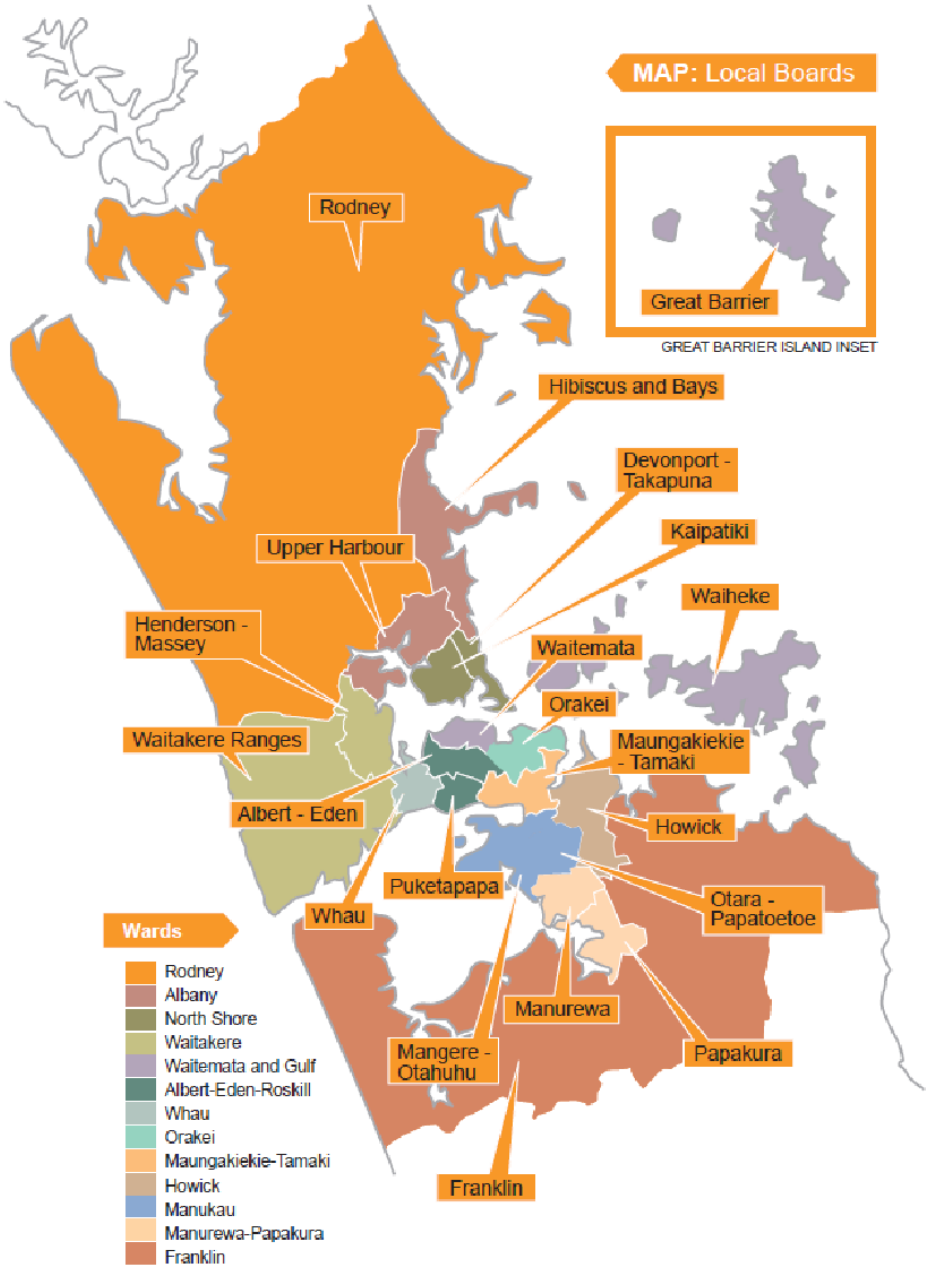
Auckland study area

The Auckland region comprises 21 local board areas (Stats NZ, Figure 4). For this report, the Auckland study area covers the Auckland City Council geographic area, excluding health domicile codes (ie census area units) in Rodney, Hibiscus and Bays, Waitakere Ranges, Franklin, Waiheke Island, and Aotea/Great Barrier local board areas. These areas were excluded because they were mostly rural and had lower temperatures than the inner city in a recent analysis of mean and maximum air temperatures across Auckland (Arup New Zealand 2024). This study area covers an estimated 1.32 million people, making it the most populous region in New Zealand (Appendix Table 1).

The Auckland region, located in the northern part of New Zealand and north of the main mountain ranges and volcanic plateau, is less affected by cold Antarctic air than most regions in the country. However, it is often among the first to experience tropical storms. Rainfall mainly accompanies

northerly winds, and the region's relatively warm temperatures and higher humidity contribute to a distinct climate compared to the southern and eastern regions. The highest recorded temperature in Auckland was 34.0°C at Lincoln Road, West Auckland, on 12 February 2009 (Chappell, 2013).

Figure 4: Map of Auckland Region, wards and local areas



Note: Our Auckland study area excluded Rodney, Hibiscus and Bays, Waitakere Ranges, Franklin, Waiheke Island, and Great Barrier Island local board areas.
Source: Fathimath (2017)

Meteorological data

The following methodology details the process undertaken to update and analyse temperature, rainfall, and soil moisture deficit indicators in the EHINZ Climate Change domain.

Data source

Climate station data was sourced from the DataHub web service provided by NIWA (now Earth Sciences New Zealand). The database contains data from approximately 7,500 climate stations, which have been operating for varying periods since observations began, collecting different types of raw data.

The data enquiries form was used to download a spreadsheet of available climate stations recording relevant data in the relevant climate region (Canterbury and Auckland). The following parameters were selected:

- Data Category: Climate station data (daily)
- Time period: 01/01/1981 – 31/12/2021

The period from 1981 to 2021 was selected as the minimum time period for inclusion in this study. The period 1981–2010 represents the Climate Normal Period available at the time of the study that was most relevant to the study period, while the period 2010–2021 further extends the record to analyse links between extreme temperatures and mortality.

The Climate Normal Period is defined as a baseline period from which to measure temperature anomalies (WMO 2017), and is used as part of the EHF. Temperature anomalies are defined as the difference (in °C) between contemporary observations and the baseline period (calculated as the 30-year average, 1981–2010).

Selecting a representative climate station to use for the pilot study

For the Canterbury region, the query above resulted in a list of 23 climate stations in the Canterbury region, with only one station (Christchurch Aero) recording complete data for the relevant time period of 1981–2021. Therefore, the Christchurch Aero climate station was used as the designated climate station for this project.

For the Auckland region, the query above resulted in a list of 31 climate stations in the Auckland region, with only one station (Auckland Aero) recording complete data for the relevant time period of 1981–2021. Therefore, the Auckland Aero climate station was used as the designated climate station for this project.

To validate the selections, the EHINZ methodology for selecting stations based on their proximity to the population-weighted centroid (EHINZ 2021) was carried out. A list with all potential stations was imported into an ArcGIS Pro project, and latitude/longitude information was converted and displayed on the map. The method of population-weighted centroids was used due to its use in the analysis of possible effects of exposure to weather conditions on population health outcomes. It allowed us to review the weather closest to where the majority of people in a district live.

The population-weighted centroids of the Auckland and Canterbury regions were calculated from the 2018 Census, using the geographic centroid of statistical area 1 (SA1) weighted by their usual resident populations (Hanigan et al 2006). A 25km buffer was created around the centroid, and the distance between each climate station and the centroid was entered into a spreadsheet.

The following selection criteria are based on NIWA's (2020) report, which describes the datasets used to write the Ministry for the Environment and Stats NZ's (2020) *Our Atmosphere and Climate 2020* domain report:

- Proximity to the population-weighted centroid for the region
- Currently open climate station (as of 2021)
- Long record of reliable data (ie, minimum of 10 years of data)
- One climate station per region

The 25km buffer zone around the Canterbury district's population-weighted centroid included 23 climate stations. Distances ranged from 2.64km to 22.65km, and Christchurch Aero was selected and validated as the representative climate station due to its proximity to the centroid, completeness of data, and current open status.

The 25km buffer zone around the Auckland region's population-weighted centroid included 31 climate stations. Distances ranged from 2.64km to 22.65km, and Auckland Aero was selected and validated as a representative climate station due to its proximity to the centroid, completeness of data, and current open status.

Christchurch Aero (agent # 4843) started observing weather conditions 31/12/1953. Daily maximum and minimum temperature data was downloaded for the period 1954–2021.

Auckland Aero (agent #1962) started observing weather conditions on 31/12/1965. Daily maximum and minimum temperature data were downloaded for the period from 1966 to 2021.

Measurements used from temperature data

The following temperature measurements were used from the NIWA (now Earth Sciences New Zealand) DataHub database:

- T_{max}: the daily maximum temperature
- T_{min}: the daily minimum temperature.

In DataHub, daily temperature readings are taken at 9 pm UTC time (corresponding to 9am NZST the following day) and cover the previous 24 hours. This means that the daily maximum temperature (T_{max}) will have usually occurred in the afternoon on that day, whereas the daily minimum temperature (T_{min}) occurs on the day of measurement (in NZ time) (usually in the early hours of the morning). The T_{max} in the late afternoon, therefore, precedes the T_{min} in the early morning, emphasising that the health effects of an unusually warm night following a warm day are more significant than the reverse (Nairn & Fawcett, 2015). In the DataHub output, the observation time is recorded in UTC, so both T_{max} and T_{min} meet the standard practices for daily temperature data.

Excess Heat Factor (EHF) heatwave definition

Two different heatwave definitions were chosen to test their ability to recognise potential heat-related excess deaths: Excess Heat Factor (EHF), and MetService's Heat Alerting scheme.

The Excess Heat Factor (EHF) was developed in Australia to identify significant and health-relevant heat events (WMO and WHO 2015). It identifies periods of three or more consecutive days where excess heat conditions are experienced, taking an acclimatisation period of 30 previous days into account. This definition was chosen because it is widely researched, peer-reviewed and tested in multiple countries (Oliveira et al, 2022). The method uses both the maximum and minimum daily temperature to take into account the impact of hot nights.

Overview of the EHF approach

The EHF uses the three-day average of daily maximum temperatures (T_{max}) and daily minimum temperatures (T_{min}) to create two indices that describe long-term and short-term temperature anomalies (Nairn et al 2009; Nairn and Fawcett 2013, 2015).

For these calculations, the daily mean temperature (DMT, also known as T_{mean}) is calculated as the average of T_{max} and T_{min}:

$$DMT = T_{mean} = \frac{T_{max} + T_{min}}{2} \quad (1)$$

The EHF approach creates two indices: the Excess Heat Index (which needs to be positive in order to identify a heatwave), and the Acclimatisation Index (which compares sudden increases in the daily mean temperature to the recent past).

Significant Excess Heat Index (EHI_{sig})

The first index is the Excess Heat Index for a significant heat event (EHI_{sig}), which measures how hot a three-day period is in comparison to the 95th percentile (DMT_{95}) of the daily mean temperature (DMT) over a reference period (1981–2010).

EHI_{sig} is calculated as follows:

$$EHI_{sig} = \left(\frac{DMT_i + DMT_{i+1} + DMT_{i+2}}{3}\right) - DMT_{95} \quad (2)$$

where T_i is the first day, DMT_i is the daily mean temperature of day *i*, and DMT_{95} is the 95th percentile of the DMT over the 30-year Climate Normal Period 1981–2010, calculated using all days of the year.

If the EHI_{sig} is positive (ie, the DMT averaged over the three-day period is higher than DMT_{95}), then the three-day period in question is considered to be unusually warm (Nairn and Fawcett 2015).

Acclimatisation Index (EHI_{accl})

The second index is the Acclimatisation Index (EHI_{accl}), which identifies sudden sharp increases in temperature (compared with the recent past) that people may not have had time to acclimatise to.

The EHI_{accl} is calculated by comparing the same three-day period to the previous 30 days:

$$EHI_{accl} = \left[\frac{DMT_i + DMT_{i+1} + DMT_{i+2}}{3}\right] - \left[\frac{DMT_{i-1} + \cdots + DMT_{i-30}}{30}\right] \quad (3)$$

If the EHI_{accl} is positive, then the three-day period in question is considered to be warmer, on average, than the recent past, suggesting a lack of acclimatisation to warmer temperatures (Nairn and Fawcett 2015).

Deriving the EHF

The results from EHI_{sig} and EHI_{accl} are combined to derive EHF as follows:

$$\mathrm{EHF} = \max(0, \mathrm{EHI_{sig}}) \times \max(1, \mathrm{EHI_{accl}}) \quad (4)$$

As evident from equation 4, EHF will be positive only if EHI_{sig} is positive. If EHI_{accl} is also positive, this would increase the severity of the heatwave. All positive EHF values indicate heatwave conditions, which apply to all days in the three-day period in question (Nairn and Fawcett 2015).

EHF severity thresholds

In this study, we also identified EHF severe and extreme heatwaves using the definition by Nairn and Fawcett (2015). EHF severity/intensity thresholds have been developed and implemented in Australia to inform heatwave hazard plans, and to identify trigger levels for emergency management and public health actions (Department of Health, Western Australia, 2025). These threshold levels have been developed based on health impacts of heatwaves at varying levels (Table 1).

A severity threshold for EHF heatwaves is obtained by computing the 85th percentile of all positive EHF values within the climatology period. We used the climatology period from the first year of data collection (1954 for Christchurch, and 1966 for Auckland) through to 2021, to increase the accuracy of the threshold, and to be consistent with the long time periods used in Australian approach. The severity threshold is denoted as EHF_{85}.

A heatwave is considered severe if EHF severity >= 1 (that is, if EHF ≥ EHF_{85}). We also considered the extreme heatwave definition proposed by Nairn and Fawcett (2015), where a heatwave is considered extreme if EHF ≥ 3 × EHF_{85} (Table 1).

$$EHF\ severity\ value = EHF_{sev} = \frac{EHF}{EHF_{85}} \quad (5)$$

Table 1: EHF classification thresholds used in Australia

EHF Classification	Description	EHF and EHF_{sev} value
All heatwaves	All heatwaves (of any intensity)	EHF > 0
Low-intensity heatwaves	Low-intensity heatwaves are the most common type of heatwave. Most people can cope during these heatwaves.	EHF_{sev} > 0 and EHF_{sev} < 1
Severe heatwaves	Severe heatwaves are less common. They are likely to be more challenging for vulnerable people, such as older people and those with a medical condition.	EHF_{sev} >= 1 and EHF_{sev} < 3
Extreme heatwaves	Extreme heatwaves are rare. They are a problem for people who don't take precautions to keep cool—even for people who are healthy. People who work or exercise outdoors are at greater risk of being affected. These heatwaves can also impact infrastructure such as power and transport. In Australia, this trigger point activates the State Hazard plan, as it has been identified as the threshold for sub-optimal health outcomes for the public.	EHF_{sev} >= 3

Notes: EHF_{sev} is the ratio of EHF / EHF_{85}.

Source: Department of Health, Western Australia (2025)

The following combinations of EHF thresholds were tested:

- EHF heatwaves – all heatwaves
- EHF heatwaves – severe + extreme heatwaves
- EHF heatwaves – extreme heatwaves

EHF thresholds used in this study

The following thresholds were calculated and used in this study:

- Canterbury (Christchurch Aero):
    - DMT_{95} = 19.90°C (for 1981–2010)
    - EHF_{85} = 11.0 (for 1954–2021)
- Auckland (Auckland Aero):
    - DMT_{95} = 21.45°C (for 1981–2010)
    - EHF_{85} = 4.0 (for 1966–2021)

For example, in this study, the EHF approach defined Auckland heatwaves as occurring when the average daily mean temperature over a three-day period was higher than 21.45°C at Auckland Aero weather station. Severe heatwaves were defined when the three-day EHF_{sev} value was at least 4.0, and considered as extreme if EHF_{sev} values was at least 12 (ie three times EHF_{sev}). Heatwaves identified with these trigger points apply to all days in the three-day period.

MetService heat alert definition

In 2021, the MetService introduced the Heat Alerting scheme, developed together with the Climate Change Research Institute (CCRI) at Te Herenga Waka – Victoria University of Wellington, and the then Institute of Environmental Science and Research (ESR) (Victoria University of Wellington 2021). This heat alert system was piloted over the 2021/22 summer season in 22 locations in New Zealand. It was then revised and run over the 2022/23 summer season in 44 locations, and further revised for the 2023/24 summer for 46 locations, and has run every summer since then. According to the MetService, in the 2024/25 summer season, 46 cities and towns were part of the 'heat alert trial', with the heat alerts not designed to capture all hot days, but to identify the 'top end heat' (MetService n.d).

Overview of MetService heat alert definitions

When a potentially severe heat event for a region is forecast over the summer months, the MetService publishes heat alert banners on their website advising people to stay hydrated, seek shade and check on the vulnerable.

Temperature thresholds were selected by the research group for each location. A heat alert is triggered when temperatures on one day (for the daily maximum temperature threshold) or two consecutive days (for the daily mean temperature threshold) are forecast to be above certain location-specific thresholds. The MetService notes that the thresholds were selected to be high (ie conservative) in part to allow flexibility in the system for future warming (Morton 2022).

For the 2023/2024 summer season, MetService's heat alerting scheme used two distinct thresholds to identify unusually hot conditions: a one-day maximum temperature threshold, and a two-day mean temperature threshold.

1. One-day threshold (daily maximum temperature)

Alerts are issued when the forecast maximum temperature (T_{max}) for a specific location exceeds a threshold, set at the 99.5th percentile of historical maximum temperatures over the past 20 years for that site. These thresholds are location-specific and are designed to capture short-duration but intense heat events. These thresholds are designed to trigger about 1–3 times per year on average. The thresholds are reviewed each year and have sometimes been raised for specific locations (Griffiths and Nabi 2024).

2. Two-day threshold (daily mean temperature)

To capture more prolonged periods of heat, MetService also issues alerts based on two consecutive days where the daily mean temperature (DMT, also known as T_{mean}) exceeds a specified threshold (the 99.5th percentile). As above, T_{mean} is calculated as the average of the daily maximum and minimum temperatures:

$$T_{mean} = DMT = \frac{T_{max} + T_{min}}{2} \quad (1)$$

The two-day T_{mean} thresholds are also location-specific and were selected through historical data over 20 years. However, to avoid alerting on less impactful heat (e.g. warm, humid days with low maximum

temperatures), the MetService applies an additional condition: the maximum temperature must also reach at least 27°C on each of the two days. These thresholds are also set very high, and are designed to trigger 1–2 times per year on average. The thresholds are reviewed each year, and have sometimes been raised for specific locations.

For the MetService heat alert definition, a heat day can be defined by exceeding either a one-day threshold (ie daily maximum temperature exceeding a threshold) or a two-day threshold (ie daily mean temperature exceeding a threshold, and daily maximum temperature is at least 27°C, for two consecutive days).

In practice for the heat alerting scheme, the MetService forecast system generates forecast temperatures for specific locations, and these are the exact spots used to derive heat alerts from. For Auckland City, these are Auckland Airport, Whangaparaoa and Whenuapai, and for Christchurch City, Christchurch Airport. In the Auckland case, any of the locations reaching criteria may trigger a heat alert for "Auckland City". There is also a final human check (and possible override) in the process, so the meteorologist has the final discretion as to whether to issue a heat alert or not, and that decision could go either way.

Thresholds used in this study

We used the specific locations of Christchurch Aero (airport) and Auckland Aero (airport), and exact daily temperatures since 1981, to identify when a heat alert would have been issued (if the heat alert system had been operating then). We use the following methods (noting that in practice, the MetService heat alerting process would have a final human check).

For Christchurch Aero, MetService based their heat alerts on a one-day threshold for daily maximum temperature (T_{max}) of 31°C during the 2022/23 and 2023/24 summer seasons, and 32°C in the 2024/25 summer season (Griffiths and Nabi, 2023, 2024). We tested both thresholds as part of sensitivity analyses. The two-day threshold for daily mean temperature (T_{mean}) was 23°C across all three summers (Griffiths and Nabi, 2023, 2024).

Auckland has had changing thresholds over the past five years. Originally in 2021/22, the MetService based their heat alerts on a one-day threshold of 28°C for the daily maximum temperature at Auckland Aero and a higher 'feels like' temperature. However, after the 2021/22 summer, public feedback was that the daily maximum temperature threshold felt too low. This led to MetService increasing the one-day threshold to 29°C, and adopting a two-day alert based on a daily mean temperature of 23°C for the 2022/23 and 2023/24 summers. In 2024/25, the one-day threshold was increased to 30°C, and the two-day threshold was increased to 24°C (Griffiths and Nabi, 2023, 2024).

Our calculation for the one-day threshold, the 99.5th percentile of T_{max} (27.8°C), was slightly lower than the implemented thresholds, so we carried out sensitivity analyses and tested with a range of one-day thresholds (27°C, 28°C, 29°C and 30°C for T_{max}). For Auckland Aero, the two-day threshold for T_{mean} was 23°C in 2022/23 and 2023/24, with an increase to 24°C in 2024/25 (Griffiths and Nabi, 2023, 2024).

Because our analyses cover the period 2001–2021, we did not want to limit analyses to only the most recent thresholds based on current temperatures. Therefore, we have tested the following combinations of thresholds for Auckland Aero:

- T_{max} = 27°C, T_{mean} = 23°C: (T_{max} threshold reflects the 99.5th percentile of T_{max} rounded down to 27°C, although this is a lower threshold than has been used in practice by MetService)
- T_{max} = 28°C, T_{mean} = 23°C: (original T_{max} threshold used in 2021/22 summer)
- T_{max} = 29°C, T_{mean} = 23°C: (thresholds used in 2022/23 and 2023/24 summers)
- T_{max} = 30°C, T_{mean} = 24°C: (new thresholds used for 2024/25 summer)

Mortality data

Mortality data was sourced from Health New Zealand's Mortality Collection (MORT). Total, all-cause (WMO and WHO 2015) daily mortality counts of people were summarised for the years 1998 to 2021.

For the Canterbury analysis, we included all people living in the Canterbury district (previously Canterbury District Health Board) at the time of death. We excluded the 147 victims of the Christchurch earthquakes on 4 September 2010 and 22 February 2011 from the analysis, based on ICD-10AM code X34 (victim of earthquake). We also excluded the 50 Canterbury residents who were killed in the Christchurch mosque attack in 2019 (ICD-10AM code X9596).

For the Auckland analysis, we included people residing in the Auckland City Council area, excluding health domicile codes in Rodney, Hibiscus and Bays, Waitakere Ranges, Franklin, and Aotea/Great Barrier local board areas at the time of death. This ensured that the geographic area covered mostly urban Auckland, with a similar heat level (see Appendix).

Estimating excess mortality

To understand the mortality-temperature relationship, excess mortality was calculated as the difference between the expected baseline mortality and the observed mortality (Gosling et al 2009). For each day of the year, a baseline mortality value was calculated from mortality counts averaged across the previous three years (Gosling et al 2009). To obtain a stable baseline, days were matched by day of the year as well as three days before and after the day in question (Hajat et al 2010). A three-year average was used for the baseline to give stability, and was an increase from the two-year baseline used in the previous pilot study (Haenfling et al 2023).

The heatwave-mortality relationship was evaluated using the confidence interval (CI) method (Rustemeyer and Howells, 2021). The 95% confidence intervals (95% CI) were calculated for the cumulative observed deaths for each heatwave episode, assuming a Poisson distribution. These 95% CIs were subtracted from the baseline mortality to obtain 95% CIs for the excess mortality during the same heatwave episode.

When presenting excess mortality results in this report, the term 'significant' refers to statistically significant results (that is, where the 95% confidence interval for excess mortality does not include 0).

Results for the Canterbury study area

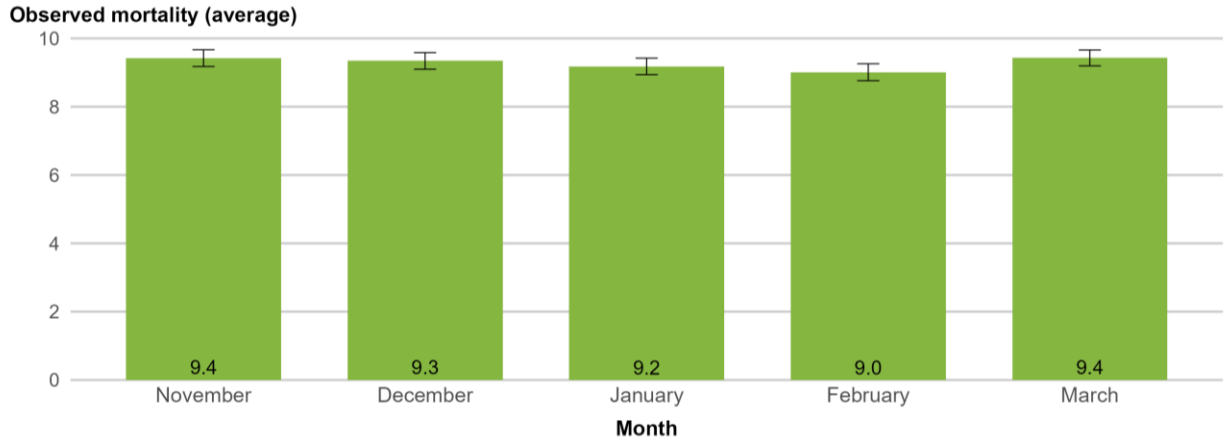
The results here are for the Canterbury study area as described on page 15.

Average daily mortality and temperatures in summer

On average, 9–10 people died daily during summer in Canterbury from 2001 to 2021

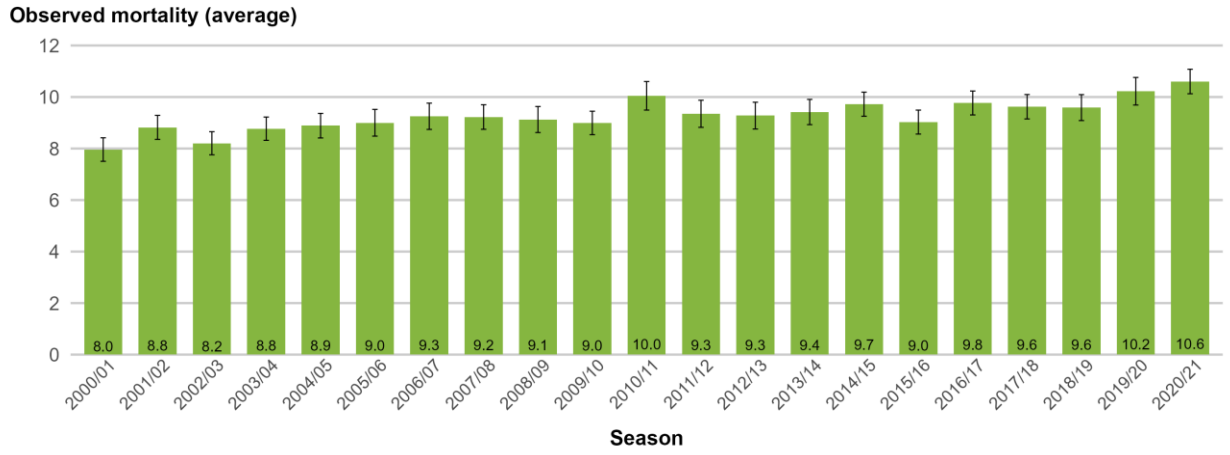
In the summer seasons from 2000/01 to 2020/21, there were 30,754 deaths in the Canterbury study area, ranging between 1 death and 23 deaths per day. The average observed mortality was 9.2 deaths per day during the summer season (November–March), with similar numbers of average deaths per month across the summer season (Figures 4 and 5).

Figure 5: Average observed daily number of deaths, by summer month, Canterbury, 2000/01–2020/21



Notes: 95% confidence intervals are shown.

Figure 6: Average observed daily number of deaths in the summer season (November–March), Canterbury, 2000/01 to 2020/21

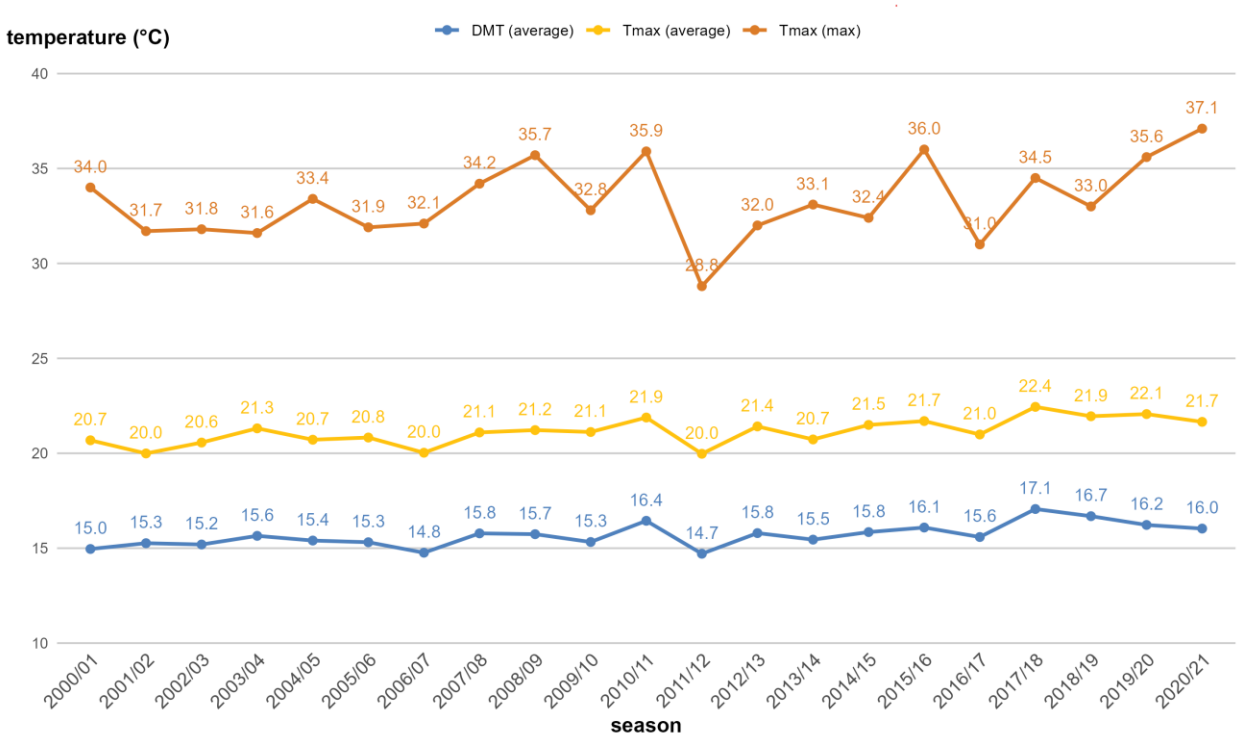


Notes: 95% confidence intervals are shown.

Canterbury district sometimes experiences daily maximum temperatures over 35°C

During the Canterbury summer seasons from 2000/01 to 2020/21, the average daily maximum temperature was 21.1°C, and the average daily mean temperature (DMT) was 15.7°C. The highest recorded temperature was 37.1°C on 26/01/2021 (Figure 7).

Figure 7: Average of daily mean temperature (DMT (average)), daily maximum temperature (T_{max} (average)), and highest recorded daily temperature (T_{max} (max)), per summer season, Canterbury, 2000/01–2020/21

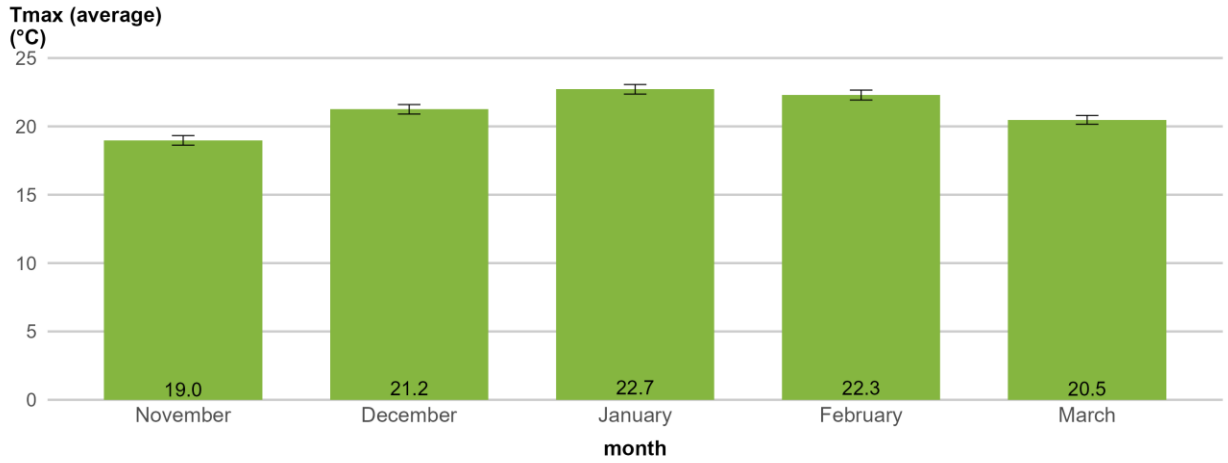


Note: Temperatures refer to the summer season from November–March.

January and February were generally the hottest months in Canterbury

On average, January had the highest average daily maximum temperature (T_{max}) (22.7°C) in Canterbury during the study period, followed by February (22.3°C) and December (21.2°C) (Figure 8).

Figure 8: Average daily maximum temperature (T_{max}(average)), by summer month, Canterbury, 2000/01–2020/21



Notes: 95% confidence intervals are shown.

Heatwaves identified using the Excess Heat Factor (EHF)

This section presents heatwaves identified using the Excess Heat Factor (EHF) for Canterbury during the summer seasons from 2000/01 to 2020/21. We present heatwave days and heatwave episodes using the main EHF approach, as well as the EHF 'severe heatwave' threshold.

The Excess Heat Factor (EHF) identifies periods of three or more consecutive days where the three-day daily mean temperature is unusually high at a location, compared with the long-term daily mean temperature at that location (and taking into account an acclimatisation period of the previous 30 days). Severity thresholds have also been applied to determine if a heatwave is low-intensity, severe or extreme.

The Excess Heat Factor approach identified many heatwaves in Canterbury

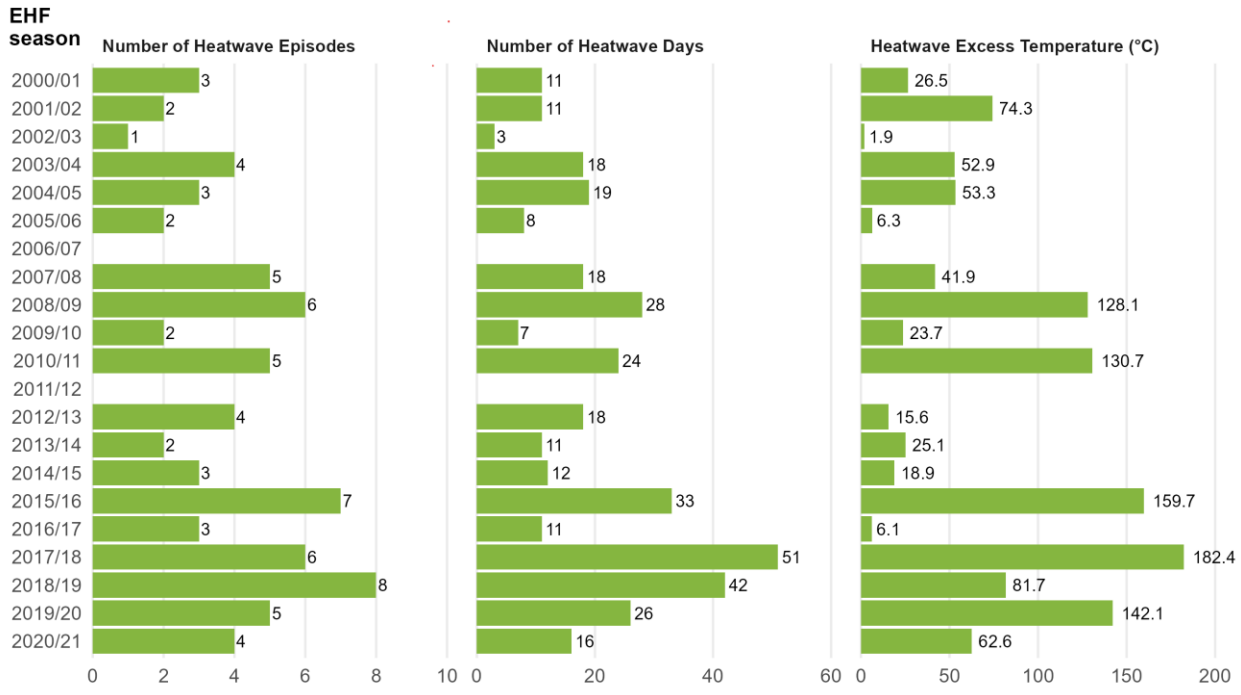
The EHF identified 367 heatwave days across 75 heatwave episodes in Canterbury between 2000/01 and 2020/21 (Figure 9). On average, there were approximately 4 heatwave episodes per year.

The 2017/18 summer season had the most heatwave days (51 days) across six episodes. This was followed by the 2018/19 summer season, with 42 heatwave days across eight episodes. Heatwave episodes in the 2017/18 season were considerably longer (8.5 days on average) than in 2018/19 (5.3 days on average).

In Canterbury, the summer seasons with the highest excess heat, according to the EHF, were 2017/18, 2015/16, and then 2019/20. Excess heat was calculated as the sum of the (positive) EHF values for each heatwave episode, taking duration and temperature into consideration.

Figure 9: Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, EHF approach, Canterbury, 2000/01–2020/21

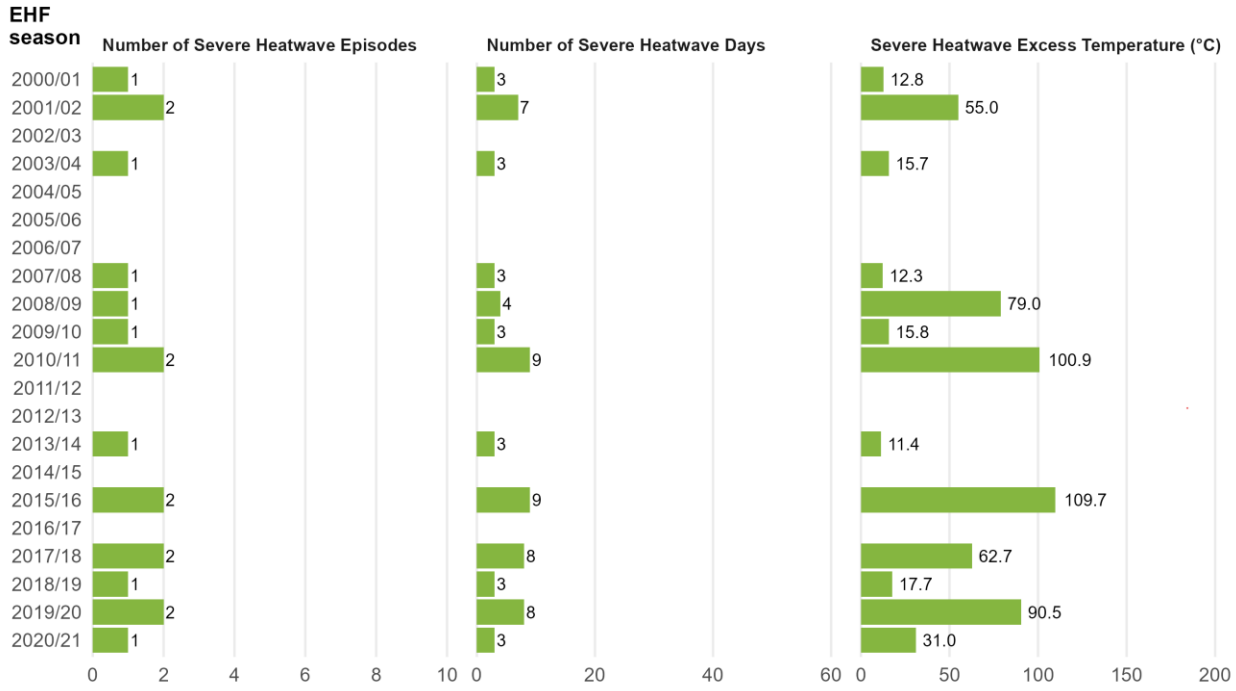
EHF (All heatwaves)



Severe EHF heatwaves occurred only 0–2 times per year

Using the EHF 'severe heatwave' threshold identified 66 severe heatwave days, across 18 severe heatwave episodes from 2000/01 to 2020/21 (Figure 10). On average, EHF severe heatwaves occurred about once per year.

Figure 10: Number of severe heatwave episodes and heatwave days, and excess heat during heatwave episodes, EHF approach, Canterbury, 2000/01–2020/21



Note: 'Severe' heatwaves refer to EHF heatwave days exceeding the 'severe' threshold, and includes heatwave days in the 'extreme' category.

Using the EHF 'extreme heatwave' threshold, there were two heatwave episodes (2008/09 and 2019/20), with a total of seven extreme heatwave days in Canterbury during the study timeframe.

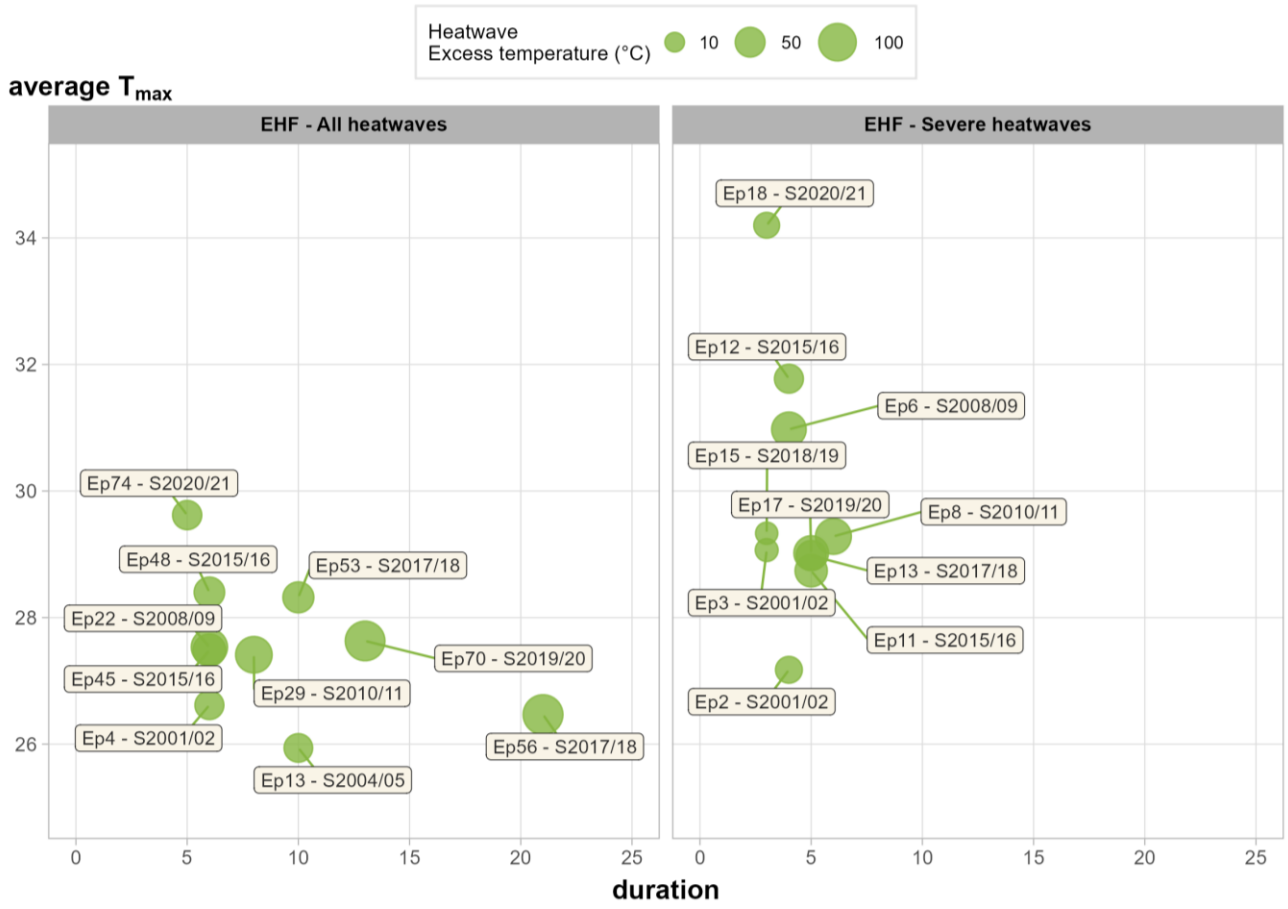
Among the ten worst EHF heatwaves identified in Canterbury, most occurred in recent years

The ten worst EHF heatwave episodes from 2000/01 to 2020/21 were ranked based on excess temperature, and plotted as duration vs average daily maximum temperature (Figure 11). Six of these ten worst heatwave episodes have occurred since 2015/16. They all had average daily maximum temperatures below 30°C, but the heatwaves generally lasted a relatively long time (between 5 and 20 days).

Episode 56 (season 2017/18, occurring from 13/01/2018 to 02/02/2018) had the highest excess temperature, despite a relatively lower average daily maximum temperature (T_{max}) compared to other episodes. It was the longest heatwave episode identified by the EHF approach (21 days).

The ten worst EHF heatwaves meeting the 'severe heatwave' threshold had relatively hotter daily maximum temperatures, and were shorter in duration, lasting between 3 and 6 days.

Figure 11: Ten worst heatwave episodes (based on excess temperature) using the EHF approach, duration (days) and average daily maximum temperature (T_{max}), Canterbury, 2000/01–2020/21



Heatwaves identified using the MetService heat alert approach

This section presents heatwaves identified using the New Zealand MetService 'heat alert' approach, for Canterbury, in the 2000/01 to 2020/21 summer seasons.

The New Zealand MetService's heat alert approach uses two distinct thresholds to identify unusually hot conditions: a single-day daily maximum temperature threshold, as well as a two-day daily mean temperature threshold (where both days also reached a daily maximum temperature of at least 27°C). Temperature thresholds are specific to locations and are revised each year, and are designed to identify 'top end heat'.

For our main Canterbury analyses, we use the MetService threshold of 31°C /23°C used operationally by the MetService for Canterbury heat alerts, from 2022/23 to 2023/24. This 31°C/23°C threshold means that a heat alert was triggered if the daily maximum temperature (T_{max}) exceeded 31°C, or if the two-day daily mean temperature (T_{mean}) exceeded 23°C (see methods for more details). As part of the sensitivity analysis, we also tested the higher MetService threshold (32°C/23°C) used operationally for Canterbury heat alerts since 2024/25.

In this report, we refer to MetService heat alert days as 'heatwave days', and episodes as 'heatwaves', although the MetService heat alert approach is not strictly a measure of heatwaves.

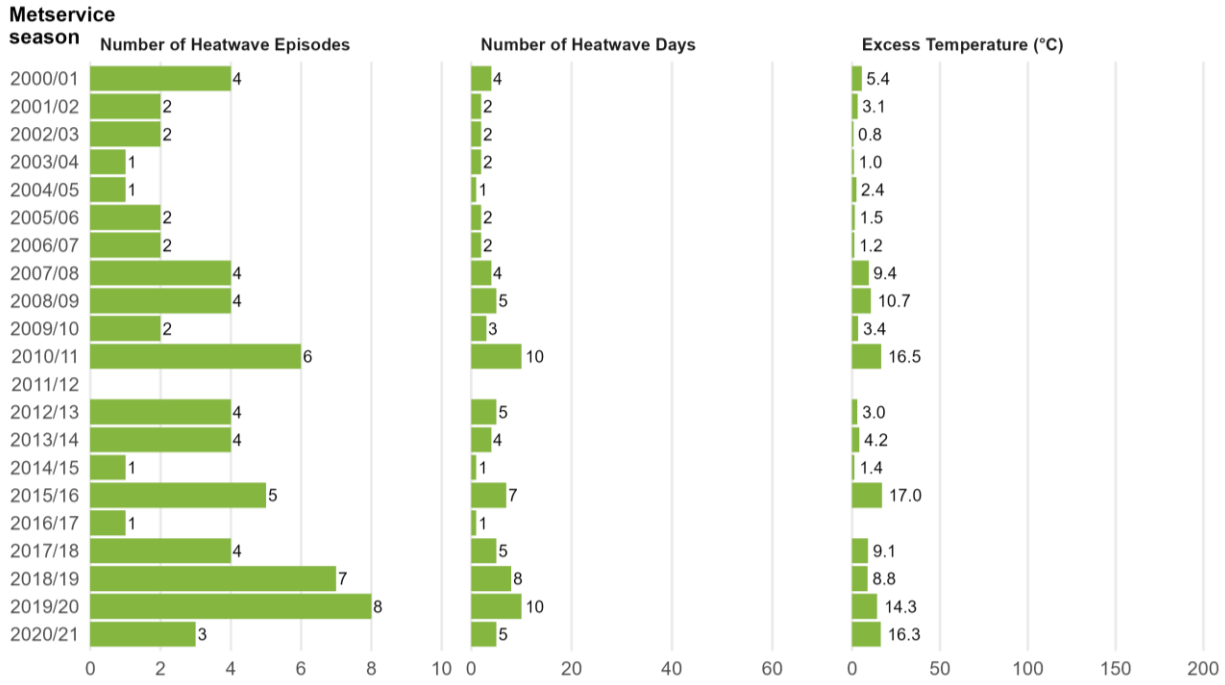
The MetService approach identified a number of heatwave days in Canterbury

The main MetService heat alert threshold (31°C/23°C) identified 83 heatwave days across 67 heatwave episodes (Figure 12). On average, there were 3.2 heatwave episodes per year. The 2019/20 summer season had the most heatwave days (10 days) across eight episodes, followed by the 2018/19 summer season (8 days).

The summer seasons with the highest excess temperatures overall were 2015/16, 2020/21, 2010/11 and 2019/20. Excess temperature was calculated as the cumulative temperature above one of the two thresholds (one-day or two-day, depending on which was positive and higher) for each heatwave episode, therefore taking duration and temperature into consideration.

Figure 12: Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, MetService approach (31°C/23°C), Canterbury, 2000/01–2020/21

Threshold - 31°C/23°C



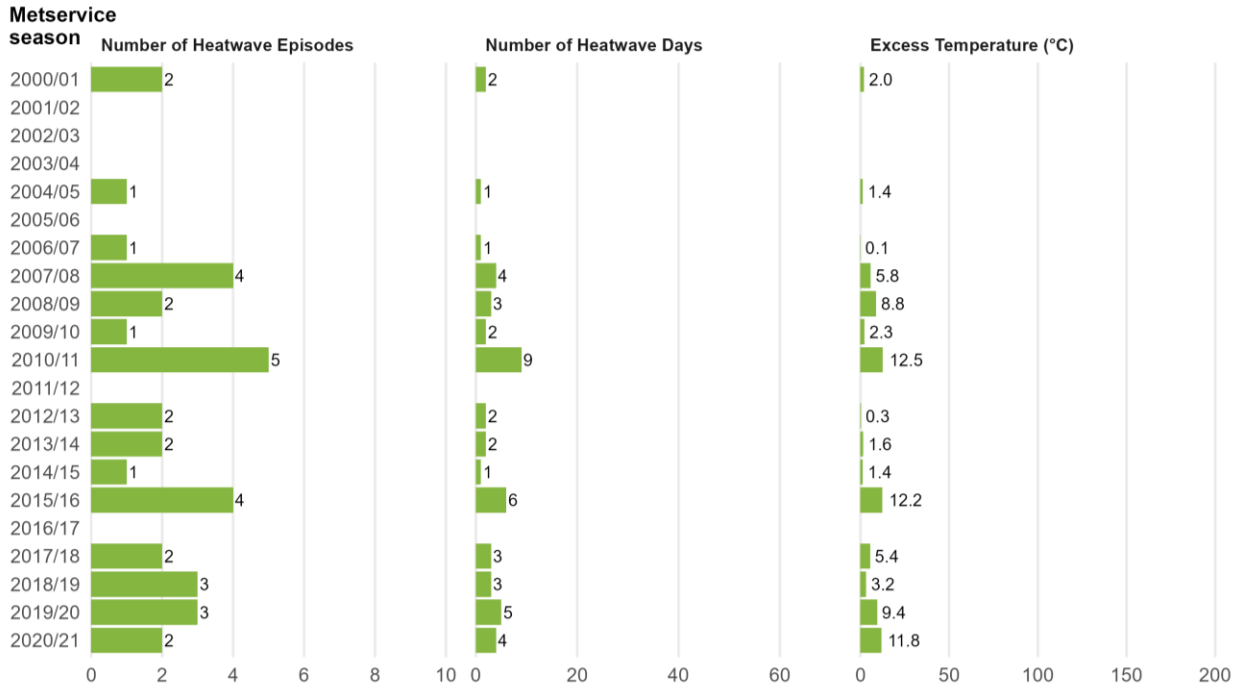
Using a higher threshold for daily maximum temperature (one-day threshold) halved the number of MetService heat alerts

Additionally, we tested the higher MetService heat alert threshold of 32°C/23°C (ie increasing the one-day daily maximum temperature threshold). This sensitivity analysis helps show the impact of changing the daily maximum temperature threshold level on the number of heatwaves identified.

Using the higher threshold of 32°C/23°C gave 48 heatwave days across 35 heatwave episodes (Figure 13). On average, there were 1.7 heatwave episodes per year for the threshold 32°C/23°C. Our analysis showed that increasing the daily maximum temperature threshold resulted in only about half the number of identified heatwave episodes and heatwave days, compared with the main threshold of 31°C/23°C. It suggests that the one-day threshold for daily maximum temperature was driving many of the heat alerts in Canterbury for the main 31°C/23°C threshold.

Figure 13: Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, MetService approach (32°C/23°C), Canterbury, 2000/01–2020/21

Threshold - 32°C/23°C

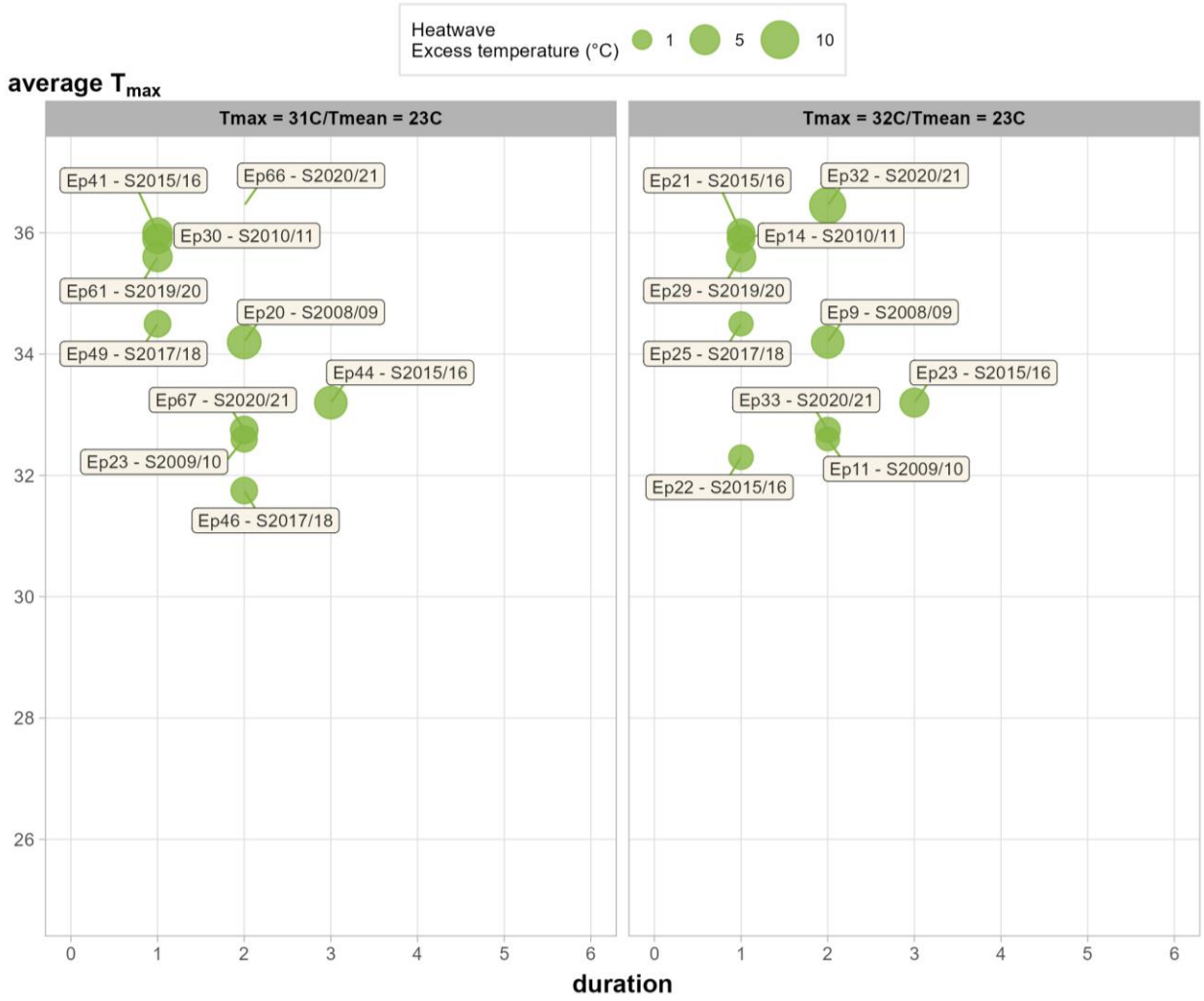


Seven of the ten worst MetService heatwave episodes since 2000/01 have occurred since 2015/16, and all tended to be of short duration

The ten worst heatwave episodes using the MetService approach were ranked based on the excess temperature, and plotted by the duration of heatwave episodes (in days) versus the average daily maximum temperatures (T_{max}) (Figure 14). For these ten worst heatwave episodes, the duration was between 1 and 3 days, and the daily maximum temperature was high, ranging from 31°C to 37°C.

Episode 34 (season 2020/21) had the highest excess temperature, with a duration of only two days, but a very high average daily maximum temperature (T_{max}) of 36.5°C.

Figure 14: Ten heatwave episodes identified using the MetService approach, duration (days) and average daily maximum temperature (T_{max}), Canterbury, 2000/01–2020/21



Comparison of the two approaches for identifying heatwaves

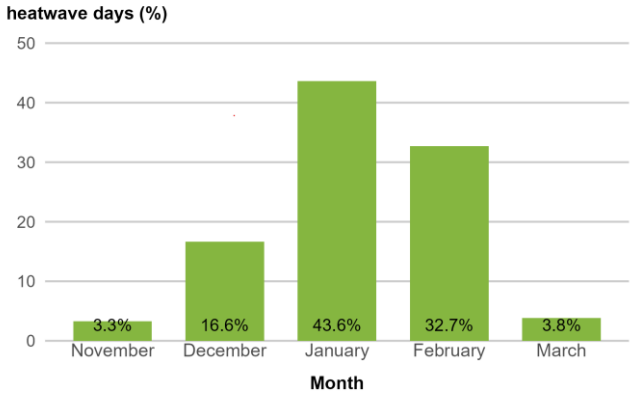
The month of January had the most heatwave days, according to both the EHF and MetService methods

Comparing the EHF and MetService methods showed that they both identified the most heatwave days in the month of January. Across all EHF heatwaves, 44% of all identified EHF heatwave days occurred in the month of January, 33% in February, and 17% in December (Figure 15). For EHF 'severe' heatwaves, there were similar findings, with 41% of heatwave days occurring in January, and 32% in February.

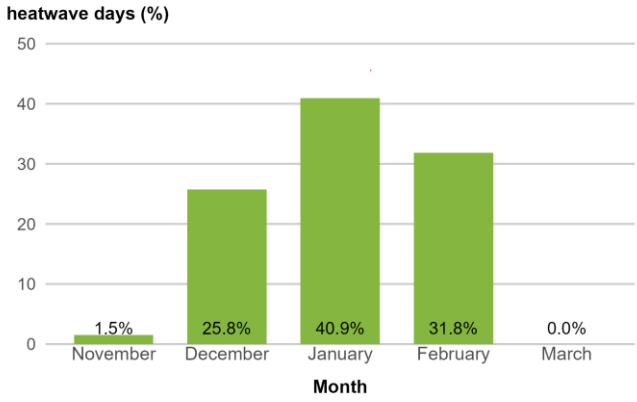
Using the MetService approach with a 31°C/23°C threshold found 44% of heatwave days occurred in January, and 36% occurred in February. For the 32°C/23°C threshold, January and February had equal numbers of heatwave days (about 44% each) (Figure 15).

Figure 15: Distribution of heatwave days by month (percentage of heatwave days, among all heatwave days), Canterbury, 2000/01 to 2020/21

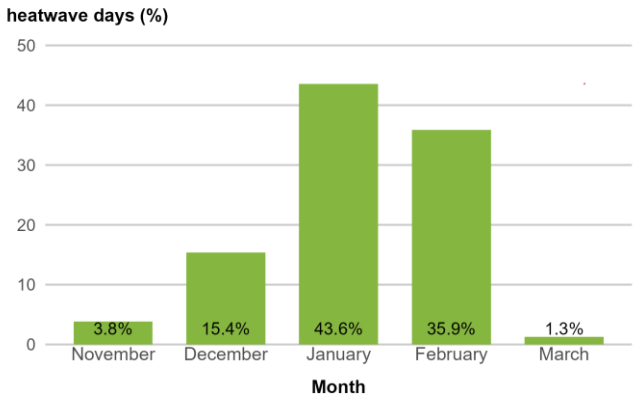
EHF (All heatwaves)



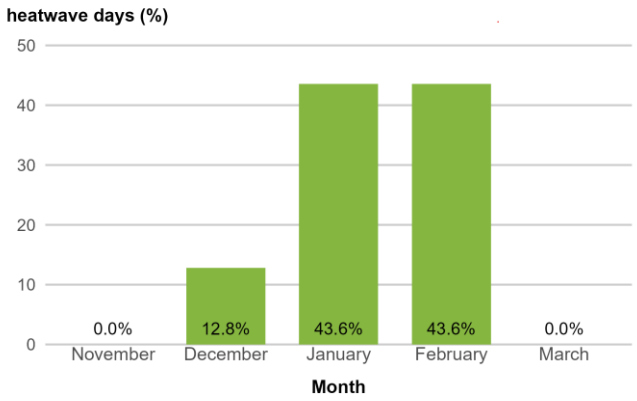
EHF (severe heatwaves)



MetService (Threshold: 31°C/23°C)



MetService (Threshold: 32°C/23°C)



Both the EHF and MetService approaches found that recent summers had the worst heatwaves

Table 2 presents the highest-ranked summer seasons for the number of heatwave episodes, number of heatwave days, and excess temperature, according to the EHF and MetService approaches. This table shows that summer seasons 2015/16, 2017/18, 2018/19 and 2019/20 appeared commonly in the top three worst seasons, for both the EHF and MetService approaches, regardless of the measure used (Table 2).

This is consistent with results from NIWA's seven station temperature series, which found the years 1998, 1999, 2016, 2018, 2019, 2021 and 2022 were the warmest years on record since measurements began in 1909 (NIWA nd).

Table 2: Top five worst summer seasons for (i) number of heatwave episodes, (ii) number of heatwave days, and (iii) excess heat, according to EHF and MetService (31°C/23 threshold) approaches, Canterbury, 2000/01 to 2020/21

Rank of summer seasons (1 = highest number of heatwave days/episodes or excess heat)	Number of heatwave episodes		Number of heatwave days		Excess heat	
	EHF	MetService	EHF	MetService	EHF	MetService
1.	2018/19	2019/20	2017/18	2019/20, 2010/11 (=)	2017/18	2015/16
2.	2015/16	2018/19	2018/19		2015/16	2010/11
3.	2017/18, 2008/09 (=)	2010/11	2015/16	2018/19	2019/20	2020/21
4.		2015/16	2008/09	2015/16	2010/11	2019/20
5.	2019/20, 2007/08 (=)	2017/18, 2013/14, 2012/13, 2008/09, 2007/08, 2000/01 (=)	2019/20	2020/21, 2017/18, 2012/13, 2008/09 (=)	2008/09	2008/09

Note: An equals sign (=) shows that the seasons had the same number of heatwave episodes/days, so have the same ranking.

The MetService approach identified much shorter and hotter heatwave episodes than the EHF method

Figure 16 shows all heatwaves for each method, by the duration of heatwave episodes (in days) versus the average daily maximum temperatures (T_{max}). The MetService approach tends to identify short but very hot heatwaves. The EHF approach, on the other hand, identified longer and relatively cooler heatwaves (ie lower overall average daily maximum temperature). EHF severe heatwaves lay between these two extremes.

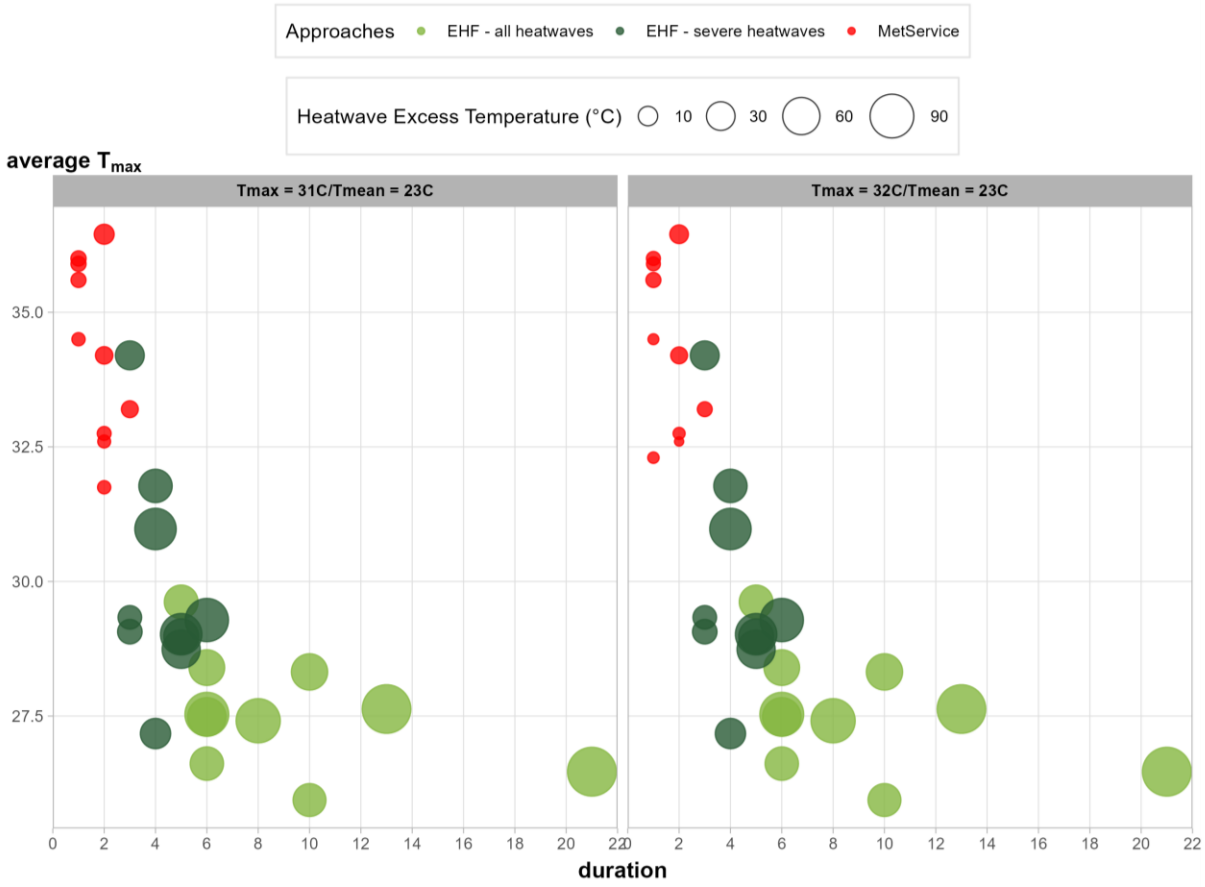
Figure 16: Comparison of heatwave duration (days) versus average T_{max}, Canterbury, 2000/01 to 2020/21



The ten worst heatwaves episodes for each approach also show that the MetService approach identified short and hot heatwave episodes

When looking at only the ten worst heatwave episodes identified by each approach (based on excess temperature), similar patterns emerged (Figure 17). The MetService approach still identified much hotter and shorter heatwaves than the EHF, while EHF severe heatwaves lay between the two. These results suggest that the different heatwave definitions are picking up on somewhat different heatwave periods with different characteristics.

Figure 17: Duration (days) and average daily maximum temperature (T_{max}) for the ten worst heatwave episodes for EHF heatwaves, EHF severe heatwaves, and MetService heat alert approach, Canterbury, 2000/01–2020/21



Association between heatwave periods and daily mortality

This section presents graphs for the summer seasons of 2015/16 (Figure 18), 2017/18 (Figure 19), 2018/19 (Figure 20), and 2019/20 (Figure 21), which had some of the worst heatwave episodes overall (as above). For each summer season, the graph shows daily mortality, daily maximum temperatures, and identified heatwave periods.

The EHF and MetService heatwave approaches mostly identified similar heatwave periods

Overall, the EHF and MetService heatwave approaches mostly identified similar time periods of heatwaves and hot weather. In particular, the MetService approach (using the main threshold of 31°C/23°C) often aligned with the EHF severe heatwaves.

EHF heatwaves tended to represent longer and more extended periods of hot weather, while the MetService approach tended to identify single days or very short periods of noticeably hotter weather (based on daily maximum temperatures). These findings can be seen across all four summer seasons shown.

The heatwave periods identified sometimes correlated with higher observed daily mortality, although not necessarily in the 2015/16 summer season.

Figure 18: Heatwave episodes during the 2015/16 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Canterbury

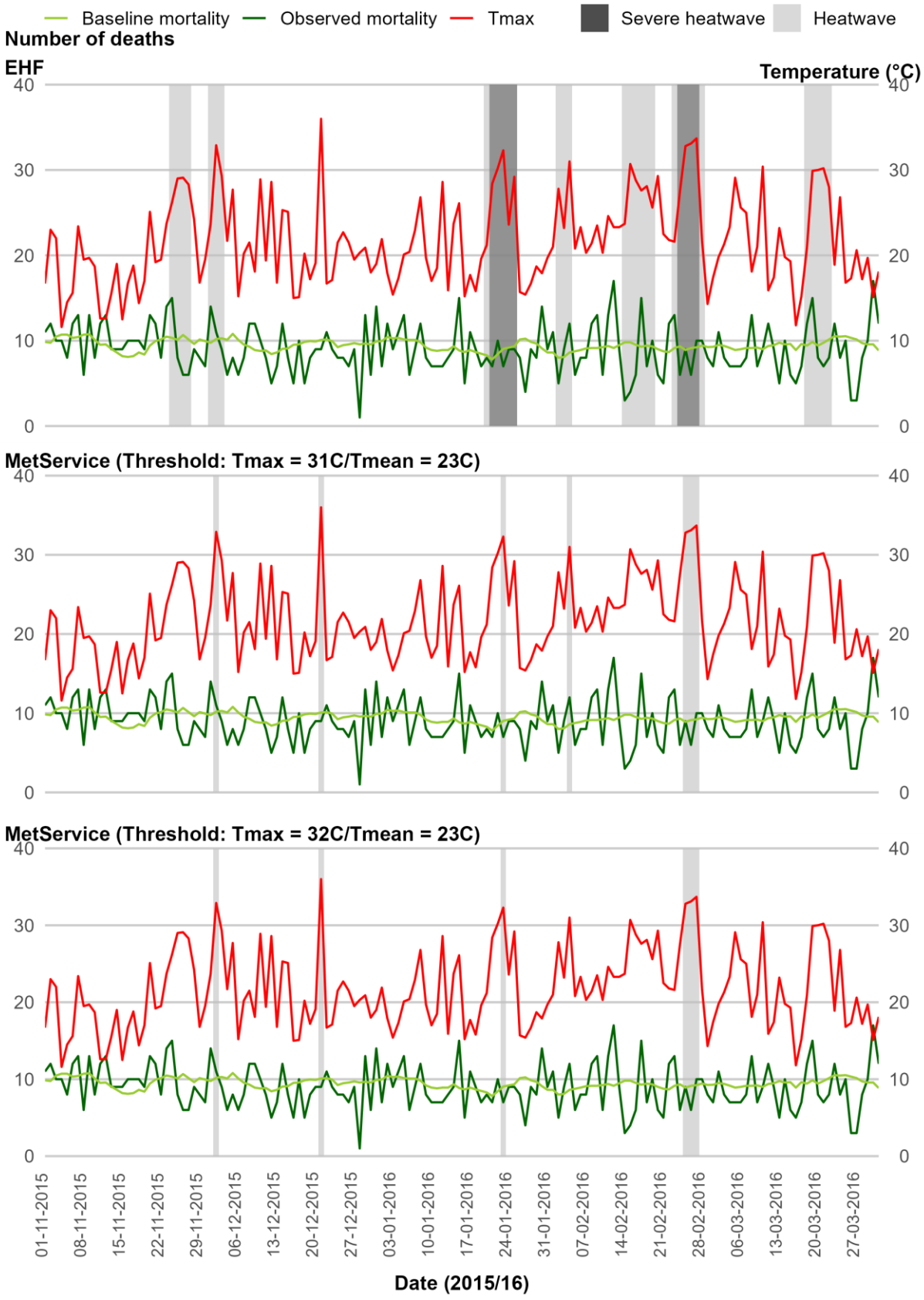


Figure 19: Heatwave episodes during the 2017/18 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Canterbury

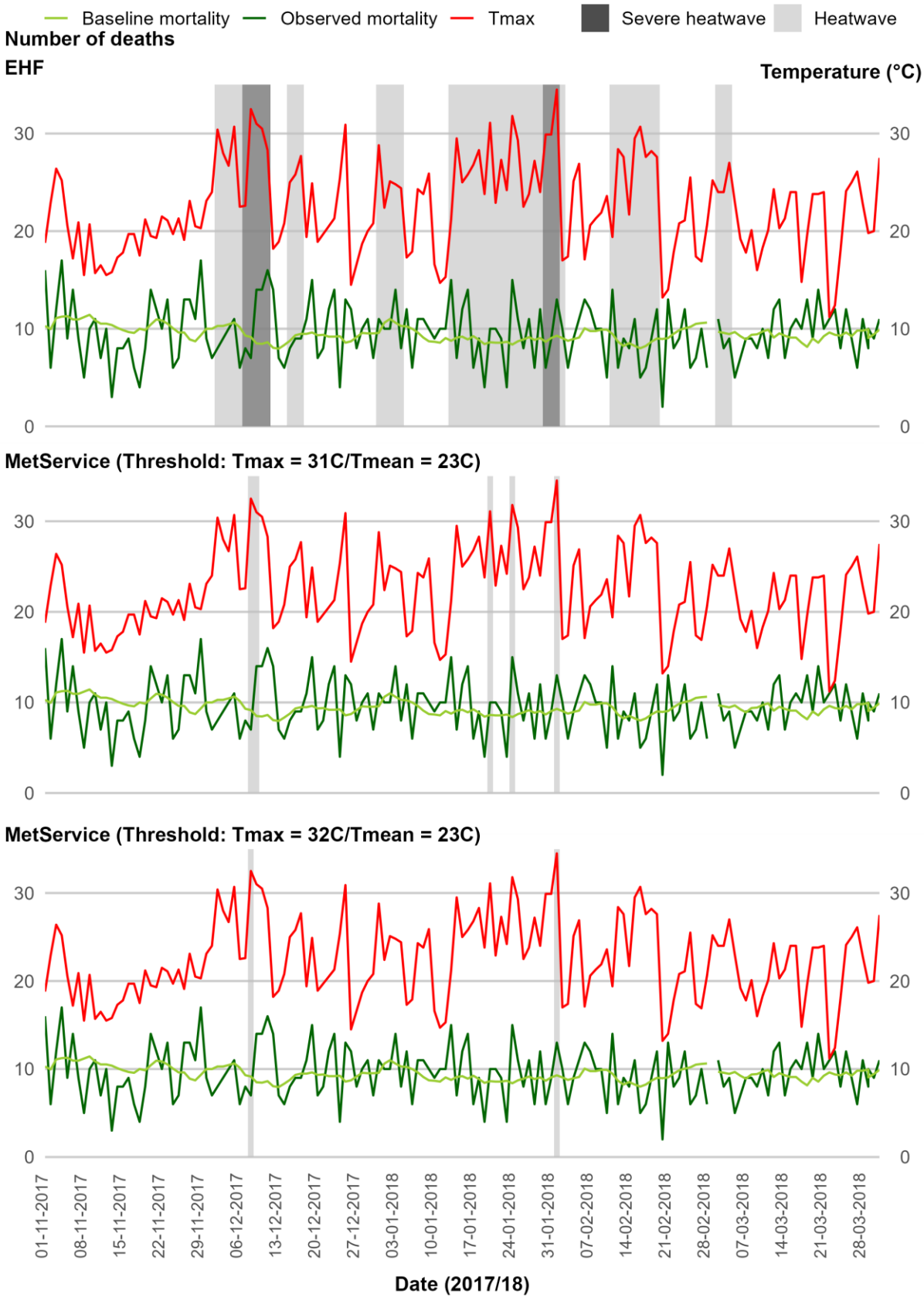
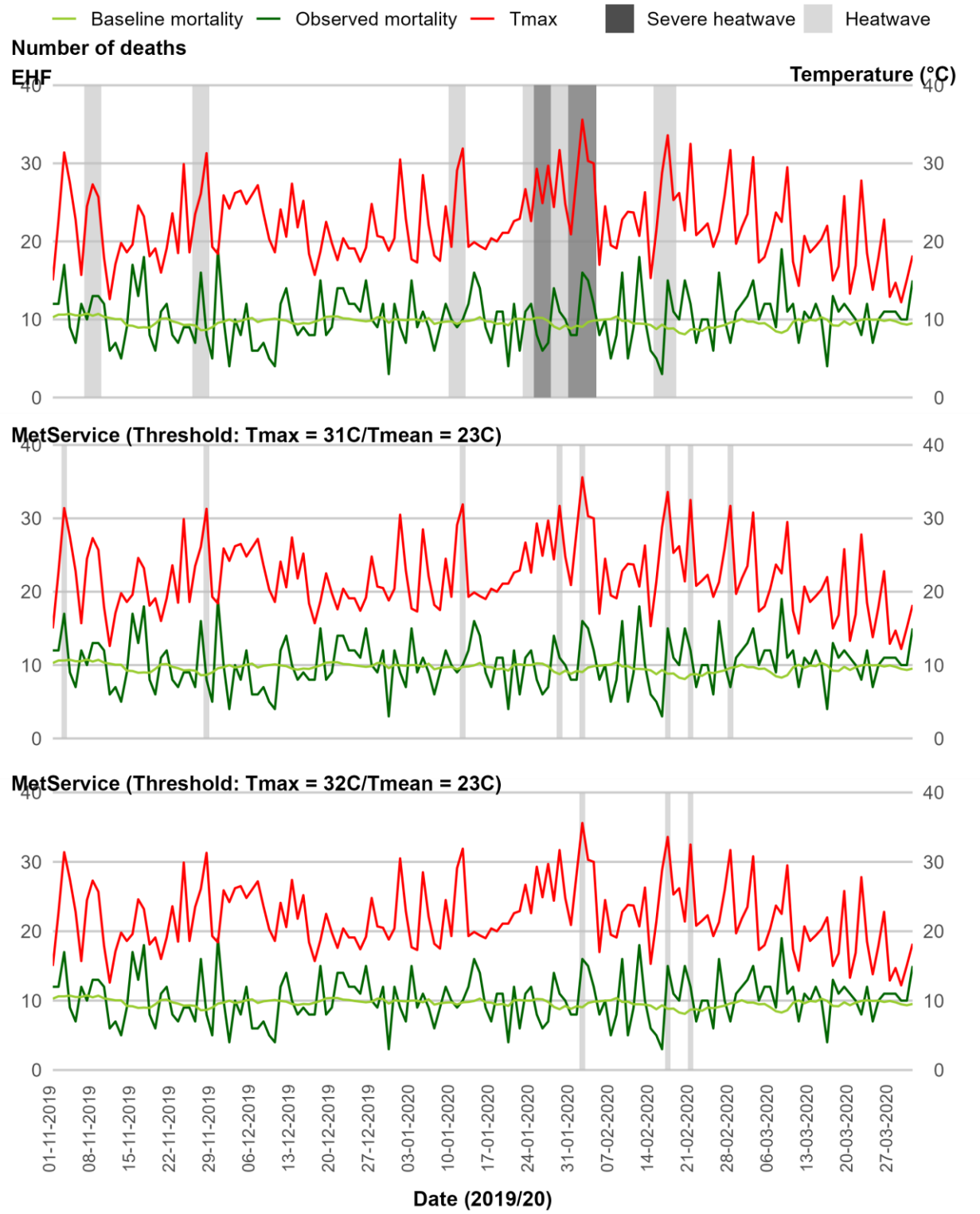


Figure 20: Heatwave episodes during the 2018/19 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Canterbury



Figure 21: Heatwave episodes during the 2019/20 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Canterbury



Excess mortality during heatwaves

A retrospective analysis of the summer seasons from 2000/01 to 2020/21 was carried out to quantify excess mortality during heatwave episodes.

Both the EHF and MetService approach found significant excess mortality during Canterbury heatwaves across the study period

Overall, the EHF had the highest estimated number of excess deaths on identified heatwave days across the study period (114.2 excess deaths, 95% confidence interval 0.3 to 231) (Table 3, Figure 22). The EHF also identified the most heatwave days, at 367 heatwave days.

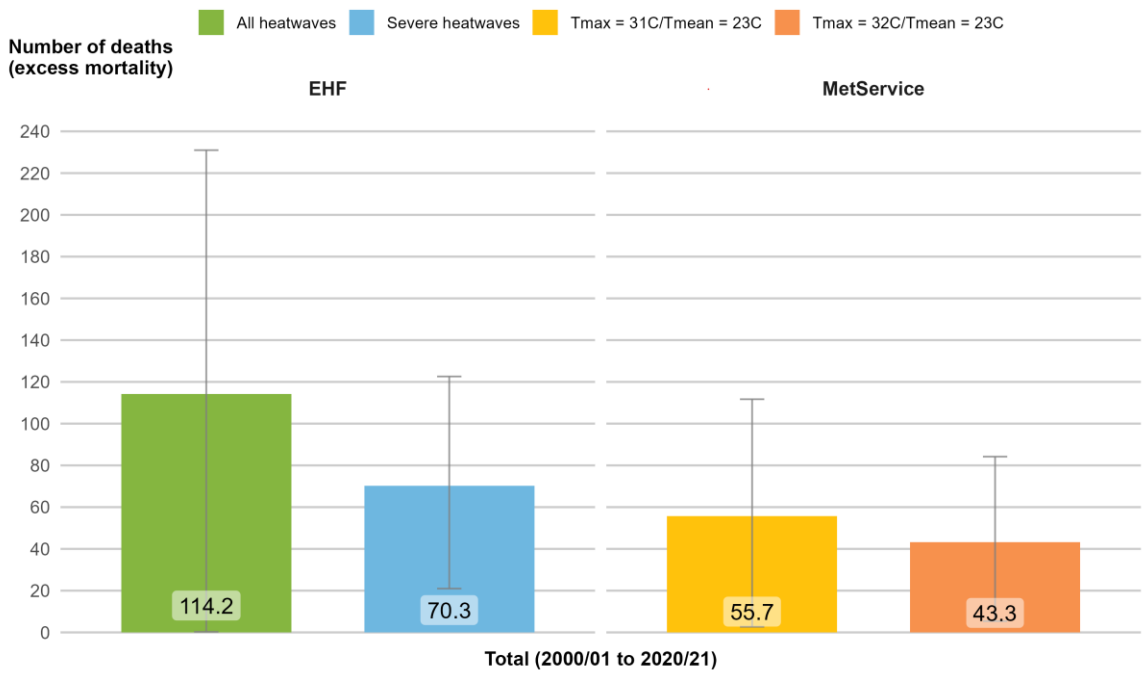
The EHF 'severe' heatwave definition identified 18 severe heatwave episodes and 66 severe heatwave days, which overall were associated with 70.3 excess deaths (95% CI: 21.0 to 122.6).

The MetService approach with threshold 31°C/23°C resulted in an estimated 55.7 excess deaths (95% CI: 2.7 to 111.7) during 78 heat alert days over 67 episodes. Many of these heat alert days were single day heat alert episodes. The MetService approach with a higher threshold of T_{max} = 32°C identified fewer heatwave episodes (33 heatwave episodes) and lower excess mortality (43.3 deaths, 95% CI: 5.4 to 84.2).

Table 3: Summary of heatwave episodes, heatwave days, and excess mortality due to heatwaves, EHF and MetService approaches, total (2000/01 to 2020/21), Canterbury

Method	Heatwave episodes	Heatwave days	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)	
EHF (all heatwaves)	75	367	3316.8	3431	114.2 (0.3 to 231.0)	*
EHF (severe/extreme heatwaves)	18	66	587.7	658	70.3 (21.0 to 122.6)	*
MetService (31°C/23°C)	67	78	703.3	759	55.7 (2.7 to 111.7)	*
MetService (32°C/23°C)	33	39	350.7	394	43.3 (5.4 to 84.2)	*

Figure 22: Number of cumulative excess deaths during heatwave episodes, total (2000/01 to 2020/21), Canterbury

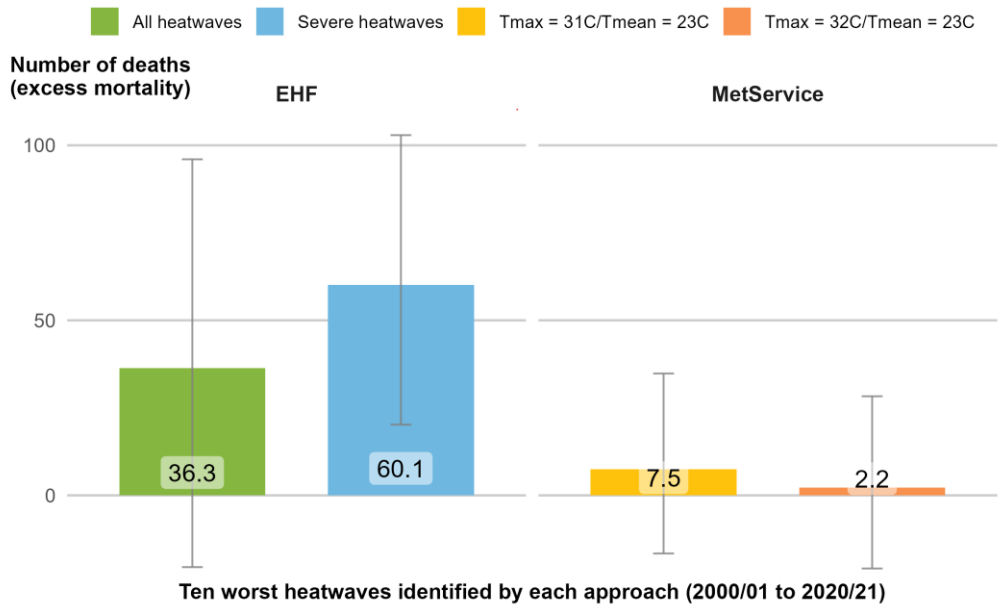


Notes: 95% confidence intervals are shown.

Among the ten worst heatwave episodes per approach, EHF severe heatwaves were associated with significant excess mortality overall

Figure 23 focuses on the ten worst episodes (based on excess temperature) identified by EHF and MetService approaches. The EHF severe heatwave definition identified the highest number of excess deaths during the ten worst episodes (60.1 excess deaths), the only statistically significant result. The main EHF identified 36.3 excess deaths, while the MetService approach identified the smallest number of excess deaths, using both threshold levels.

Figure 23: Number of excess deaths during the ten worst heatwave episodes identified by each approach, 2000/01 to 2020/21, Canterbury



Notes: 95% confidence intervals are shown.

Table 4 shows the specific ten worst heatwave episodes by each approach. Few of the heatwave episodes for any approach had significant excess mortality, due to low counts for daily mortality. Results suggest that the four main heatwave periods in Canterbury with statistically significant excess mortality occurred during January 2002, December 2010, December 2017, and December 2020. Heatwaves identified by the EHF approach were substantially longer (in days) than the EHF severe heatwaves, or the MetService heat alert periods (which were often a single day in duration).

Table 4: Heatwave characteristics for the ten worst heatwave episodes by each approach (2000/01 to 2020/21), Canterbury

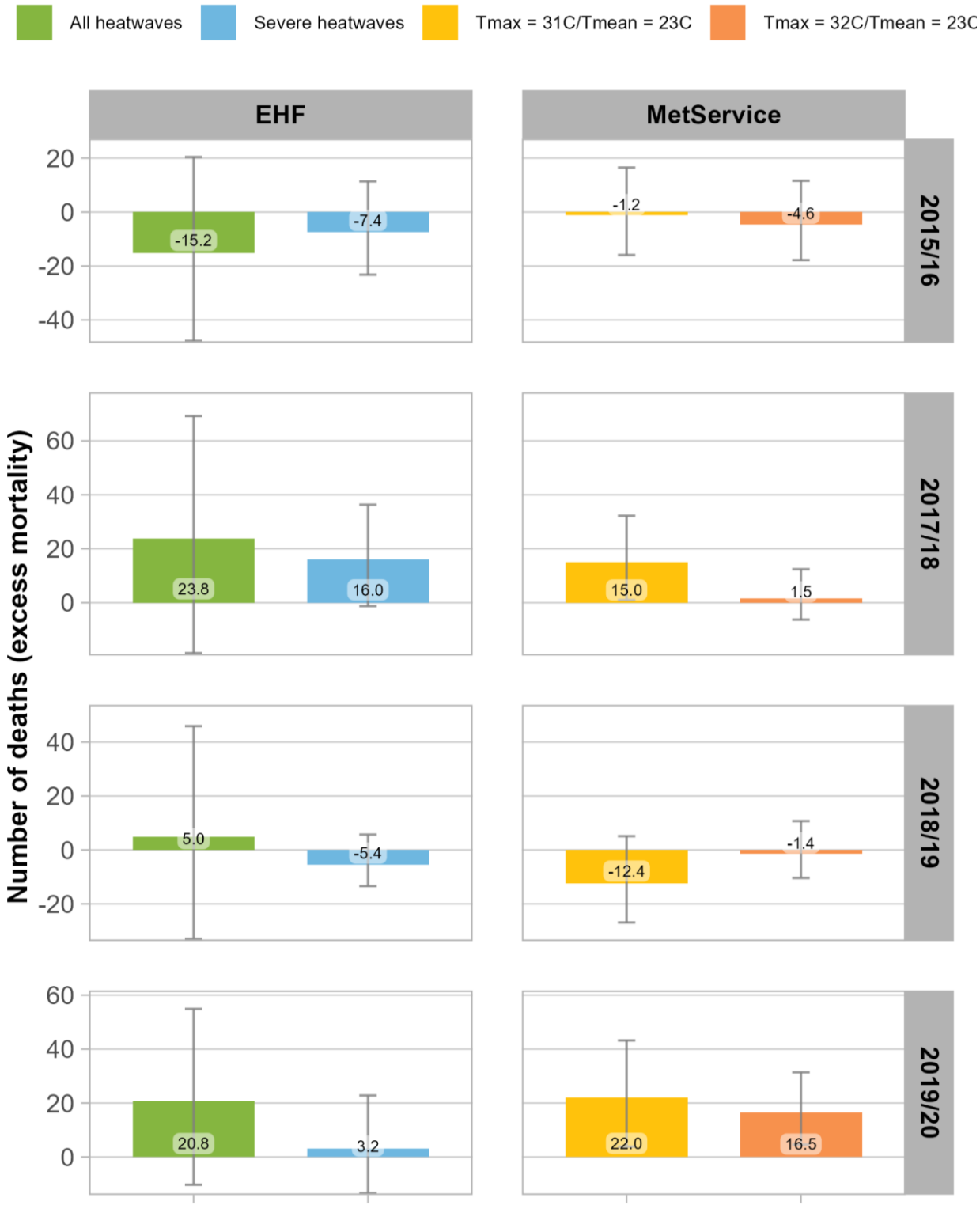
Method	Heatwave episodes	Duration (days)	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF (all heatwaves)	29/11/2001 – 04/12/2001	6	51.6	43	-8.6 (-20.5 to 6.3)
	01/02/2005 – 10/02/2005	10	95.2	79	-16.2 (-32.7 to 3.3)
	05/01/2009 – 10/01/2009	6	54.4	62	7.6 (-6.9 to 25.1)
	16/12/2010 – 23/12/2010	8	69.7	94	24.3 (6.3 to 45.3) *
	20/01/2016 – 25/01/2016	6	52.1	50	-2.1 (-15.0 to 13.8)
	23/02/2016 – 28/02/2016	6	55.2	54	-1.2 (-14.6 to 15.3)
	02/12/2017 – 11/12/2017	10	95.8	103	7.2 (-11.7 to 29.1)
	13/01/2018 – 02/02/2018	21	186.0	201	15.0 (-11.8 to 44.8)
	23/01/2020 – 04/02/2020	13	123.9	138	14.1 (-8.0 to 39.1)
	24/01/2021 – 28/01/2021	5	47.8	44	-3.8 (-15.8 to 11.3)
	Total		**831.7**	**868**	**36.3 (-20.5 to 96.0)**
EHF (Severe/extreme heatwaves)	30/11/2001 – 03/12/2001	4	35.1	34	-1.1 (-11.6 to 12.4)
	01/01/2002 – 03/01/2002	3	24.4	43	18.6 (6.7 to 33.5) *
	06/01/2009 – 09/01/2009	4	35.8	48	12.2 (-0.4 to 27.8)
	17/12/2010 – 22/12/2010	6	51.9	75	23.1 (7.1 to 42.1) *

	21/01/2016 – 25/01/2016	5	43.8	42	-1.8 (-13.5 to 13.0)	
	24/02/2016 – 27/02/2016	4	36.6	31	-5.6 (-15.5 to 7.4)	
	07/12/2017 – 11/12/2017	5	44.0	59	15.0 (0.9 to 32.1)	*
	19/02/2019 – 21/02/2019	3	26.4	21	-5.4 (-13.4 to 5.7)	
	31/01/2020 – 04/02/2020	5	46.6	59	12.4 (-1.7 to 29.5)	
	25/01/2021 – 27/01/2021	3	29.3	22	-7.3 (-15.5 to 4.0)	
	Total		**373.9**	**434**	**60.1 (20.2 to 102.9)**	*
MetService (31°C/23°C)	07/01/2009 – 08/01/2009	2	17.9	23	5.1 (-3.3 to 16.6)	
	01/01/2010 – 02/01/2010	2	20.9	18	-2.9 (-10.2 to 7.5)	
	06/02/2011 – 06/02/2011	1	8.4	7	-1.4 (-5.6 to 6.0)	
	21/12/2015 – 21/12/2015	1	10.1	9	-1.1 (-6.0 to 7.0)	
	25/02/2016 – 27/02/2016	3	27.3	25	-2.3 (-11.1 to 9.6)	
	08/12/2017 – 09/12/2017	2	17.6	21	3.3 (-4.6 to 14.5)	
	01/02/2018 – 01/02/2018	1	9.3	13	3.7 (-2.4 to 12.9)	
	02/02/2020 – 02/02/2020	1	9.0	16	7.0 (0.1 to 17.0)	*
	26/01/2021 – 27/01/2021	2	19.5	15	-4.5 (-11.1 to 5.2)	
	23/02/2021 – 24/02/2021	2	17.4	18	0.6 (-6.7 to 11.0)	
	Total		**157.4**	**165**	**7.5 (-16.6 to 34.8)**	
MetService (32°C/23°C)	07/01/2009 – 08/01/2009	2	17.9	23	5.1 (-3.3 to 16.6)	
	01/01/2010 – 02/01/2010	2	20.9	18	-2.9 (-10.2 to 7.5)	
	06/02/2011 – 06/02/2011	1	8.4	7	-1.4 (-5.6 to 6.0)	
	21/12/2015 – 21/12/2015	1	10.1	9	-1.1 (-6.0 to 7.0)	
	23/01/2016 – 23/01/2016	1	9.0	7	-2.0 (-6.2 to 5.4)	
	25/02/2016 – 27/02/2016	3	27.3	25	-2.3 (-11.1 to 9.6)	
	01/02/2018 – 01/02/2018	1	9.3	13	3.7 (-2.4 to 12.9)	
	02/02/2020 – 02/02/2020	1	9.0	16	7.0 (0.1 to 17.0)	*
	26/01/2021 – 27/01/2021	2	19.5	15	-4.5 (-11.1 to 5.2)	
	23/02/2021 – 24/02/2021	2	17.4	18	0.6 (-6.7 to 11.0)	
	Total		**148.8**	**151**	**2.2 (-20.9 to 28.3)**	

The 2017/18 and 2019/20 summer seasons showed overall significant excess mortality during heatwave episodes

Figure 24 shows the overall excess mortality during all heatwave periods during four example summer seasons: 2015/16, 2017/18, 2018/19, and 2019/20. These results show that, using the MetService approach, the only statistically significant results for excess mortality were during the summer seasons of 2017/18 and 2019/20. The summer seasons of 2015/16 and 2018/19 had no statistically significant excess deaths during heatwaves, either overall or during specific heatwave periods (Table 5, Table 7). Small mortality numbers may be driving some of these findings.

Figure 24: Number of excess deaths, 2015/16, 2017/18, 2018/19 and 2019/20, Canterbury



Notes: 95% confidence intervals are shown.

Table 5: Heatwave characteristics for each approach, 2015/16 season, Canterbury

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF (All heatwaves)	24/11/2015 – 27/11/2015	41.2	35	-6.2 (-16.8 to 7.5)
	01/12/2015 – 03/12/2015	30.2	34	3.8 (-6.7 to 17.3)
	20/01/2016 – 25/01/2016	52.1	50	-2.1 (-15.0 to 13.8)
	02/02/2016 – 04/02/2016	24.7	26	1.3 (-7.7 to 13.4)
	14/02/2016 – 19/02/2016	57.2	45	-12.2 (-24.4 to 3.0)
	23/02/2016 – 28/02/2016	55.2	54	-1.2 (-14.6 to 15.3)
	18/03/2016 – 22/03/2016	48.6	50	1.4 (-11.5 to 17.3)
	Total	**309.2**	**294**	**-15.2 (-47.8 to 20.4)**
EHF (Severe/extreme heatwaves)	21/01/2016 – 25/01/2016	43.8	42	-1.8 (-13.5 to 13.0)
	24/02/2016 – 27/02/2016	36.6	31	-5.6 (-15.5 to 7.4)
	Total	**80.4**	**73**	**-7.4 (-23.2 to 11.4)**
MetService (31°C/23°C)	02/12/2015 – 02/12/2015	10.2	11	0.8 (-4.7 to 9.5)
	21/12/2015 – 21/12/2015	10.1	9	-1.1 (-6.0 to 7.0)
	23/01/2016 – 23/01/2016	9.0	7	-2.0 (-6.2 to 5.4)
	04/02/2016 – 04/02/2016	8.6	12	3.4 (-2.4 to 12.4)
	25/02/2016 – 27/02/2016	27.3	25	-2.3 (-11.1 to 9.6)
	Total	**65.2**	**64**	**-1.2 (-15.9 to 16.5)**
MetService (32°C/23°C)	02/12/2015 – 02/12/2015	10.2	11	0.8 (-4.7 to 9.5)
	21/12/2015 – 21/12/2015	10.1	9	-1.1 (-6.0 to 7.0)
	23/01/2016 – 23/01/2016	9.0	7	-2.0 (-6.2 to 5.4)
	25/02/2016 – 27/02/2016	27.3	25	-2.3 (-11.1 to 9.6)
	Total	**56.6**	**52**	**-4.6 (-17.8 to 11.6)**

Table 6: Heatwave characteristics for each approach, 2017/18 season, Canterbury

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF (All heatwaves)	02/12/2017 – 11/12/2017	95.8	103	7.2 (-11.7 to 29.1)
	15/12/2017 – 17/12/2017	27.6	26	-1.6 (-10.6 to 10.5)
	31/12/2017 – 04/01/2018	52.1	53	0.9 (-12.4 to 17.2)
	13/01/2018 – 02/02/2018	186	201	15.0 (-11.8 to 44.8)
	11/02/2018 – 19/02/2018	77.0	80	3.0 (-13.6 to 22.6)
	02/03/2018 – 04/03/2018	28.7	28	-0.7 (-10.1 to 11.8)
	Total	**467.2**	**491**	**23.8 (-18.7 to 69.2)**
EHF (Severe/extreme heatwaves)	07/12/2017 – 11/12/2017	44.0	59	15.0 (0.9 to 32.1) *
	30/01/2018 – 01/02/2018	27.0	28	1.0 (-8.4 to 13.5)
	Total	**71.0**	**87**	**16.0 (-1.3 to 36.3)**
MetService (31°C/23°C)	08/12/2017 – 09/12/2017	17.6	21	3.4 (-4.6 to 14.5)
	20/01/2018 – 20/01/2018	8.6	10	1.4 (-3.8 to 9.8)
	24/01/2018 – 24/01/2018	8.4	15	6.6 (0.0 to 16.3)
	01/02/2018 – 01/02/2018	9.3	13	3.7 (-2.4 to 12.9)
	Total	**43.9**	**59**	**15.0 (1.0 to 32.2) ***
MetService	08/12/2017 – 08/12/2017	9.2	7	-2.1 (-6.4 to 5.2)

(32°C/23°C)	01/02/2018 – 01/02/2018	9.3	13	3.7 (-2.4 to 12.9)
	Total	**18.5**	**20**	**1.5 (-6.3 to 12.4)**

Table 7: Heatwave characteristics for each approach, 2018/19 season, Canterbury

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF (All heatwaves)	01/01/2019 – 06/01/2019	60.3	62	1.7 (-12.8 to 19.2)
	08/01/2019 – 11/01/2019	37.0	34	-3.0 (-13.5 to 10.5)
	18/01/2019 – 23/01/2019	53.2	65	11.8 (-3.0 to 29.6)
	25/01/2019 – 01/02/2019	74.0	67	-7.0 (-22.1 to 11.1)
	03/02/2019 – 05/02/2019	28.4	26	-2.4 (-11.4 to 9.7)
	09/02/2019 – 15/02/2019	65.4	71	5.6 (-9.9 to 24.2)
	18/02/2019 – 22/02/2019	44.0	37	-7.0 (-17.9 to 7.0)
	25/03/2019 – 27/03/2019	27.7	33	5.3 (-5.0 to 18.6)
	Total	**390.0**	**295**	**5.0 (-33.0 to 45.9)**
EHF (Severe /extreme heatwaves)	19/02/2019 – 21/02/2019	26.4	21	-5.4 (-13.4 to 5.7)
	Total	**26.4**	**21**	**-5.4 (-13.4 to 5.7)**
MetService (31°C/23°C)	02/01/2019 – 02/01/2019	10.4	4	-6.4 (-9.3 to -0.2)
	19/01/2019 – 19/01/2019	8.6	9	0.4 (-4.5 to 8.5)
	23/01/2019 – 23/01/2019	9.3	13	3.7 (-2.4 to 12.9)
	30/01/2019 – 30/01/2019	9.1	4	-5.1 (-8.0 to 1.1)
	04/02/2019 – 05/02/2019	19.0	19	0.0 (-7.6 to 10.7)
	14/02/2019 – 14/02/2019	9.0	9	0.0 (-4.9 to 8.1)
	21/02/2019 – 21/02/2019	9.0	4	-5.0 (-7.9 to 1.2)
	Total	**74.4**	**62**	**-12.4 (-26.9 to 5.1)**
MetService (32°C/23°C)	23/01/2019 – 23/01/2019	9.3	13	3.7 (-2.4 to 12.9)
	30/01/2019 – 30/01/2019	9.1	4	-5.1 (-8.0 to 1.1)
	14/02/2019 – 14/02/2019	9.0	9	0.0 (-4.9 to 8.1)
	Total	**27.4**	**26**	**-1.4 (-10.4 to 10.7)**

Table 8: Heatwave characteristics for each approach, 2019/20 season, Canterbury

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF (All heatwaves)	07/11/2019 – 09/11/2019	32.0	36	4.0 (-6.8 to 17.8)
	26/11/2019 – 28/11/2019	26.5	31	4.5 (-5.4 to 17.5)
	10/01/2020 – 12/01/2020	29.0	29	0.0 (-9.6 to 12.6)
	23/01/2020 – 04/02/2020	123.9	138	14.1 (-8.0 to 39.1)
	15/02/2020 – 18/02/2020	35.8	34	-1.8 (-12.3 to 11.7)
	Total	**247.2**	**268**	**20.8 (-10.3 to 54.9)**
EHF (Severe/extreme heatwaves)	25/01/2020 – 27/01/2020	30.2	21	-9.2 (-17.2 to 1.9)
	31/01/2020 – 04/02/2020	46.6	59	12.4 (-1.7 to 29.5)
	Total	**76.8**	**80**	**3.2 (-13.4 to 22.8)**
MetService (31°C/23°C)	03/11/2019 – 03/11/2019	10.6	17	6.4 (-0.7 to 16.6)
	28/11/2019 – 28/11/2019	8.7	8	-0.7 (-5.2 to 7.1)
	12/01/2020 – 12/01/2020	9.8	10	0.2 (-5.0 to 8.6)

	29/01/2020 – 29/01/2020	8.8	11	2.2 (-3.3 to 10.9)	
	02/02/2020 – 02/02/2020	9.0	16	7.0 (0.1 to 17.0)	*
	17/02/2020 – 17/02/2020	8.8	15	6.2 (-0.4 to 15.9)	
	21/02/2020 – 21/02/2020	8.7	12	3.3 (-2.5 to 12.3)	
	Total	**74.0**	**96**	**22.0 (3.8 to 43.2)**	*****
MetService (32°C/23°C)	02/02/2020 – 02/02/2020	9.0	16	7.0 (0.1 to 17.0)	*
	17/02/2020 – 17/02/2020	8.8	15	6.2 (-0.4 to 15.9)	
	21/02/2020 – 21/02/2020	8.7	12	3.3 (-2.5 to 12.3)	
	Total	**26.5**	**43**	**16.5 (4.6 to 31.4)**	*****

Results for the Auckland study area

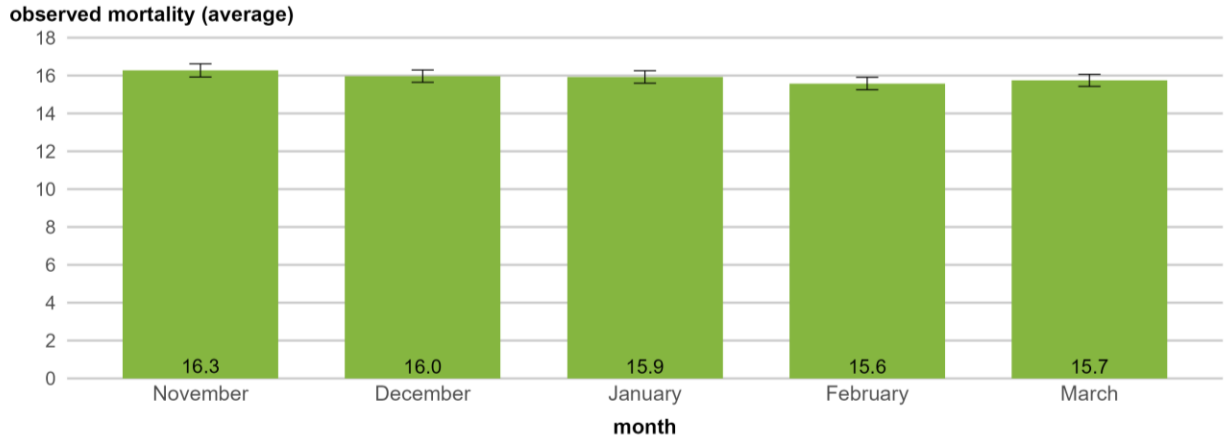
The Auckland region is quite different meteorologically from the Canterbury district. Auckland has relatively warm temperatures and higher humidity levels, but a lower highest recorded temperature than Canterbury. The results here are for the Auckland study area as described on page 16.

Average daily mortality and temperatures in summer

On average, about 16 people died daily during summer in Auckland

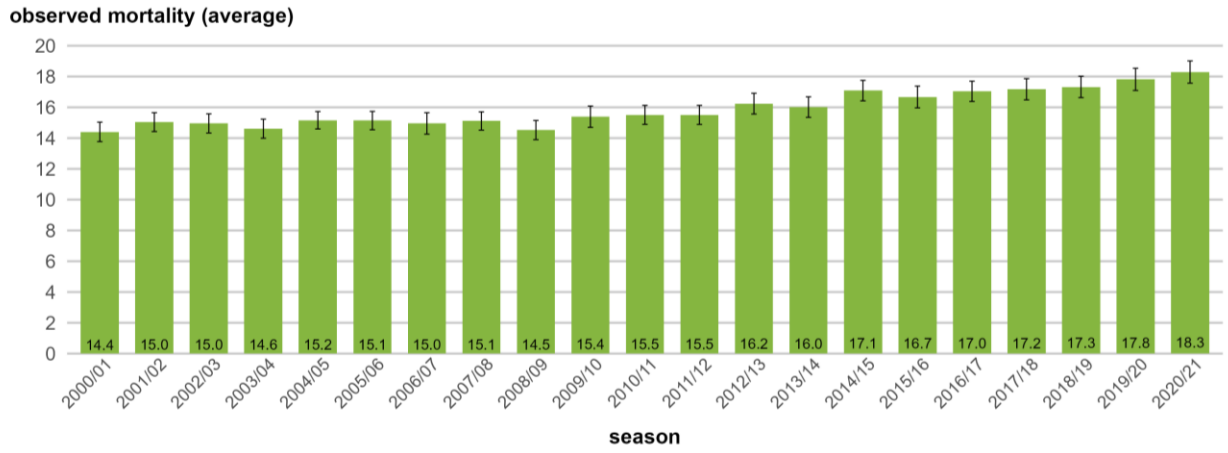
In the summer seasons from 2000/01 to 2020/21, there were 50,507 deaths in the Auckland study area, with a maximum of 33 and a minimum of 4 deaths per day. The average observed mortality was 15.9 deaths per day during the summer season (November–March) (Figure 25 and Figure 26).

Figure 25: Average observed daily number of deaths, by summer month, 2000/01–2020/21, Auckland



Notes: 95% confidence intervals are shown.

Figure 26: Average observed daily number of deaths in the summer season (November–March), 2000/01 to 2020/21, Auckland

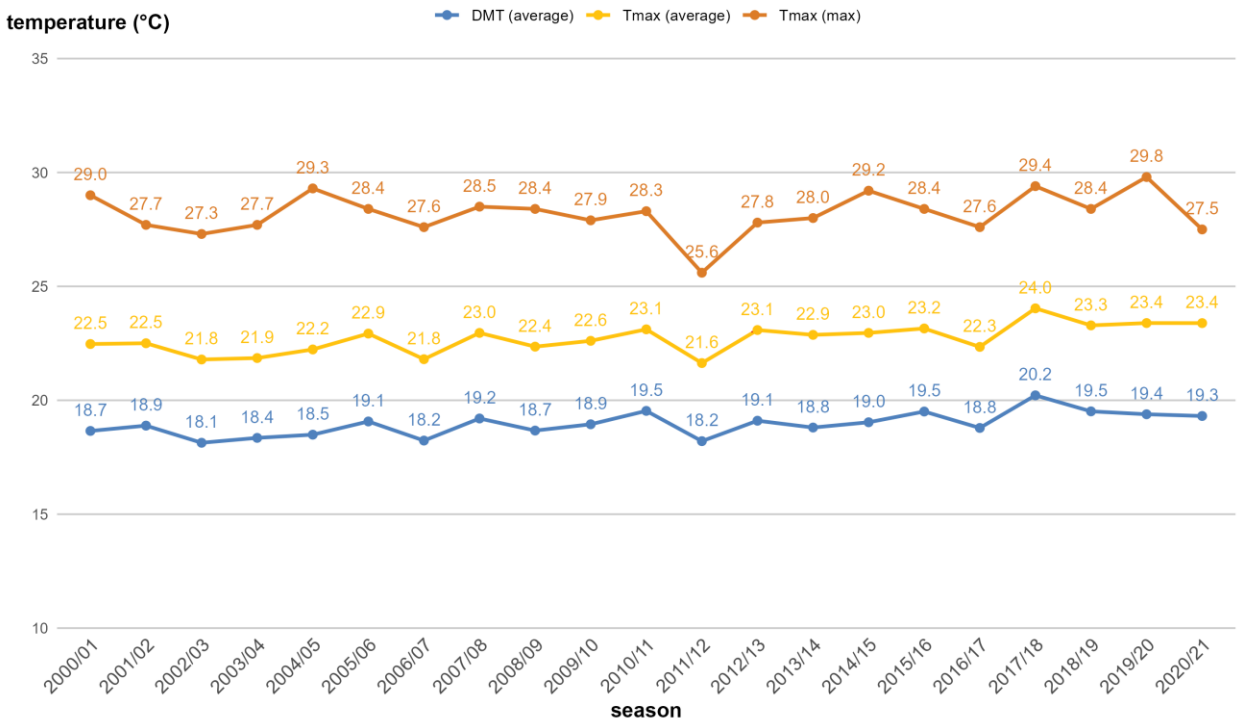


Notes: 95% confidence intervals are shown.

Daily maximum temperatures in Auckland were always below 30°C from 2001 to 2021

During the Auckland summer seasons from 2000/01 to 2020/21, the average daily maximum temperature was 22.7°C, and the average daily mean temperature (DMT) was 19.0°C. The highest recorded temperature was 29.8°C on 4/02/2020 (Figure 27).

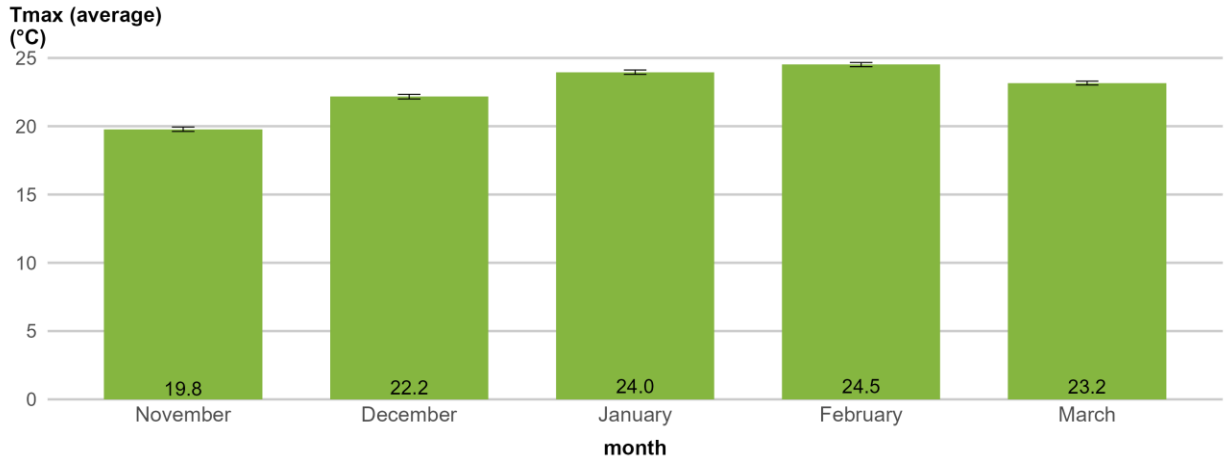
Figure 27: Highest recorded daily temperature (T_{max} (max)), average daily maximum temperature (T_{max} (average)), and average daily mean temperature (DMT (average)), per summer season, 2000/01 – 2020/21, Auckland



February was generally the hottest month in Auckland

On average, February had the highest average daily maximum temperature (T_{max}) in the study period (24.5°C), followed by January (24.0°C) and March (23.2°C) (Figure 28).

Figure 28: Average daily maximum temperature (T_{max}(average)), by summer month, Auckland, 2000/01–2020/21



Notes: 95% confidence intervals are shown.

Heatwaves identified using the Excess Heat Factor (EHF)

This section presents results using the Excess Heat Factor (EHF) to identify heatwaves in Auckland, during the summer seasons from 2000/01 to 2020/21. The Excess Heat Factor (EHF) identifies periods of three or more consecutive days where the daily mean temperature is high at a location, compared with the long-term daily mean temperature at that location (and taking into account an acclimatisation period of the previous 30 days). Severity thresholds have also been applied to determine if a heatwave is low-intensity, severe or extreme.

We present heatwave days and heatwave episodes using the main EHF definition, as well as the EHF 'severe heatwave' and 'extreme heatwave' thresholds.

The EHF heatwave definition identified many heatwaves in Auckland

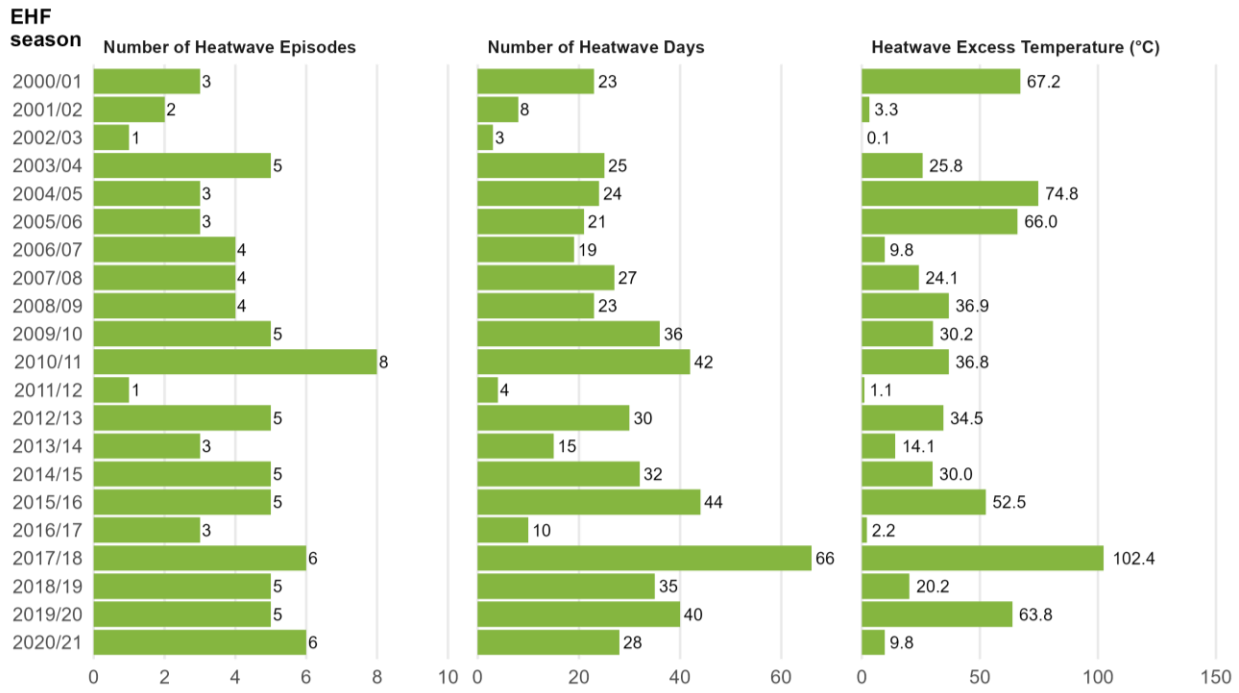
The EHF identified 555 heatwave days across 86 heatwave episodes from 2000/01 to 2020/21, in Auckland (Figure 29). On average, there were four EHF heatwave episodes per year in Auckland.

The 2017/18 summer season had the most heatwave days (66 days), across six episodes. This was followed by the 2015/16 summer season, with 44 heatwave days across five episodes. Heatwave episodes in the 2017/18 season were also considerably longer (11 days on average) than in 2015/16 (8.8 days on average).

The 2017/18 season also had the highest excess heat across all summer seasons. Excess heat was calculated as the sum of the (positive) EHF values for each heatwave episode, taking duration and temperature into consideration.

Figure 29: Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, EHF approach, 2000/01–2020/21, for all EHF heatwaves, Auckland

(i) All EHF heatwaves



Severe EHF heatwaves occurred several times in Auckland

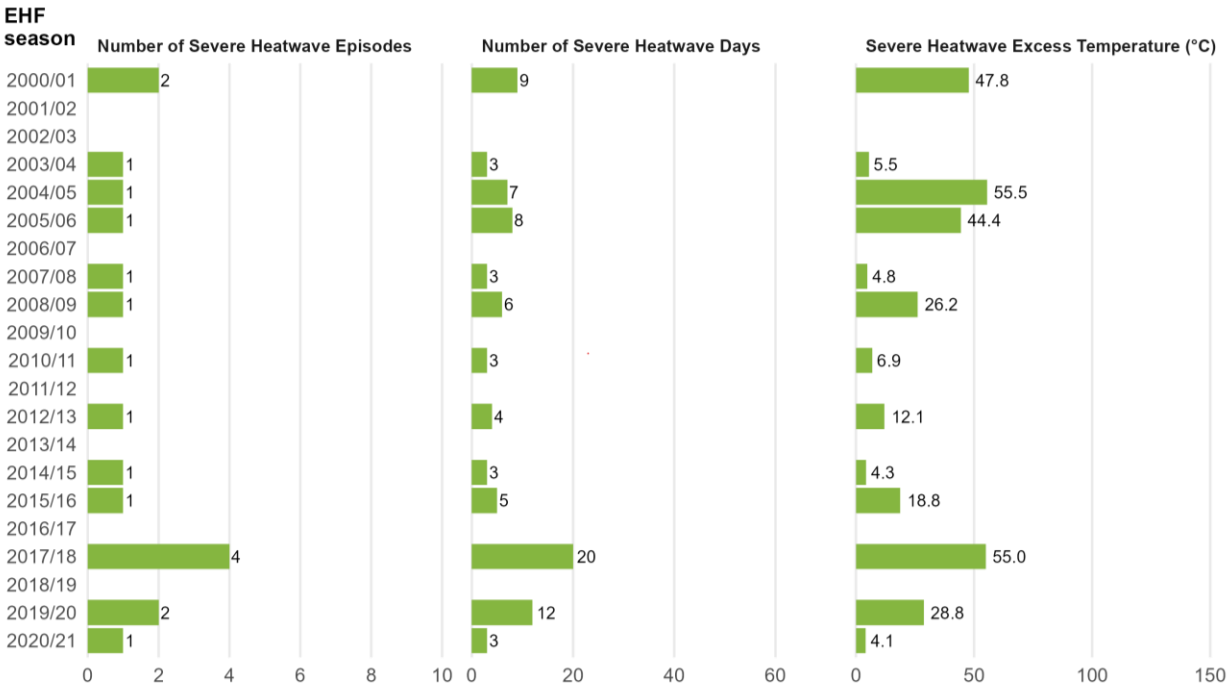
Using the EHF 'severe heatwave' and 'extreme heatwave' thresholds, a much smaller number of more severe heatwave episodes were identified in Auckland.

Overall, 86 days were identified as exceeding the EHF severe heatwave threshold, across 18 severe heatwave episodes. Of these, 8 days were also considered 'extreme heatwave' days, across two episodes (Figure 30).

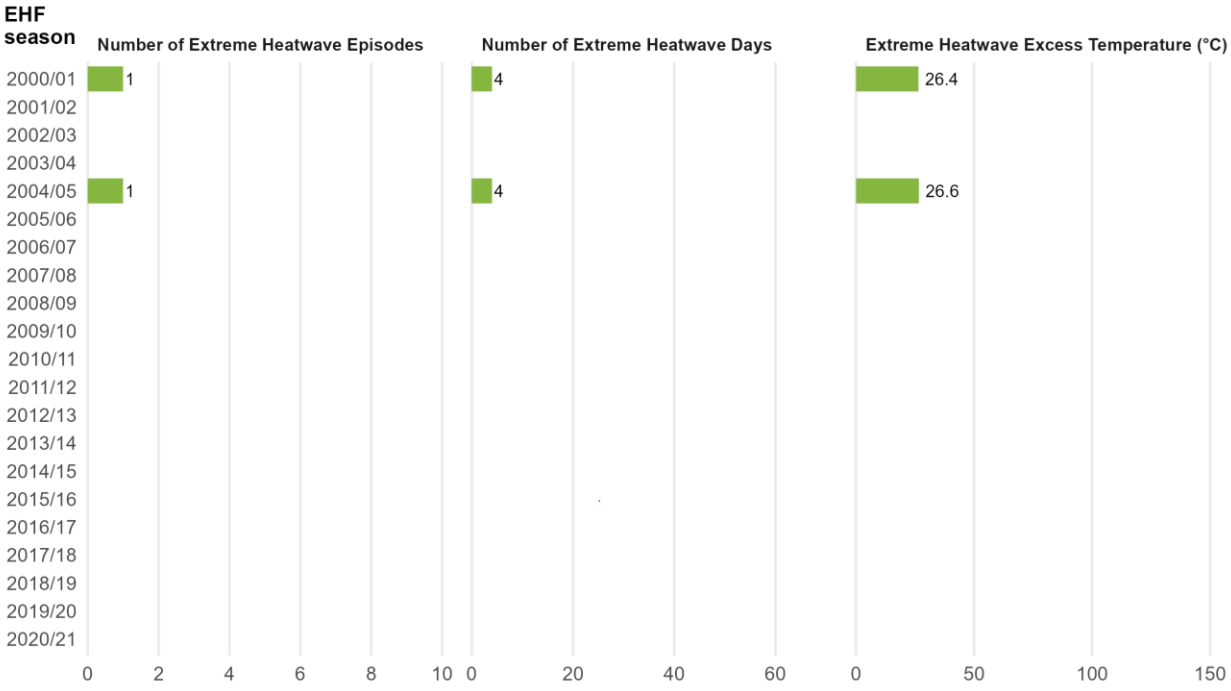
The 2017/18 season had the highest number of severe heatwave episodes, with 20 severe heatwave days and 4 episodes. On average, EHF severe heatwaves occurred about once per year. The only summer seasons with extreme heatwave days in Auckland were 2000/01 and 2004/05.

Figure 30: Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, EHF approach, 2000/01–2020/21, for (i) severe/extreme heatwaves, and (ii) extreme heatwaves, Auckland

(i) EHF severe heatwaves (including extreme heatwave days)



(ii) EHF extreme heatwaves



The EHF identified some long heatwave periods in Auckland

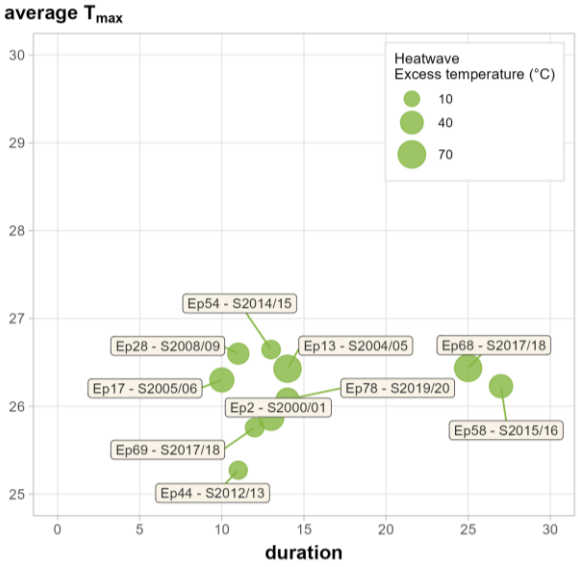
The ten worst EHF heatwave episodes were ranked based on the excess temperature, for both all EHF heatwaves, and EHF severe heatwaves (incluing extreme heatwave days) (Figure 31).

For these ten worst EHF heatwave episodes, the duration was between 10 and 27 days, and the average daily maximum temperature during these episodes ranged from 25°C to 27°C. The longest heatwave episodes identified with the EHF approach were in the summer seasons of 2015/16 (27 days) and 2017/18 (25 days).

The ten worst EHF severe heatwaves in Figure 31 showed higher average daily maximum temperatures (T_{max}), but shorter durations compared to all EHF heatwaves.

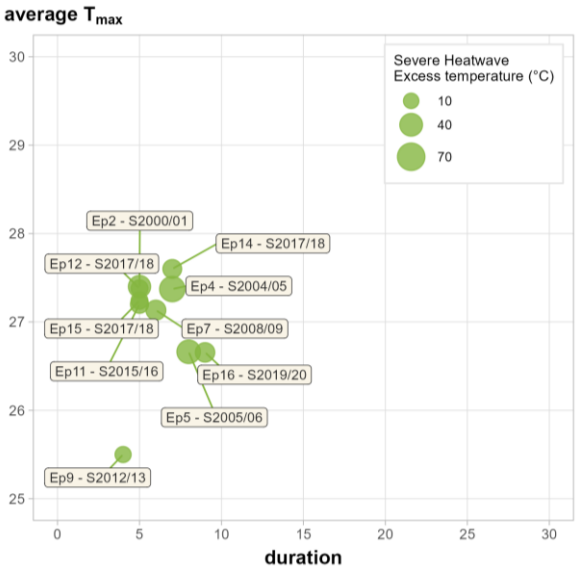
Figure 31: Ten worst heatwave and severe heatwave episodes (based on excess temperature) using the EHF approach, duration (days) and average daily maximum temperature (T_{max}), 2000/01–2020/21, for (i) all EHF heatwaves, and (ii) severe EHF heatwaves, Auckland

(i) All EHF heatwaves



Episode	Season	Duration	Heatwave Excess temperature (°C)	Tmax (average)
13	2004/05	14	68.3	26.4
68	2017/18	25	67.7	26.4
2	2000/01	13	54.3	25.9
17	2005/06	10	47.7	26.3
58	2015/16	27	43.0	26.2
78	2019/20	14	40.1	26.1
28	2008/09	11	32.2	26.6
69	2017/18	12	21.0	25.8
54	2014/15	13	20.6	26.6
44	2012/13	11	19.2	25.3

(ii) EHF severe heatwaves



Episode	Season	Duration	Severe Heatwave Excess temperature (°C)	Tmax (average)
4	2004/05	7	55.5	27.4
5	2005/06	8	44.4	26.7
2	2000/01	5	37.6	27.4
7	2008/09	6	26.2	27.1
16	2019/20	9	24.2	26.7
14	2017/18	7	21.5	27.6
11	2015/16	5	18.8	27.2
15	2017/18	5	14.5	27.2
12	2017/18	5	14.4	27.4
9	2012/13	4	12.1	25.5

Heatwaves identified using the MetService heat alert approach

This section presents heatwaves identified using the MetService heat alert approach for Auckland, in the summer seasons from 2000/01 to 2020/21. The MetService heat alert approach uses two thresholds to trigger a heat alert day: a one-day daily maximum temperature (T_{max}) threshold (ie the daily maximum temperature exceeds a certain temperature), and a two-day daily mean temperature (T_{mean}) threshold (ie, the daily mean temperature over two days exceeds a certain threshold, as well as the daily maximum temperature reaching at least 27°C both days). Temperature thresholds are specific to locations and are revised each year, and are designed to identify 'top end heat'.

For this report, we refer to MetService heat alert days as 'heatwave days', and episodes as 'heatwaves', although the MetService heat alert approach is not strictly a measure of heatwaves.

Four different MetService heat alert thresholds were tested for Auckland

In this section, we tested four different options for these two thresholds. For the one-day daily maximum temperature (T_{max}) threshold, the MetService has operationally used the values of 28°C, 29°C and 30°C for Auckland Aero since 2021/22. Additionally, we calculated the one-day daily maximum temperature threshold to be 27.8°C (using the MetService methodology of 99.5th percentile of previous 20 years), which could potentially be rounded down to 27°C. Furthermore, the MetService has recently increased the two-day daily mean temperature threshold from 23°C to 24°C.

We tested the four options in Table 9 as part of the sensitivity analysis, to investigate the impact of threshold levels on the number of heat alert (heatwave) days.

For main interpretation, the 28°C/23°C thresholds represent the calculated values of thresholds for 2021/22, using the MetService stated methodology. The 29°C/23°C thresholds represent the thresholds operationally used by MetService in 2022/23 and 2023/24 (with an increased threshold as a result of public feedback). The other two thresholds (27°C/23°C and 30°C/24°C) give outer bounds.

Table 9: Four MetService heat alert threshold combinations tested for the Auckland study area

Thresholds	Thresholds (full)	Description	Summer seasons in use by MetService
27°C/23°C	T_{max} = 27°C / T_{mean} = 23°C	The lower bound of thresholds (rounding down the one-day daily maximum temperature threshold of 27.8°C to 27°C)	–
28°C/23°C	T_{max} = 28°C / T_{mean} = 23°C	Calculated values of thresholds (rounding up the the one-day daily maximum temperature threshold of 27.8°C to 28°C)	2021/22
29°C/23°C	T_{max} = 29°C / T_{mean} = 23°C	Thresholds implemented operationally by MetService in response to public's feedback that the T_{max} was too low	2022/23, 2023/24
30°C/24°C	T_{max} = 30°C / T_{mean} = 24°C	Thresholds recently implemented by MetService	2024/25, 2025/26

The MetService approach identified a number of heatwave episodes, with the thresholds making a substantial difference

The MetService approach identified different heatwave days and episodes based on various thresholds for 1-day T_{max} and 2-day T_{mean}. The stricter the thresholds, the fewer heatwave days and episodes were detected.

Using the 27°C/23°C threshold, there were 125 heatwave days across 91 episodes. When using the 28°C/23°C threshold, the numbers dropped to 40 heatwave days across 24 episodes. Using the higher thresholds of 29°C/23°C and 30°C/24°C resulted in 29 and 6 heatwave days, respectively (Table 10).

Table 10: Number of heatwave episodes, heatwave days and excess temperature by MetService thresholds, Auckland, 2000/01–2020/21

Thresholds (T_{max} / T_{mean})	Number of heatwave episodes	Number of heatwave days	Excess temperature (°C)
27°C/23°C	91	125	170.5
28°C/23°C	24	40	56.7
29°C/23°C	13	29	59.4
30°C/24°C	3	6	6.7

The 2017/18 and 2019/20 summer seasons were some of the worst for heatwaves in Auckland, according to the MetService approach

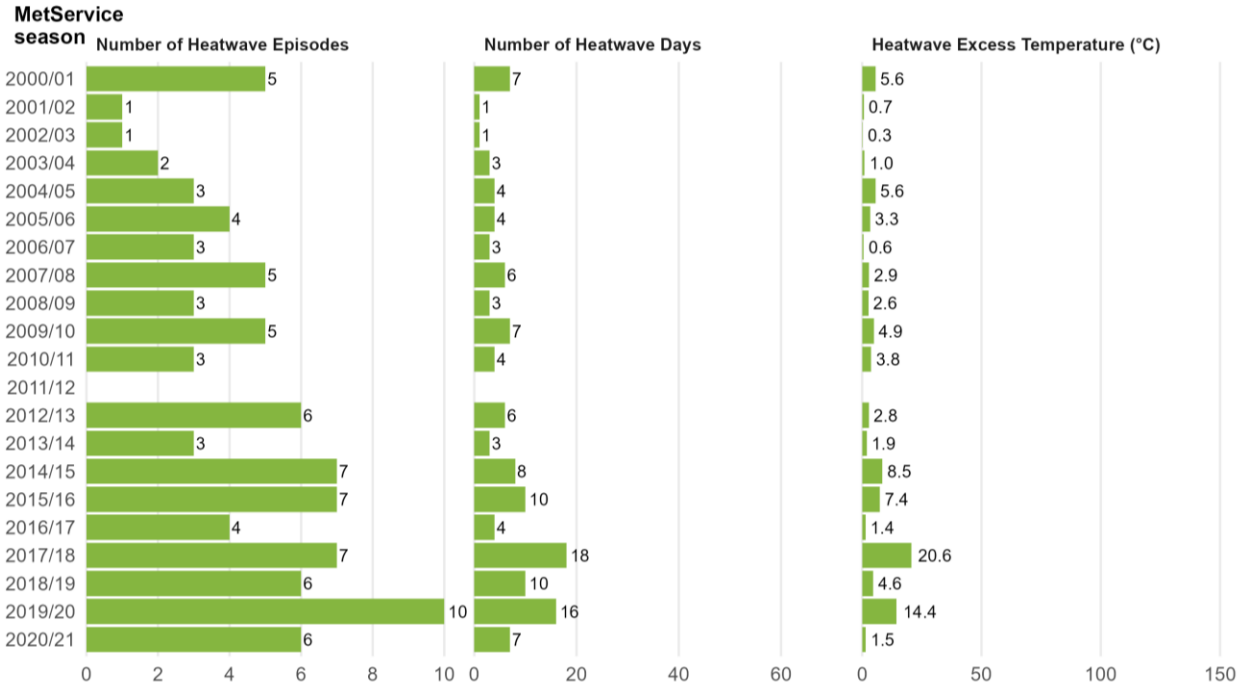
In Auckland, the 2017/18 and 2019/20 summer seasons had the highest numbers of MetService heatwave days and episodes across all threshold cases, followed by the 2014/15 season (Figure 32).

Using the 27°C/23°C threshold, heatwave episodes in the 2017/18 season were considerably longer than those in the 2019/20 season (2.3 days on average in the 2017/18 season, compared with 1.6 days on average in the 2019/20 season).

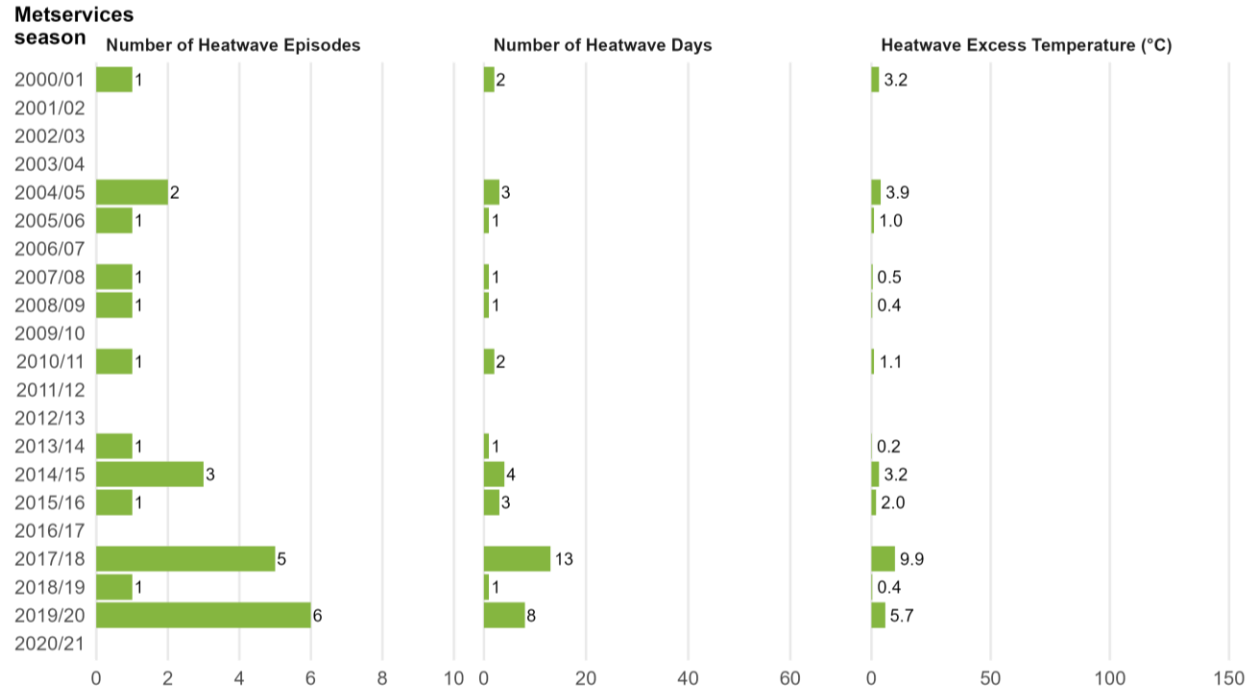
Using the higher thresholds of 28°C/23°C and 29°C/23°C resulted in far fewer heatwave episodes and days overall, with the highest number still occurring during the 2017/18 and 2019/20 summer seasons. The highest threshold of 30°C/24°C has historically only been met on six days across the 20 years from 2000/01 to 2020/21.

Figure 32: Number of heatwave episodes and heatwave days, and excess heat during heatwave episodes, MetService approach, Auckland, 2000/01–2020/21

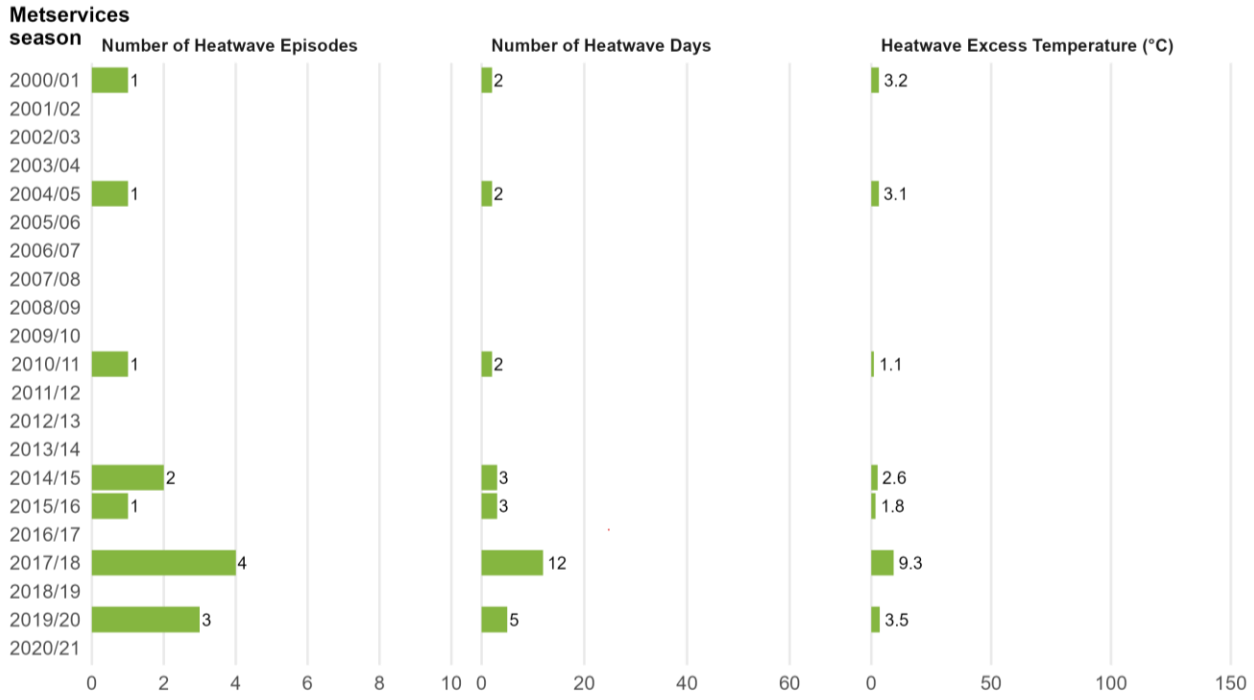
Thresholds: T_{max} = 27°C, T_{mean} = 23°C



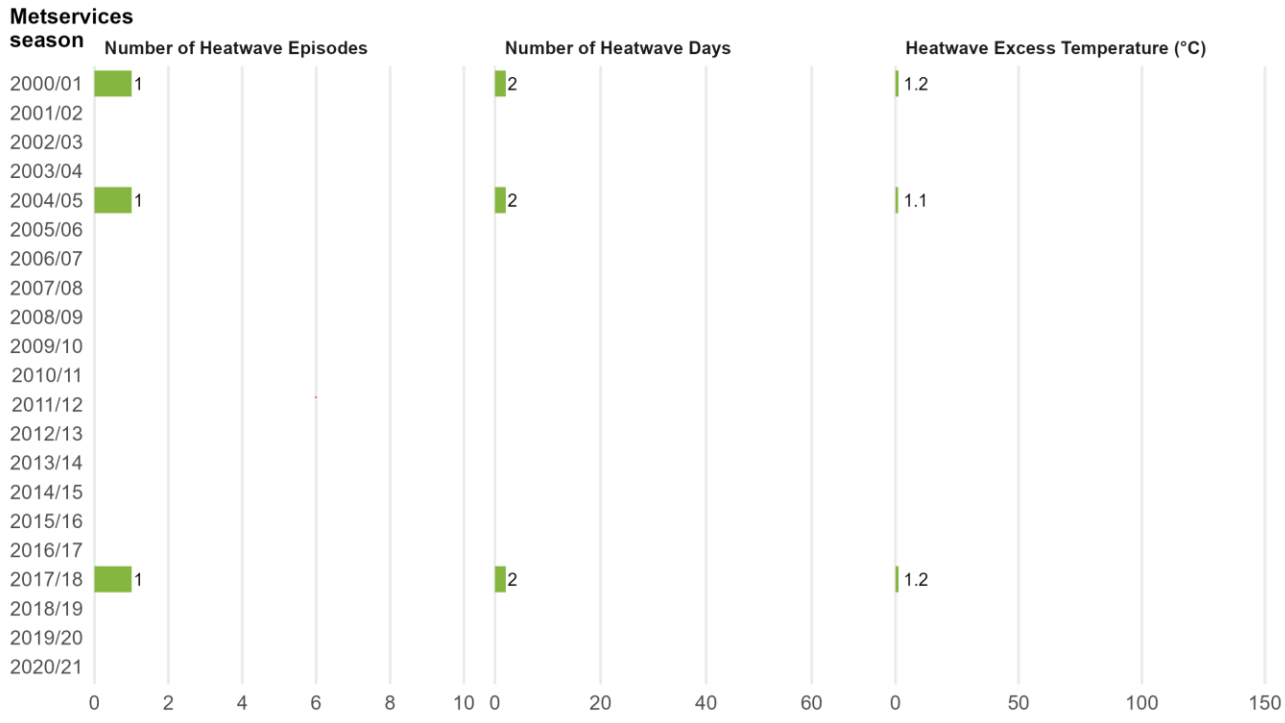
Thresholds: T_{max} = 28°C, T_{mean} = 23°C



Thresholds: T_{max} = 29°C, T_{mean} = 23°C



Thresholds: T_{max} = 30°C, T_{mean} = 24°C

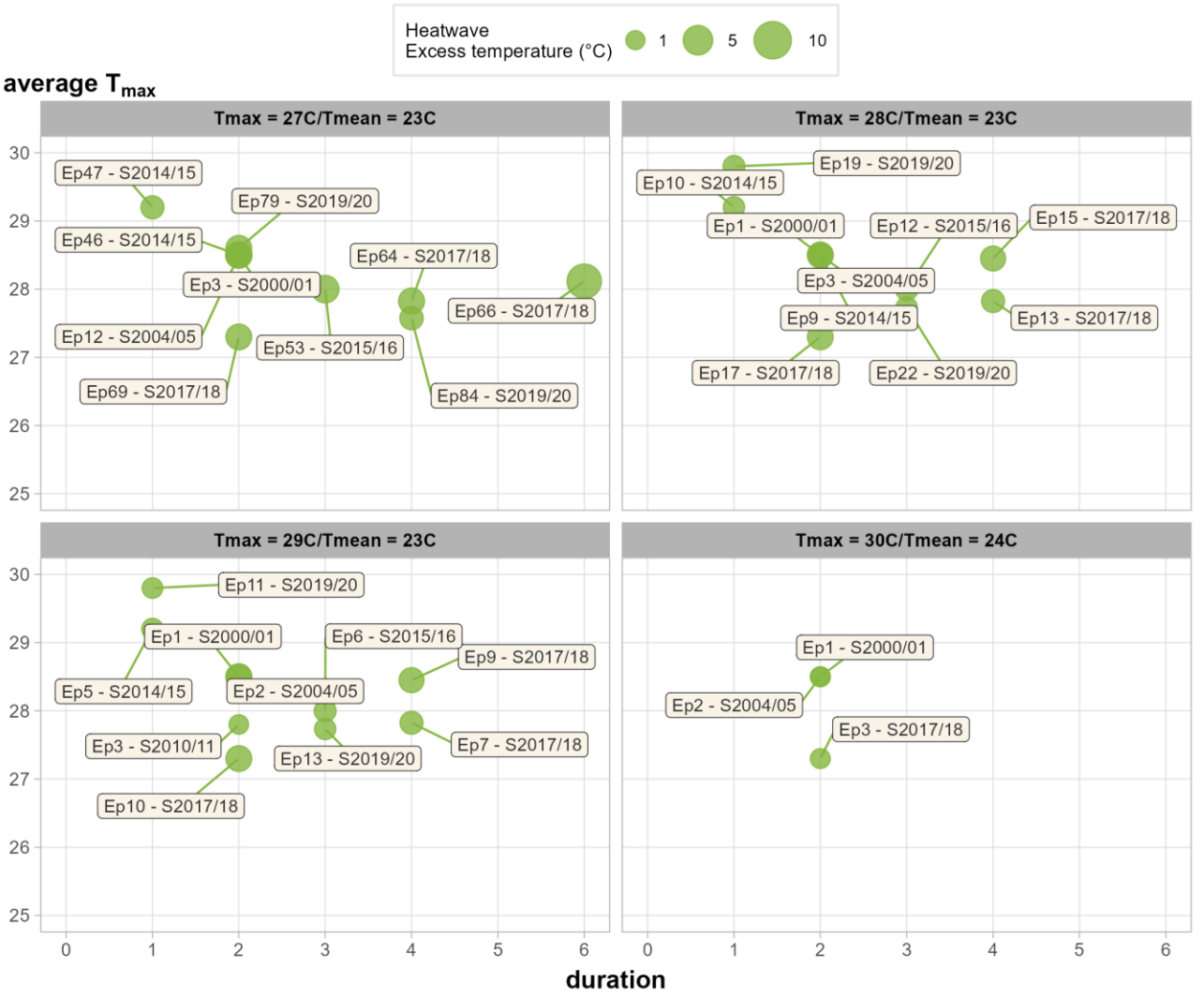


MetService heatwaves were relatively short in duration in Auckland

The ten worst heatwave episodes according to the MetService approach were ranked based on excess temperature (Figure 33). Excess temperature was calculated as the cumulative temperature above whichever of the two thresholds was positive and higher for each heatwave episode, taking into account both duration and temperature.

Across all thresholds, the 2017/18 season had the longest heatwave episodes, while the 2014/15 season had shorter episodes but a higher average maximum temperature. The 2017/18 season also had the highest excess temperature, making it the season with both the highest intensity and the highest frequency of heatwaves.

Figure 33: Ten heatwave episodes identified using the MetService approach, duration (days) and average daily maximum temperature (T_{max}), Auckland, 2000/01–2020/21



Comparison of the two approaches for identifying heatwaves

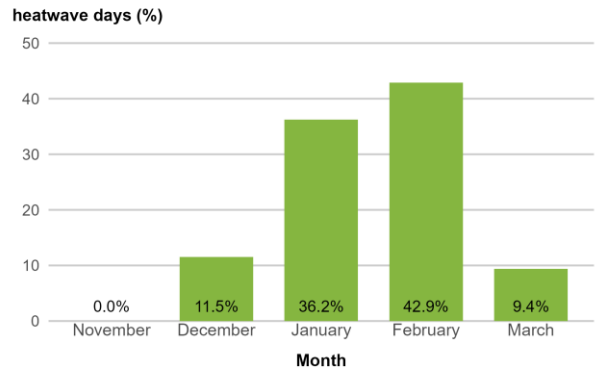
January and February had the most heatwave days in Auckland

In Auckland, 43% of all identified EHF heatwave days occurred in the month of February, with a further 36% of heatwave days occurring in the month of January (Figure 34). For EHF 'severe' heatwaves, January had the most severe heatwave days (44%), followed by February (36%). Most MetService thresholds tested showed the largest percentage of heatwave days in February, with the exception of the 29°C/23°C.

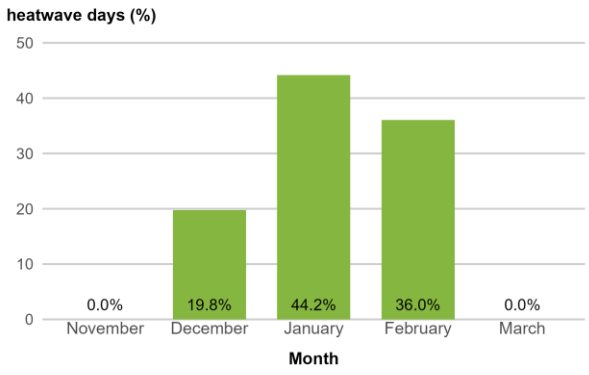
Figure 34: Distribution of heatwave days by month (percentage of heatwave days, among all heatwave days), Auckland, 2000/01 to 2020/21

By EHF approach

Heatwaves

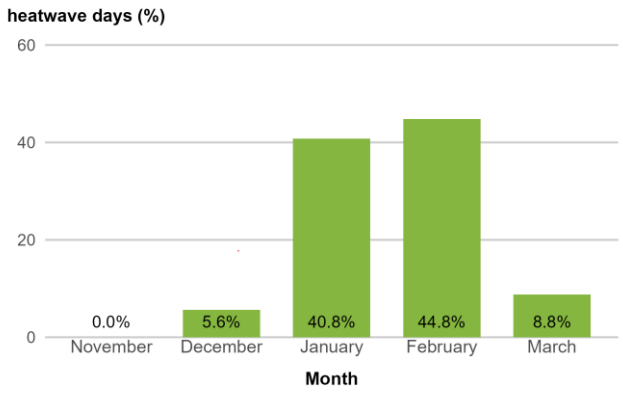


Severe heatwaves

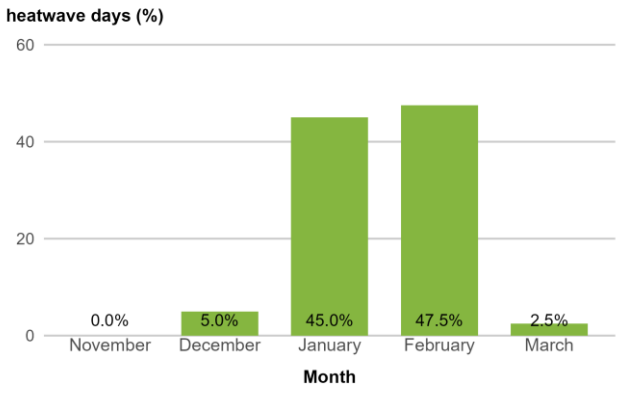


By MetService

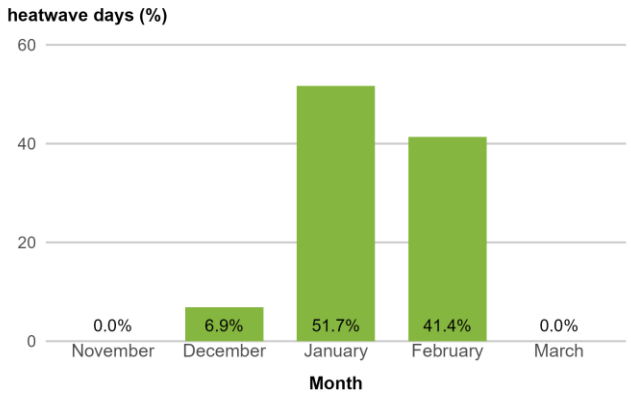
Thresholds: T_{max} = 27°C, T_{mean} = 23°C



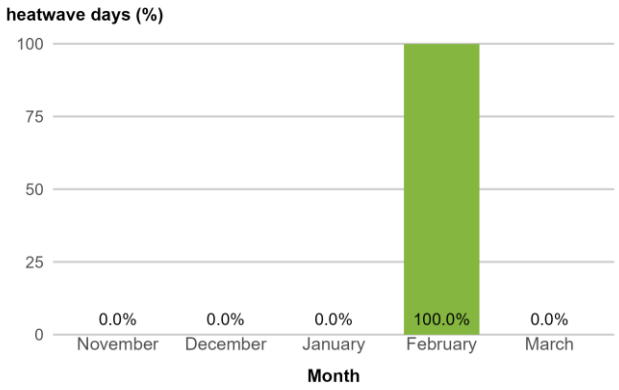
Thresholds: T_{max} = 28°C, T_{mean} = 23C



Thresholds: T_{max} = 29°C, T_{mean} = 23°C



Thresholds: T_{max} = 30°C, T_{mean} = 24°C



Most heatwave days identified by both approaches occurred in 2017/18, 2019/20 and 2015/16 summer seasons

Table 11 presents the highest-ranked summer seasons for the number of heatwave episodes, number of heatwave days, and excess temperature, according to the EHF and MetService approaches. While there are some inconsistencies, this table shows that the summer seasons 2017/18, 2019/20 and 2015/16 appeared commonly in the top five worst seasons for heatwaves, for both the EHF and MetService approaches.

This is consistent with results from NIWA's seven station temperature series, which found the years 1998, 1999, 2016, 2018, 2019, 2021 and 2022 were the warmest years on record since measurements began in 1909 (NIWA nd).

Table 11: Top five worst summer seasons for (i) number of heatwave episodes, (ii) number of heatwave days, and (iii) excess heat, according to EHF and MetService approaches, Auckland, 2000/01 to 2020/21

Rank of summer seasons (1 = highest number of heatwave days/episodes or excess heat)	Number of heatwave episodes		Number of heatwave days		Excess heat	
	EHF	MetService	EHF	MetService	EHF	MetService
1.	2010/11	2019/20	2017/18	2017/18	2017/18	2017/18
2.	2020/21, 2017/18 (=)	2017/18	2015/16	2019/20	2003/04	2019/20
3.		2014/15	2010/11	2014/15	2000/01	2004/05
4.	2003/04, 2009/10, 2012/13, 2014/15, 2015/16, 2018/19, 2019/20 (=)	2004/05	2019/20	2004/05, 2015/16 (=)	2004/05	2014/15, 2000/01 (=)
5.		2000/01, 2007/08, 2008/09, 2010/11, 2013/14, 2015/16, 2018/19 (=)	2009/10		2019/20	

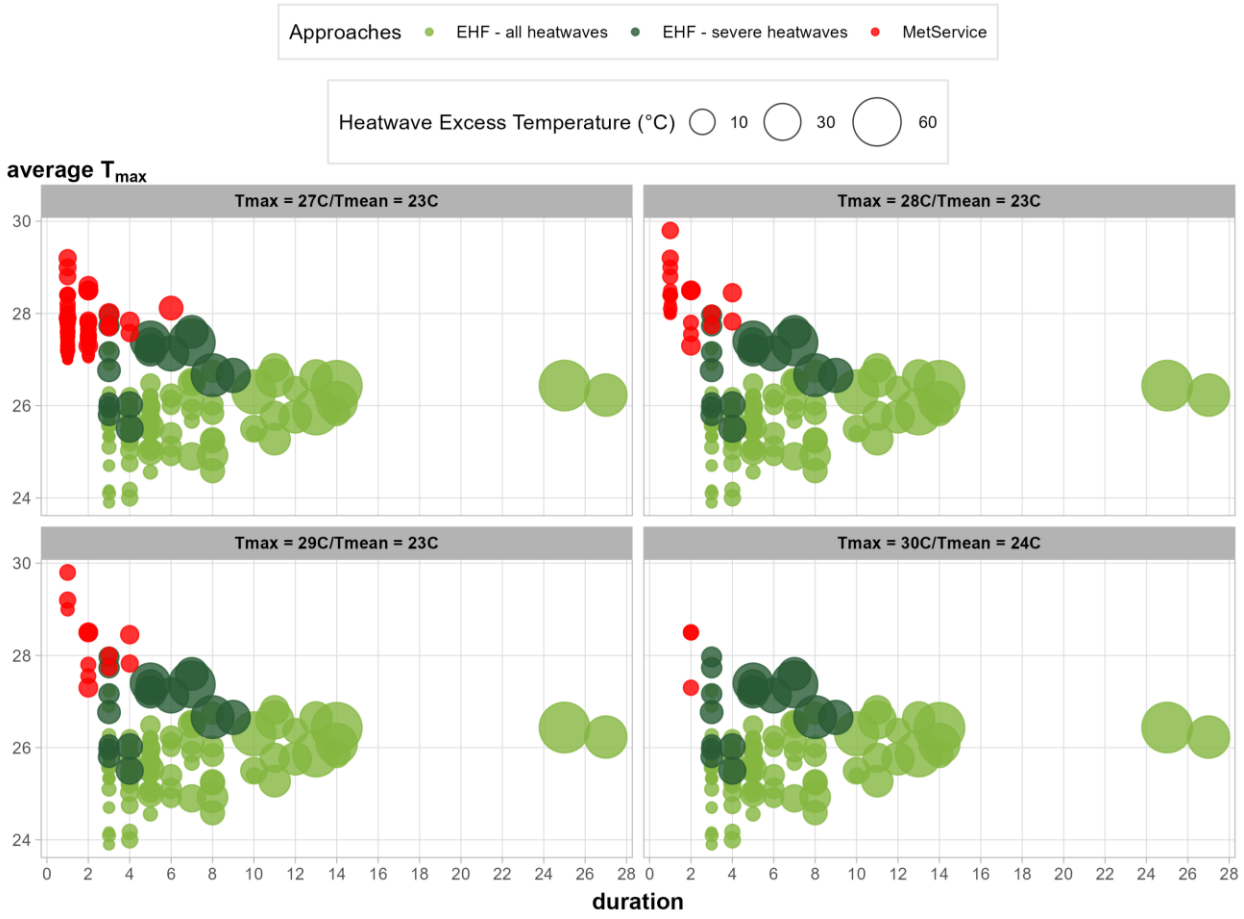
Note: An equals sign (=) shows that the seasons had the same number of heatwave episodes/number of heatwave days/excess heat, so have equal rank.

The MetService approach identified shorter and hotter heatwaves than the EHF

The distribution of heatwave duration versus average daily maximum temperature (T_{max}) across all EHF and MetService thresholds shows that the MetService approach tends to identify short but very hot heatwaves (Figure 35).

The EHF, on the other hand, identifies longer and relatively cooler heatwaves. EHF severe heatwaves are shorter and hotter than all EHF heatwaves, but still longer than those identified by the MetService approach.

Figure 35: Comparison of heatwave duration (days) versus average T_{max}, Auckland, 2000/01 to 2020/21



Among the ten worst heatwave episodes per approach, MetService approach identified hotter and shorter heatwaves than the EHF

When considering only the ten worst heatwave episodes identified by the two approaches (based on excess temperature), similar patterns emerged. The MetService approaches still identified much hotter and shorter heatwaves than the EHF (regardless of which MetService thresholds were used). EHF severe heatwaves lay between the two (Figure 36). These figures show that the different heatwave definitions identify heatwave periods with different characteristics.

Figure 36: Duration (days) and average daily maximum temperature (T_{max}) for the worst heatwave episodes, Auckland, 2000/01–2020/21



Association between heatwave periods and daily mortality

This section presents graphs for the summer seasons of 2015/16 (Figure 37), 2017/18 (Figure 38), and 2019/20 (Figure 39), which had some of the worst heatwave episodes overall in Auckland (Table 11). For each summer season, the graph shows daily mortality, daily maximum temperatures, and identified heatwave periods.

To show the association between heatwaves and mortality, we focus here on the EHF heatwaves (including EHF severe heatwaves), and the MetService thresholds of 28°C/23°C and 29°C/23°C. These thresholds have been used operationally by the MetService and are high enough to capture impactful heatwaves, but not so high that very few events are recorded, allowing it to represent the results under the MetService approach.

Some episodes of hot weather in Auckland identified by both the EHF and the MetService heat alert approach

Overall, the EHF and MetService heatwave approaches mostly identified similar time periods of heatwaves and hot weather in Auckland. In particular, the MetService approach (using both the 28°C/23°C and 29°C/23°C thresholds) mostly aligned with the EHF 'severe' heatwaves. However, in 2019/20, there were several EHF heatwave periods that the MetService approach did not detect.

Overall, EHF heatwaves tended to be longer and more extended periods of hot weather. In contrast, the MetService approach tended to identify single days or very short periods of noticeably hotter weather (based on daily maximum temperatures).

The heatwave periods identified sometimes correlated with higher observed daily mortality, although daily mortality counts in Auckland had a lot of random variation.

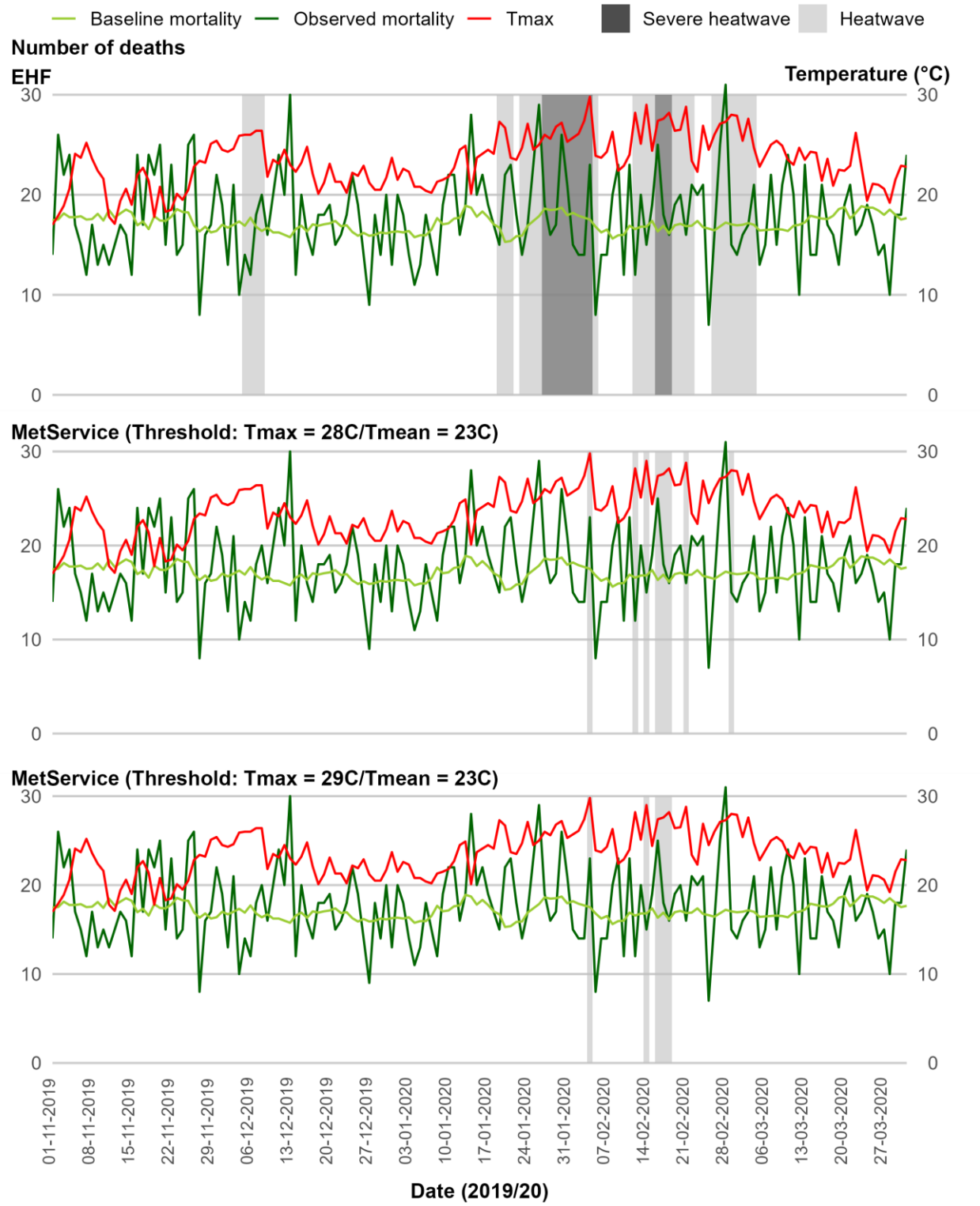
Figure 37: Heatwave episodes during the 2015/16 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Auckland



Figure 38: Heatwave episodes during the 2017/18 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Auckland



Figure 39: Heatwave episodes during the 2019/20 season, observed and baseline mortality, and daily maximum temperature (T_{max}) for EHF and MetService approaches, Auckland



Excess mortality during heatwaves

The EHF approach, and some MetService threshold levels, identified significant excess mortality during heatwaves in Auckland

A retrospective analysis of the summer seasons from 2000/01 to 2020/21 was carried out to quantify excess mortality during heatwave episodes. This analysis found that the EHF, and the three lower MetService thresholds, had statistically significant excess deaths during heatwave episodes.

Overall, the EHF main heatwave definition was associated with the highest estimated number of excess deaths on identified heatwave days across the study period (379.0 excess deaths, 95% confidence interval: 193.3 to 567.6) (Table 12, Figure 40). This EHF approach identified the most heatwave days, with 555 heatwave days across 86 heatwave episodes. The EHF severe heatwave definition identified 86 severe heatwave days over 18 heatwave episodes, which had a lower overall number of excess deaths on these days (67.1 excess deaths, 95% CI: -6.8 to 143.9).

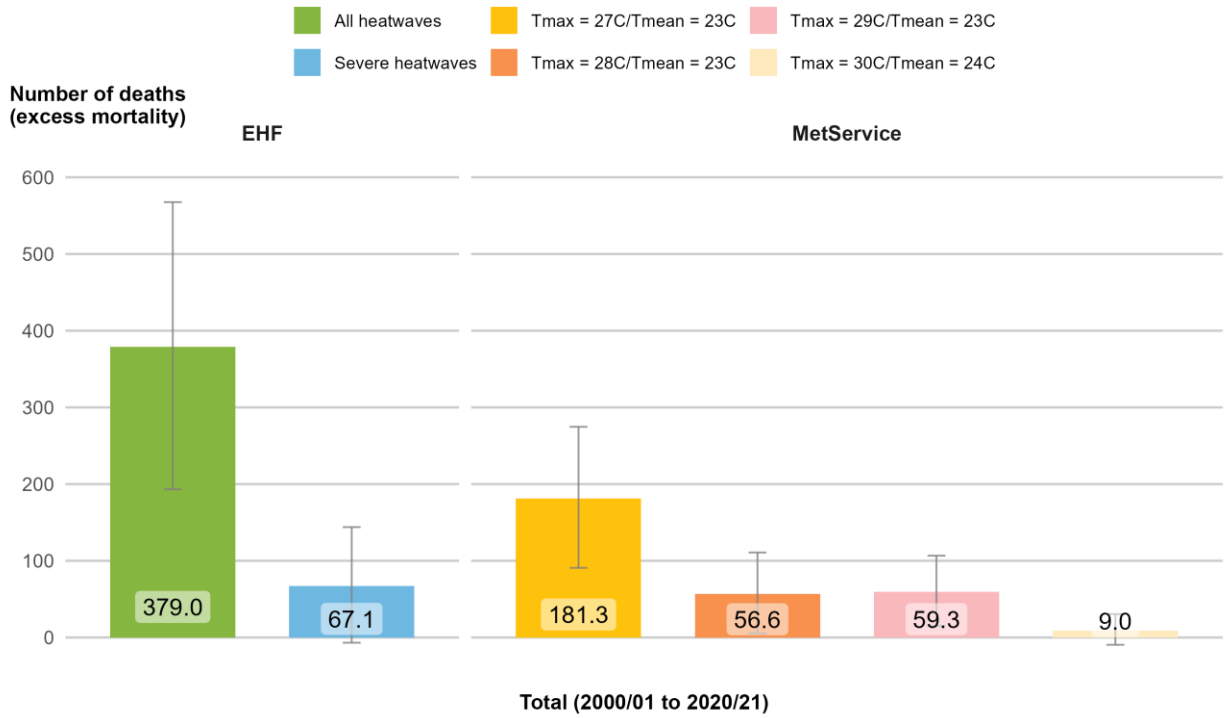
The MetService approach identified various heatwave days and episodes based on different thresholds. The main MetService thresholds of 28°C/23°C and 29°C/23°C had relatively similar number of heatwave days (40 and 29 days respectively), and resulted in similar estimated excess mortality (56.6 and 59.3 excess deaths respectively).

The MetService threshold of 27°C/23°C had 125 heatwave days and 91 episodes, resulting in 181.3 excess deaths (95% CI: 90.8 to 274.7). Meanwhile, the threshold of 30°C/24°C had the lowest numbers of heatwave episodes and days, and the lowest number of excess deaths (9.0 excess deaths, 95% CI: −9.5 to 30.5).

Table 12: Summary of key heatwave and mortality variables for each heatwave approach (on heatwave days), total (2000/01 to 2020/21), Auckland

Heatwave definition approach	Heatwave episodes	Heatwave days	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF – All heatwaves	86	555	8693.0	9072	379.0 (193.3 to 567.6) *
EHF – Severe heatwaves	18	86	1389.9	1457	67.1 (-6.8 to 143.9)
MetService (Thresholds)					
27°C/23°C	91	125	1996.7	2178	181.3 (90.8 to 274.7) *
28°C/23°C	24	40	653.4	710	56.6 (5.3 to 110.8) *
29°C/23°C	13	29	476.7	536	59.3 (14.9 to 106.7) *
30°C/24°C	3	6	90.0	99	9.0 (-9.5 to 30.5)

Figure 40: Number of cumulative excess deaths during heatwave episodes, total (2000/01 to 2020/21), Auckland



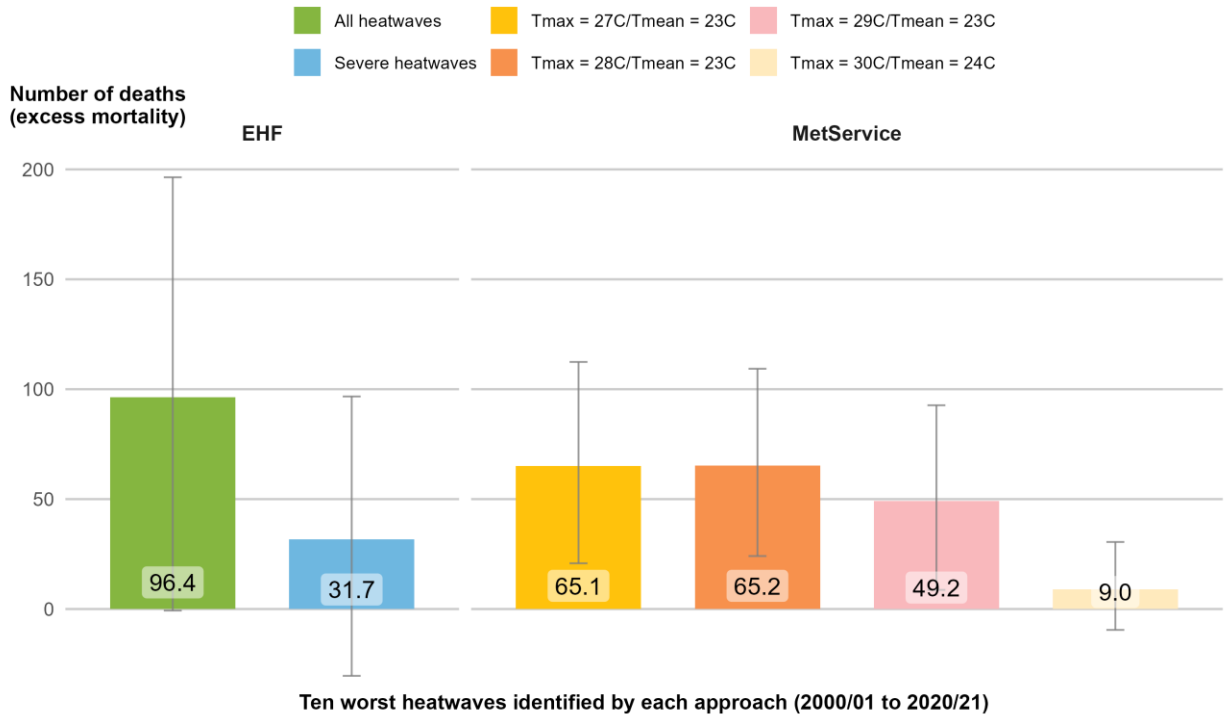
Notes: 95% confidence intervals are shown.

Among the ten worst heatwave episodes per approach, the EHF approach found significant excess mortality

Figure 41 and Table 13 highlight the ten worst episodes (based on excess temperature) identified by each approach. EHF heatwaves were associated with the highest number of excess deaths during these heatwave episodes, at 96.4 excess deaths (95% confidence interval: −0.7 to 196.4) (Figure 41). EHF severe heatwave definition found 31.7 excess deaths during these heatwave episodes, which was not statistically significant (95% CI: −30.4 to 96.7).

Using the MetService approach, the numbers of excess deaths were relatively similar for the three lower thresholds of 27°C/23°C, 28°C/23°C and 29°C/23°C, ranging from 49 to 65 excess deaths, all of which were statistically significant. The higher MetService threshold of 30°C/24°C had a low number of excess deaths.

Figure 41: Number of excess deaths during the ten worst heatwave episodes identified by each approach, Auckland, 2000/01 to 2020/21



Notes: 95% confidence intervals are shown.

Table 13: Heatwave characteristics for the ten worst heatwave episodes by each approach, Auckland, 2000/01 to 2020/21

Method	Heatwave episodes	Duration (days)	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF - All heatwaves	10/02/2001 – 22/02/2001	13	181.0	202	21.0 (-5.9 to 50.9)
	29/01/2005 – 11/02/2005	14	209.5	206	-3.5 (-30.7 to 26.6)
	26/01/2006 – 04/02/2006	10	145.9	139	-6.9 (-29.0 to 18.2)
	03/02/2009 – 13/02/2009	11	164.7	167	2.3 (-22.1 to 29.6)
	20/12/2012 – 30/12/2012	11	185.1	181	-4.1 (-29.5 to 24.3)
	22/01/2015 – 03/02/2015	13	187.5	253	65.5 (35.3 to 98.7) *
	23/01/2016 – 18/02/2016	27	428.7	449	20.3 (-20.3 to 63.8)
	09/01/2018 – 02/02/2018	25	449.9	446	-3.9 (-44.3 to 39.5)
	10/02/2018 – 21/02/2018	12	203.8	202	-1.8 (-28.7 to 28.1)
	23/01/2020 – 05/02/2020	14	248.5	256	7.5 (-22.9 to 40.9)
	Total		**2404.6**	**2501**	**96.4 (-0.7 to 196.4)**
EHF - Severe heatwaves	12/02/2001 – 16/02/2001	5	71.2	77	5.8 (-10.4 to 25.0)
	30/01/2005 – 05/02/2005	7	102.9	105	2.1 (-17.0 to 24.2)
	27/01/2006 – 03/02/2006	8	117.0	118	1.0 (-19.3 to 24.3)
	07/02/2009 – 12/02/2009	6	93.2	91	-2.2 (-19.9 to 18.5)
	22/12/2012 – 25/12/2012	4	68.2	63	-5.2 (-19.8 to 12.4)
	24/01/2016 – 28/01/2016	5	81.0	104	23.0 (4.0 to 45.0) *

	11/01/2018 – 15/01/2018	5	88.2	89	0.8 (-16.7 to 21.3)	
	23/01/2018 – 29/01/2018	7	134.7	134	-0.7 (-22.4 to 24.0)	
	16/02/2018 – 20/02/2018	5	82.3	88	5.7 (-11.7 to 26.1)	
	27/01/2020 – 04/02/2020	9	163.6	165	1.4 (-22.8 to 28.6)	
	Total		**1002.3**	**1034**	**31.7 (-30.4 to 96.7)**	
MetService 27°C/23°C	14/02/2001 – 15/02/2001	2	29.0	38	9.0 (-2.1 to 23.2)	
	02/02/2005 – 03/02/2005	2	28.9	32	3.1 (-7.0 to 16.3)	
	29/01/2015 – 30/01/2015	2	27.7	41	13.3 (1.7 to 27.9)	*
	02/02/2015 – 02/02/2015	1	13.9	19	5.1 (-2.5 to 15.8)	
	24/01/2016 – 26/01/2016	3	48.6	68	19.4 (4.2 to 37.6)	*
	12/01/2018 – 15/01/2018	4	71.2	72	0.8 (-14.9 to 19.5)	
	26/01/2018 – 31/01/2018	6	114.3	113	-1.3 (-21.2 to 21.6)	
	18/02/2018 – 19/02/2018	2	32.1	29	-3.1 (-12.7 to 9.5)	
	03/02/2020 – 04/02/2020	2	35.2	37	1.8 (-9.1 to 15.8)	
	27/02/2020 – 01/03/2020	4	68.0	85	17.0 (-0.1 to 37.1)	
	Total		**468.9**	**534**	**65.1 (20.8 to 112.4)**	*
MetService 28°C/23°C	14/02/2001 – 15/02/2001	2	29.0	38	9.0 (-2.1 to 23.2)	
	02/02/2005 – 03/02/2005	2	28.9	32	3.1 (-7.0 to 16.3)	
	29/01/2015 – 30/01/2015	2	27.7	41	13.3 (1.7 to 27.9)	*
	02/02/2015 – 02/02/2015	1	13.9	19	5.1 (-2.5 to 15.8)	
	24/01/2016 – 26/01/2016	3	48.6	68	19.4 (4.2 to 37.6)	*
	12/01/2018 – 15/01/2018	4	71.2	72	0.8 (-14.9 to 19.5)	
	26/01/2018 – 29/01/2018	4	77.5	80	2.5 (-14.1 to 22.1)	
	18/02/2018 – 19/02/2018	2	32.1	29	-3.1 (-12.7 to 9.5)	
	04/02/2020 – 04/02/2020	1	17.5	23	5.5 (-2.9 to 17.0)	
	16/02/2020 – 18/02/2020	3	49.4	59	9.6 (-4.5 to 26.7)	
	Total		**395.8**	**461**	**65.2 (24.1 to 109.3)**	*
MetService 29°C/23°C	14/02/2001 – 15/02/2001	2	29.0	38	9.0 (-2.1 to 23.2)	
	02/02/2005 – 03/02/2005	2	28.9	32	3.1 (-7.0 to 16.3)	
	21/12/2010 – 22/12/2010	2	30.7	28	-2.7 (-12.1 to 9.8)	
	02/02/2015 – 02/02/2015	1	13.9	19	5.1 (-2.5 to 15.8)	
	24/01/2016 – 26/01/2016	3	48.6	68	19.4 (4.2 to 37.6)	*
	12/01/2018 – 15/01/2018	4	71.2	72	0.8 (-14.9 to 19.5)	
	26/01/2018 – 29/01/2018	4	77.5	80	2.5 (-14.1 to 22.1)	
	18/02/2018 – 19/02/2018	2	32.1	29	-3.1 (-12.7 to 9.5)	
	04/02/2020 – 04/02/2020	1	17.5	23	5.5 (-2.9 to 17.0)	
	16/02/2020 – 18/02/2020	3	49.4	59	9.6 (-4.5 to 26.7)	
	Total		**398.8**	**448**	**49.2 (8.7 to 92.7)**	*
MetService 30°C/24°C	14/02/2001 – 15/02/2001	2	29.0	38	9.0 (-2.1 to 23.2)	
	02/02/2005 – 03/02/2005	2	28.9	32	3.1 (-7.0 to 16.3)	
	18/02/2018 – 19/02/2018	2	32.1	29	-3.1 (-12.7 to 9.5)	
	Total		**90.0**	**99**	**9.0 (-9.5 to 30.5)**	

There were very mixed results in performance of heatwave approaches, depending on the summer season

Figure 42 shows the overall number of excess deaths in each of the 2015/16, 2017/18 and 2019/20 summer seasons. There were very mixed results in excess deaths associated with each heatwave approach, depending on the summer season.

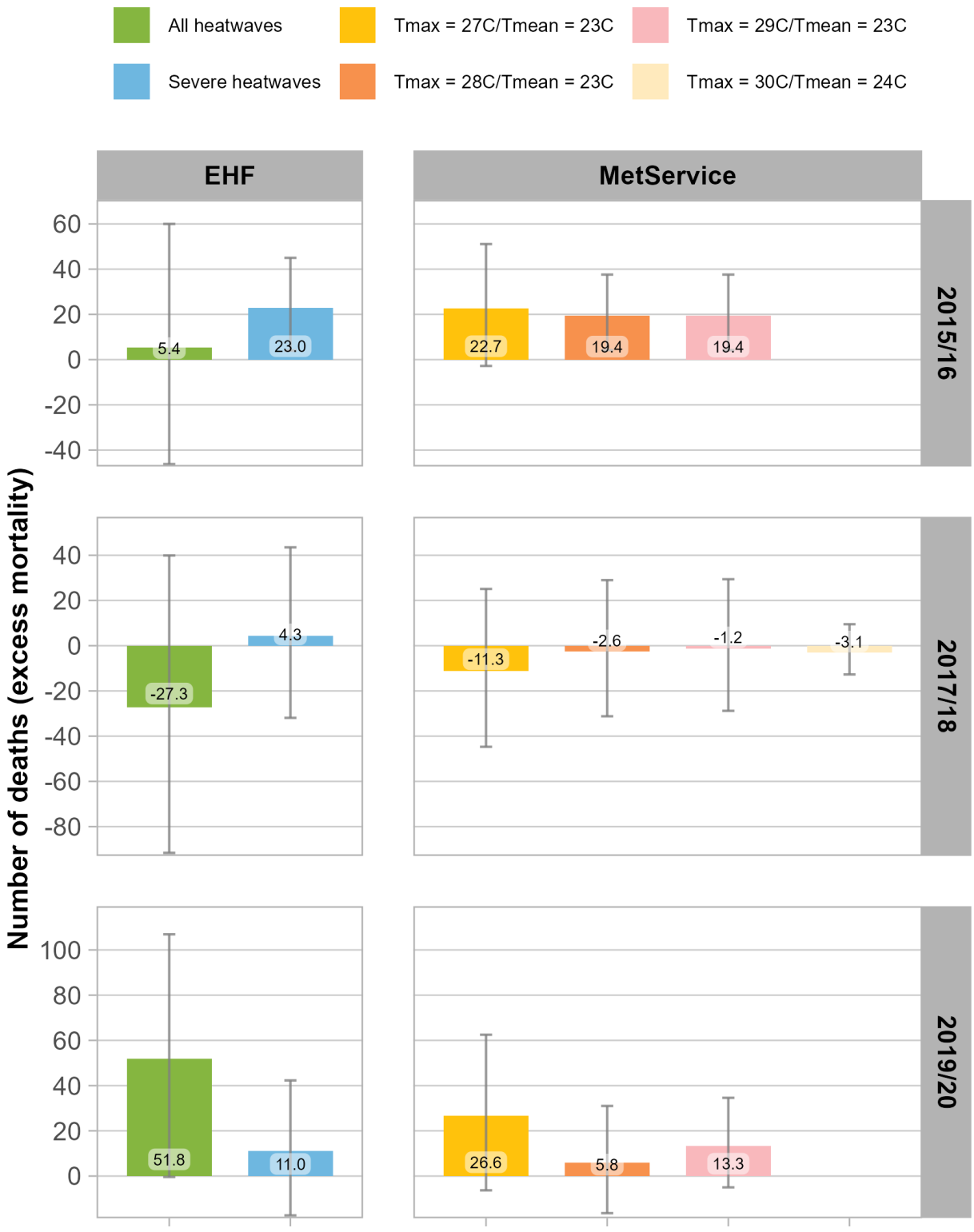
In the 2015/16 summer season, the EHF severe heatwave definition and MetService heat alert thresholds (except the highest threshold) performed well, and identified significant excess deaths during heatwave episodes. However, the main EHF heatwave definition did not find statistically significant excess deaths.

During the 2017/18 summer season, none of the heatwave approaches found statistically significant excess deaths. NIWA highlighted that the summer of the 2017/18 season was the hottest on record (NIWA, n.d.), and we found excess mortality associated with heatwaves in the Christchurch region during this season; however, the number of excess deaths in Auckland was not statistically significant in that season.

During the 2019/20 summer season, the EHF heatwave definition found the most excess deaths, which were almost statistically significant.

When looking at specific heatwaves in these summer seasons (Tables 14, 15 and 16), the EHF severe heatwave definition and the MetService approach identified a substantial heatwave in Auckland in late January 2016 (24–28 January 2016), which was associated with statistically significant excess mortality. No other heatwaves over these summer seasons had statistically significant excess mortality, using any approach.

Figure 42: Number of excess deaths during the heatwave episodes, 2015/16, 2017/18 and 2019/20, Auckland



Notes: 95% confidence intervals are shown.

Table 14: Heatwave characteristics for each approach, 2015/16 season, Auckland

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF - All heatwaves	15/01/2016 – 19/01/2016	91.0	74	-17.0 (-32.9 to 1.9)
	23/01/2016 – 18/02/2016	428.7	449	20.3 (-20.3 to 63.8)
	25/02/2016 – 01/03/2016	97.6	105	7.4 (-11.7 to 29.5)
	06/03/2016 – 08/03/2016	46.7	42	-4.7 (-16.4 to 10.1)
	21/03/2016 – 23/03/2016	50.6	50	-0.6 (-13.5 to 15.3)
	Total	**714.6**	**720**	**5.4 (-46.2 to 60.0)**
EHF - Severe heatwaves	24/01/2016 – 28/01/2016	81.0	104	23.0 (4.0 to 45.0) *
	Total	**81.0**	**104**	**23.0 (4.0 to 45.0)** *
MetService 27°C/23°C	31/12/2015 – 31/12/2015	16.4	23	6.6 (-1.8 to 18.1)
	24/01/2016 – 26/01/2016	48.6	68	19.4 (4.2 to 37.6) *
	31/01/2016 – 31/01/2016	15.2	19	3.8 (-3.8 to 14.5)
	06/02/2016 – 07/02/2016	29.9	25	-4.9 (-13.7 to 7.0)
	13/02/2016 – 13/02/2016	17.0	17	0.0 (-7.1 to 10.2)
	15/02/2016 – 15/02/2016	16.2	10	-6.2 (-11.4 to 2.2)
	27/02/2016 – 27/02/2016	16.0	20	4.0 (-3.8 to 14.9)
	Total	**159.3**	**182**	**22.7 (-2.8 to 51.1)**
MetService 28°C/23°C	**24/01/2016 – 26/01/2016**	**48.6**	**68**	**19.4 (4.2 to 37.6)** *
MetService 29°C/23°C	**24/01/2016 – 26/01/2016**	**48.6**	**68**	**19.4 (4.2 to 37.6)** *

Table 15: Heatwave characteristics for each approach, 2017/18 season, Auckland

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF - All heatwaves	06/12/2017 – 13/12/2017	136.4	121	-15.4 (-36.0 to 8.2)
	15/12/2017 – 19/12/2017	80.2	91	10.8 (-6.9 to 31.5)
	31/12/2017 – 05/01/2018	99.6	86	-13.6 (-30.8 to 6.6)
	09/01/2018 – 02/02/2018	449.9	446	-3.9 (-44.3 to 39.5)
	10/02/2018 – 21/02/2018	203.8	202	-1.8 (-28.7 to 28.1)
	26/02/2018 – 07/03/2018	165.4	162	-3.4 (-27.4 to 23.6)
	Total	**1135.3**	**1108**	**-27.3 (-91.6 to 39.9)**
EHF - Severe heatwaves	11/01/2018 – 15/01/2018	88.2	89	0.8 (-16.7 to 21.3)
	19/01/2018 – 21/01/2018	50.5	49	-1.5 (-14.2 to 14.3)
	23/01/2018 – 29/01/2018	134.7	134	-0.7 (-22.4 to 24.0)
	16/02/2018 – 20/02/2018	82.3	88	5.7 (-11.7 to 26.1)
	Total	**355.7**	**360**	**4.3 (-31.9 to 43.5)**
MetService 27°C/23°C	02/01/2018 – 03/01/2018	33.8	22	-11.8 (-20.0 to -0.5)
	12/01/2018 – 15/01/2018	71.2	72	0.8 (-14.9 to 19.5)
	20/01/2018 – 21/01/2018	33.4	32	-1.4 (-11.5 to 11.8)
	26/01/2018 – 31/01/2018	114.3	113	-1.3 (-21.2 to 21.6)
	12/02/2018 – 12/02/2018	18.1	25	6.9 (-1.9 to 18.8)
	16/02/2018 – 16/02/2018	16.4	15	-1.4 (-8.0 to 8.3)

	18/02/2018 – 19/02/2018	32.1	29	-3.1 (-12.7 to 9.5)
	Total	**319.3**	**308**	**-11.3 (-44.7 to 25.1)**
MetService 28°C/23°C	12/01/2018 – 15/01/2018	71.2	72	0.8 (-14.9 to 19.5)
	20/01/2018 – 21/01/2018	33.4	32	-1.4 (-11.5 to 11.8)
	26/01/2018 – 29/01/2018	77.5	80	2.5 (-14.1 to 22.1)
	16/02/2018 – 16/02/2018	16.4	15	-1.4 (-8.0 to 8.3)
	18/02/2018 – 19/02/2018	32.1	29	-3.1 (-12.7 to 9.5)
	Total	**230.6**	**228**	**-2.6 (-31.2 to 29.0)**
MetService 29°C/23°C	12/01/2018 – 15/01/2018	71.2	72	0.8 (-14.9 to 19.5)
	20/01/2018 – 21/01/2018	33.4	32	-1.4 (-11.5 to 11.8)
	26/01/2018 – 29/01/2018	77.5	80	2.5 (-14.1 to 22.1)
	18/02/2018 – 19/02/2018	32.1	29	-3.1 (-12.7 to 9.5)
	Total	**214.2**	**213**	**-1.2 (-28.8 to 29.4)**
MetService 30°C/24°C	18/02/2018 – 19/02/2018	32.1	29	-3.1 (-12.7 to 9.5)
	Total	**32.1**	**29**	**-3.1 (-12.7 to 9.5)**

Table 16: Heatwave characteristics for each approach, 2019/20 season, Auckland

Method	Heatwave episodes	Baseline mortality	Observed mortality	Excess mortality (95% CI) (* = statistically significant)
EHF - All heatwaves	05/12/2019 – 08/12/2019	67.8	64	-3.8 (-18.5 to 13.9)
	19/01/2020 – 21/01/2020	47.4	60	12.6 (-1.6 to 29.8)
	23/01/2020 – 05/02/2020	248.5	256	7.5 (-22.9 to 40.9)
	12/02/2020 – 22/02/2020	184.8	201	16.2 (-10.6 to 46.0)
	26/02/2020 – 04/03/2020	135.7	155	19.3 (-4.1 to 45.7)
	Total	**684.2**	**736**	**51.8 (-0.4 to 106.9)**
EHF - Severe heatwaves	27/01/2020 – 04/02/2020	163.6	165	1.4 (-22.8 to 28.6)
	16/02/2020 – 18/02/2020	49.4	59	9.6 (-4.5 to 26.7)
	Total	**213.0**	**209**	**11.0 (-17.4 to 42.3)**
MetService 27°C/23°C	19/01/2020 – 19/01/2020	16.7	15	-1.7 (-8.3 to 8.0)
	24/01/2020 – 24/01/2020	16.9	17	0.1 (-7.0 to 10.3)
	30/01/2020 – 30/01/2020	18.7	26	7.3 (-1.7 to 19.4)
	03/02/2020 – 04/02/2020	35.2	37	1.8 (-9.1 to 15.8)
	12/02/2020 – 12/02/2020	16.6	12	-4.6 (-10.4 to 4.4)
	14/02/2020 – 14/02/2020	16.8	15	-1.8 (-8.4 to 7.9)
	16/02/2020 – 18/02/2020	49.4	59	9.6 (-4.5 to 26.7)
	21/02/2020 – 21/02/2020	16.9	16	-0.9 (-7.8 to 9.1)
	27/02/2020 – 01/03/2020	68.0	85	17.0 (-0.1 to 37.1)
	03/03/2020 – 03/03/2020	17.2	17	-0.2 (-7.3 to 10.0)
	Total	**272.4**	**299**	**26.6 (-6.3 to 62.5)**
MetService 28°C/23°C	04/02/2020 – 04/02/2020	17.5	23	5.5 (-2.9 to 17.0)
	12/02/2020 – 12/02/2020	16.6	12	-4.6 (-10.4 to 4.4)
	14/02/2020 – 14/02/2020	16.8	15	-1.8 (-8.4 to 7.9)
	16/02/2020 – 18/02/2020	49.4	59	9.6 (-4.5 to 26.7)
	21/02/2020 – 21/02/2020	16.9	16	-0.9 (-7.8 to 9.1)
	29/02/2020 – 29/02/2020	17.0	15	-2.0 (-8.6 to 7.7)

	Total	**134.2**	**140**	**5.8 (-16.4 to 31.0)**
MetService 29°C/23°C	04/02/2020 – 04/02/2020	17.5	23	5.5 (-2.9 to 17.0)
	14/02/2020 – 14/02/2020	16.8	15	-1.8 (-8.4 to 7.9)
	16/02/2020 – 18/02/2020	49.4	59	9.6 (-4.5 to 26.7)
	Total	**83.7**	**97**	**13.3 (-5.0 to 34.6)**

Discussion

Key findings about heatwaves and health in Auckland and Canterbury

Both the EHF and MetService approaches successfully identified heatwave periods during the time period

Our analyses tested two approaches for identifying heatwaves/hot days: the Excess Heat Factor (EHF), and NZ MetService heat alerts. These approaches were tested in the two different climate regions of Canterbury and Auckland, from the period 2000/01 to 2020/21.

The two approaches showed reasonable agreement in identifying the summer seasons with the highest numbers of heatwave episodes and excess heat. In Canterbury, both methods identified heatwaves in 2015/16, 2017/18 and 2019/20. In Auckland, both approaches identified heatwaves in the recent summer seasons of 2017/18 and 2019/20. NIWA (now Earth Sciences New Zealand) also reported that these summer seasons had hot periods in the Canterbury and Auckland areas. In particular, NIWA reported that the 2017/18 summer season was New Zealand's hottest summer on record at the time, and that there was an intense marine heatwave (NIWA 2018).

Heatwave episodes were associated with excess mortality in Canterbury and Auckland

Using both the EHF heatwave definition and the MetService heat alert approach, we found statistically significant excess mortality associated with heatwaves, in both Canterbury and Auckland from 2000/01 to 2020/21. The EHF had the highest number of heatwave episodes, and was associated with the highest number of excess deaths overall. The EHF severe heatwave threshold and MetService approach were generally associated with a lower number of heatwave episodes and excess deaths.

In Canterbury from 2000/01 to 2020/21, the EHF heatwave approach estimated that heatwaves were associated with 114.2 excess deaths overall (95% confidence interval: 0.3 to 231). Using the EHF severe heatwave threshold, we found 70.3 excess deaths (95% CI: 21.0 to 122.6) in Canterbury. By contrast, using the MetService heat alert approach, we found 55.7 excess deaths (95% CI: 2.7 to 111.7) in Canterbury with the main 31°C/23°C threshold. In Canterbury, particular heatwave episodes with statistically significant excess deaths included: 16–23 December 2010 (according to the EHF approach); 1–3 January 2002, 17–22 December 2010 and 7–11 December 2017 (EHF severe heatwaves); and 2 February 2020 (according to MetService heat alerts).

In Auckland from 2000/01 to 2020/21, the EHF heatwave approach estimated that heatwaves were associated with 379.0 excess deaths overall (95% CI: 193.3 to 567.6). Using the EHF severe heatwave threshold, we found 67 excess deaths (95% CI: −6.8 to 143.9). Using the MetService heat alert approach, we identified 56.6 excess deaths (95% CI: 5.3 to 110.8) using the original MetService threshold of 28°C/23°C, and 59.3 excess deaths (95% CI: 14.9 to 106.7) using their raised threshold level of 29°C/23°C. In Auckland, particular heatwave episodes with statistically significant excess deaths included 22 January–4 February 2015, and 24–28 January 2016 (according to both EHF and MetService approaches).

While overall we found significant excess mortality associated with both heatwave definitions, the results were more mixed when focusing on specific summer seasons or specific heatwave episodes. Mortality can be influenced by a number of factors, and has low daily counts, so there are random fluctuations in mortality counts when focussing on short time periods. As a result, while the heatwave definitions were significantly associated with excess mortality across multiple years pooled, specific heatwave periods were not necessarily associated with significant excess mortality.

Both EHF and MetService approaches performed better than methods using only daily maximum temperature

This study built on a previous EHINZ study that compared the EHF heatwave approach with heatwave definitions from the UK and Stats NZ/Ministry for the Environment (MfE) (Haenfling et al 2023). Both the EHF and MetService heat alerts performed better than the daily maximum temperature-based measures from the UK and Stats NZ/MfE, which were not strongly associated with substantial excess mortality from heatwave episodes in Canterbury from 2000/01 to 2018/19. These comparisons suggest that heatwave definitions that take into account overnight temperatures through the daily mean temperature are better at capturing adverse health impacts from heatwaves in New Zealand.

Comparison of EHF and MetService approaches

EHF heatwaves were cooler but longer than MetService heat alert periods

The EHF and MetService approaches generally identified similar periods of hot weather. However, analyses showed that heatwaves identified by the EHF were longer and had lower daily maximum temperatures than those identified by the MetService approach. By contrast, the MetService approach identified short but very hot heatwaves (heat alert days). This was expected, as the MetService uses daily maximum temperatures as one of the thresholds, which are deliberately set very high and will often only alert a single hot day.

Threshold levels made a large difference to the number of heatwaves identified

Sensitivity analyses showed that the level that thresholds are set make a difference. For the EHF, using the more conservative EHF 'severe heatwave' threshold identified a smaller number of more intense heatwave days, compared with the main EHF heatwave threshold. The overall number of EHF severe heatwave episodes, and associated excess mortality, were of a relatively similar magnitude to that identified with the MetService heat alert approach.

Similarly, for the MetService approach, we tested multiple thresholds for each region, to reflect changes the MetService had made for operational uses and/or based on public feedback. These sensitivity analyses showed that the MetService heat alerts are very influenced by the daily maximum temperature threshold. Having a lower threshold for the daily maximum temperature alert in Auckland (27°C) resulted in a large number of heat alert days, while increasing the daily maximum temperature threshold for Canterbury (from 31°C to 32°C) resulted in a sharp decrease in the number of alerts. This suggested quite a number of the MetService heat alerts are being driven by the one-day alert for the daily maximum temperature, rather than the two-day alert for daily mean temperature.

Conceptually, MetService heat alerts are not technically identifying heatwaves

The World Meteorological Organization (WMO) and World Health Organization (WHO) guidance on heat-health warning systems (HHWS) describes a heatwave as:

> "*periods of unusually hot and dry or hot and humid weather that have a subtle onset and cessation, a duration of at least two to three days and a discernible impact on human activities*" (WMO and WHO 2015, p1).

Conceptually, the EHF heatwave definition is more closely aligned with this heatwave definition than the MetService definition. The EHF heatwave definition has a minimum three days duration, and takes into account higher overnight temperatures through using the daily mean temperature. The EHF also takes into account unusually hot weather (in comparison with the climate baseline for the local area, as well as the past 30 days), to account for acclimatisation.

While the MetService heat alert system also uses the daily mean temperature, it also has a one-day trigger based on the daily maximum temperature. This results in many of the MetService heat alerts only being one day in duration, reflecting a single hot day. This likely reflects the MetService heat alert system is only partly designed to alert for health effects, but also to alert outdoor workers and others to particularly hot conditions. MetService have noted that they have deliberately set the thresholds high, so that they only trigger 1–3 times per year in a location. Furthermore, there is no graded system for MetService thresholds, with heat alerts being publicised widely once the threshold is met. For example, there is no difference operationally between heat alerts based on daily maximum temperatures of 33°C and 40°C in Canterbury, although these temperatures may represent quite different levels of risk to people's health.

Given this, the MetService heat alerts performed reasonably well, with statistically significant excess mortality associated with the heat alert days. However, the MetService heat alert system did have a tendency to trigger a single hot day alert, and also missed some periods of hot weather that were captured by the EHF (including by the EHF severe heatwave threshold). This suggests that the MetService heat alert approach may therefore not capture all heatwave periods, and may be less reliable as the basis of a heat-health warning plan.

Further considerations

If further analyses were carried out, and/or the results of this study were to be used to inform ongoing monitoring of heatwaves and their health impacts (either through a heat-alert warning system and/or a monitoring system of heatwaves and their health impacts), the following issues could to be considered.

Low mortality numbers and including other health outcomes

Excess mortality results for each heatwave approach resulted in values that were not statistically significant for some summer seasons, which may in part be due to relatively low daily numbers of observed mortality. Other health outcome measures (with larger numbers) could also be explored, including hospitalisations for heat-related issues. Additionally, mortality data was based on domicile code of residence, but may not reflect the place of death. Mortality data also did not necessarily take

into account people being in different locations during summer holidays (particularly over the two weeks around Christmas/New Year's Day). This may particularly have impacted on mortality in Auckland over these two weeks, given many people may have left the city to go on holiday. Nonetheless, many of the heatwaves occurred in late January or February, so may have been less affected by this issue.

Time lag

We did not investigate the effect of time lag on mortality. There is evidence that most heat-related deaths take place around one to three days after the heatwave episode has started. This is especially true for deaths due to respiratory and cardiovascular illnesses. Therefore, low excess mortality might be impacted by under-reporting (Rustemeyer and Howells 2021). On the other hand, heatwaves can lead to a short-term mortality displacement effect ('harvesting effect'), which increases the number of deaths during and after the heatwave episode for a short time period. This would lead to an overreporting of heat-related mortality (Rustemeyer and Howells 2021, Stanojević et al 2014).

Baseline climate data used

The EHF and MetService use slightly different baseline climate periods for comparison. For the EHF, this study used the 1981–2010 Climate Normal Period, to give a historical time period for comparison. In future, analyses beyond 2020 could be analysed with the most current Climate Normal Period (1991–2020). Sensitivity analyses show that using a more recent Climate Normal Period would have made only a very small difference to the DMT95 threshold used in EHF calculations for both the Canterbury and Auckland analyses (ie a similar threshold value for Canterbury, and a slight increase for Auckland).

For the MetService approach, we used their recent threshold levels from 2021/22 to 2023/24, which were based on the previous 20 years of data. We selected these thresholds to show how the MetService heat alerts might perform operationally. This means that the daily mean temperatures used as a threshold for each approach were quite different, with the EHF thresholds much lower than the MetService approach. The EHF could be tested using more recent climate data (eg for the past five years) and with a more recent Climate Normal Period. Additionally, approaches such as the ones discussed in this study, which compare values against a historic baseline or Climate Normal Period, are subject to future saturation (Harrington 2021). In a future where daily temperatures are becoming increasingly higher, the comparison to the historic baseline may result in most days being identified as heatwave days, which highlights the need for using an updated baseline climate period when appropriate.

Consideration of vulnerable populations

Some population groups, including the young and the old, are particularly vulnerable to the impacts of heatwaves. We did not account for any population factors in our analysis. However, it will be important to consider population vulnerability to heatwaves alongside any further analysis, for example, young children, older adults, people with certain pre-existing medical conditions, outdoor workers, and households without air conditioning. Additionally, in New Zealand, some population groups already experience substantial health inequities, including Māori and Pacific peoples (Gurney

et al 2020), and these groups may therefore have a higher risk of experiencing negative health impacts of heatwaves. Susceptible populations may be most likely to benefit from a heat-health warning system and/or education and public health preventive action during the summer season.

Potential confounding factors and generalisability

This study recognises that high temperatures might not be the only cause of deaths, as there might be confounders and covariates (such as humidity or air pollution) present, which also contribute to excess mortality during heat wave episodes (Rustemeyer and Howells 2021). Other impacts, such as the urban heat island effect, may also have had an impact.

Additionally, this study trialled the different heatwave approaches in two different climatic conditions, primarily urban areas. Because the study was done in only two urban areas, the findings of this study may not represent the rest of the country, and it could be worthwhile carrying out a similar analysis using the heatwave definitions nationally, in a range of urban and rural settings.

Potential applications of this study

There are two main potential applications of this study for public health action. Firstly, the results of this study could inform the development of a heat-health early warning system in New Zealand, to proactively warn the general public, healthcare services and/or more vulnerable people if a heatwave is forecast. Secondly, a heatwave definition could be used to retrospectively monitor heatwaves and their impact on the health of the New Zealand population, through a national surveillance programme. For both purposes, selecting a heatwave definition driving the highest health burden is crucial to preventing and mitigating the impacts of heatwaves and gaining maximum benefit from the system (Kanti et al 2022).

Informing early heat-health warning systems

Firstly, the results may help to inform the development of a heat-health warning system (HHWS) in New Zealand. Heat-health warning systems are generally based on health impacts, and can be linked to public health actions. For example, heat-health warning systems have been developed and applied overseas to alert the public to hot days and heatwaves, so that preventive actions can be taken if needed. Early warning systems can also give alerts to the health sector, such as ambulances and emergency departments. For example, the Australian Bureau of Meteorology has publicly released national 7-day heatwave severity maps since 2014, based on the EHF (Nairn et al 2018).

When setting up a heat-health warning system, the heatwave definition should align conceptually with the description of heatwaves. Additionally, the selection of "an appropriate definition of heatwaves should consider both the number of alerts it could trigger (in terms of the number of heatwave days identified) and the scales for heatwave effect measures (RR and attributable mortality)" (Kanti et al 2022). This suggests that the definition should identify a 'middle-ground' of heatwave episodes in any given season, that is, not too many to make the definition meaningless and not too few to highlight only one-off events. The heatwave definition should also be sufficiently flexible to cope with the effects of future climate change and should allow for easy communication with the public.

From a climatological standpoint, the EHF and MetService approaches both make sense to use, as they include both the daily maximum (T_{max}) and minimum (T_{min}) temperatures in the same index (Perkins and Alexander 2013). For public health, it is useful to account for higher nighttime temperatures, as these tend to aggravate already warm daytime temperatures (while cooler nighttime temperatures can somewhat counteract hot daytime temperatures, as it allows for cooling and recovery). By accounting for minimum temperature and the climatology of each location, the EHF and MetService also intrinsically include humidity, according to the authors (Nairn and Fawcett 2015, Wondmagegn et al 2021).

The EHF conceptually aligns well with the general understanding of heatwaves, as it measures periods of unusually hot weather, for that local area, of at least three days duration. The EHF is also used already in Australia as the basis for their heat-health warning systems, with public health actions relating to each level of EHF severity (for example, only certain severity levels are used for public alerts) (Varghese el al 2019). Given that the EHF identifies many episodes and days per season, the EHF has the potential to considerably lower the impact of heatwaves on public health. However, too many alerts during a summer season might result in the public not taking the warnings seriously.

This suggests that the EHF is a useful measure for monitoring the health impacts of heatwaves. For a heat alert system, a subset of the EHF alerts (eg severe/extreme heatwaves) could be used as the basis for public alerts and public health actions (Varghese et al 2019). In this study, we identified EHF severe heatwaves by using the 85th percentile that has been published as guidance in Australia. However, there is the potential to further investigate what thresholds are used for the low-intensity, severe and extreme heatwaves if required in the New Zealand setting. For example, a study in Perth investigated these EHF thresholds, and found that either the 80th or 85th percentile worked well as the severity threshold in Perth (Epidemiology Directorate 2022).

The MetService heat alert system has been used for the past five years in New Zealand. It currently acts as an early warning system that forecasts unusually hot weather in specific locations, in part for potential health effects and also to help inform outdoor activities on particularly hot days (for example, for outdoor workers). However, the MetService approach has not been designed specifically based on heat-health relationships or as a heat-health warning system, but instead for forecasts for unusual/extreme heat (Griffiths and Nabi 2023). This heat alert system triggers alerts based on either one-day daily maximum temperatures, or two-day daily mean temperatures. The thresholds for these triggers are decided each season by the MetService, based on very high thresholds (99.5th percentile), and have sometimes been adapted based on public feedback. The aim is to warn the public, so thresholds are set very high; however, this may not capture all events of interest. The risk is that the MetService approach might miss heatwaves that have relatively cooler temperatures but go on for longer, which is known to have a substantial impact on public health.

On balance, if a heat-health warning system was being developed for New Zealand, based on known health links, the EHF should be considered, and further investigated. The EHF has strong links with excess mortality, aligns better conceptually with heatwave definitions, is more flexible, and has clear linked health action plans in Australia, that could be used as the basis for a New Zealand system.

Development of national surveillance system for the health impacts of heatwaves

Secondly, these results could be used to inform the development of a national surveillance system for New Zealand to monitor heatwaves and their effect on mortality. No surveillance system for heatwaves and health impacts currently exists in New Zealand to measure the burden of heat-attributable mortality. With an increasing number of heatwaves likely due to climate change, it will become increasingly important to monitor the impact of heatwaves on the health of New Zealanders. Additionally, overlaying nationwide heatwave patterns with population vulnerability information would help highlight the geographic areas most at risk of heat-related health outcomes during the summer months, to guide preparedness and adaptation measures.

Conclusion

This study showed that heatwaves have had a significant impact on mortality in Auckland and Canterbury since 2000/01. We found that both the Excess Heat Factor (EHF) and MetService approaches identified a number of heatwave episodes in Canterbury and Auckland from 2000/01 to 2020/21, with the EHF approach identifying the most heatwave days overall. EHF heatwave episodes also had longer duration and somewhat cooler daily maximum temperatures than MetService heat alert days, which were often only 1–2 days in duration and were generally very hot days. Both the EHF and MetService approaches were associated with significant excess mortality, although the EHF approach was associated with higher excess mortality in both Canterbury and Auckland.

Deciding which definition to use for identifying heatwaves depends considerably on the intended purpose and the desired outcomes. For a heat-health warning system, a preferred heatwave definition would ideally align conceptually to heatwave definitions from the health literature (of being unusually hot weather of at least 2–3 days duration), would identify periods of higher-than-normal temperatures (both daytime and overnight), would be strongly associated with health impacts, and would have the potential for different thresholds linked to different public health actions.

From this perspective, the EHF approach warrants further investigation, as it meets these criteria better than the current the MetService heat alert approach, was associated with higher excess mortality in our study, and has been investigated and validated more widely around the world. The EHF also has severity thresholds, which gives flexibility for public heat alerts and public health actions to focus particularly on severe and/or extreme heatwaves, as is currently done in Australia. Nonetheless, the MetService heat alert definition appears to be currently identifying periods of hot weather associated with excess mortality, and has already being implemented operationally.

The findings of this study help improve our understanding of the impact of heatwaves and hot weather on population health in New Zealand, and can help inform the development of a heat-health warning system and/or ongoing surveillance of heatwaves in New Zealand.

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Appendix

Appendix Table 1: Census usually resident population, by Auckland local board area, 2023

Auckland local board areas	Usually resident population (2023)	Number of households (2023)
Rodney Local Board Area	77,949	26,553
Hibiscus and Bays Local Board Area	114,033	40,134
Upper Harbour Local Board Area	76,959	25,095
Kaipātiki Local Board Area	88,128	29,760
Devonport-Takapuna Local Board Area	58,005	21,171
Henderson-Massey Local Board Area	124,779	38,919
Waitākere Ranges Local Board Area	53,898	18,054
Aotea/Great Barrier Local Board Area	1,251	627
Waiheke Local Board Area	9,162	3,657
Waitematā Local Board Area	81,546	36,891
Whau Local Board Area	81,273	26,388
Albert-Eden Local Board Area	96,630	32,985
Puketāpapa Local Board Area	56,949	17,952
Ōrākei Local Board Area	83,196	30,357
Maungakiekie-Tāmaki Local Board Area	78,102	26,355
Howick Local Board Area	153,570	46,872
Māngere-Ōtāhuhu Local Board Area	78,642	19,434
Ōtara-Papatoetoe Local Board Area	86,949	22,239
Manurewa Local Board Area	98,784	25,818
Papakura Local Board Area	72,318	21,567
Franklin Local Board Area	84,357	28,677
Auckland total (all local board areas)	**1,656,480**	**539,505**
Auckland study area (excluding Rodney, Hibiscus, Waitākere Ranges, Aotea/Great Barrier, and Franklin Local Board Areas)	**1,324,992**	**425,460**

Source: 2023 Census of Population and Dwellings